GEAR TECHNOLOGY

NOVEMBER/DECEMBER 2003

The Journal of Gear Manufacturing

www.geartechnology.com

GEAR FINISHING

Gear Grinding 2003
High Accuracy Finish Hobbing
Superfinishing Gears

ALSO IN THIS ISSUE:
SPC for Gear Manufacturers

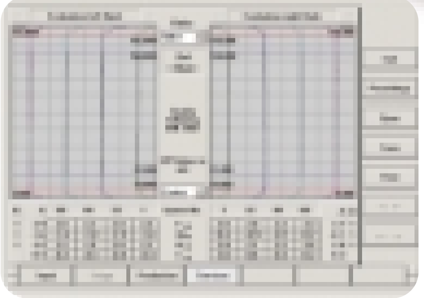
THE GEAR INDUSTRY'S INFORMATION SOURCE

THE WORLD LEADER IN FORM GRINDERS

Hundreds of Installations Worldwide...

Superior Design

- On-machine dressing integrates the dressing unit with the grinding head to ensure the highest level of repeatability. Compensation for wheel wear between dresses is automatic.
- Designed with the flexibility to also grind internal and external gears with Gleason high-precision plated CBN wheels.
- On-machine inspection analyzes stock distribution, and compensates for heat treat distortion and part runout. The grinding cycle is optimized automatically.

Powerful Software

- Grinding technology database recommends and optimizes the “perfect production” methodology.
- K-Chart inspection allows specific input for both profile and lead modifications.
- Tooth twist compensation for noise-control and high performance applications corrects tooth profile deviations.

For gear diameters from 400 to 4,000 mm, Gleason-Pfauter Form Grinders can take the time, cost and question marks out of your process, and put more profitability in.

Call us, or visit www.gleason.com for real-world examples of this technology at work.

Gleason Corporation

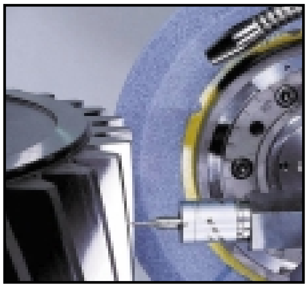
1000 University Ave., P.O. Box 22970
Rochester, NY 14607-1282 U.S.A.
Phone: 585/473-1000 Fax: 585/461-4348
Web site: www.gleason.com E-mail: sales@gleason.com

GEAR TECHNOLOGY

NOVEMBER/DECEMBER 2003

The Journal of Gear Manufacturing

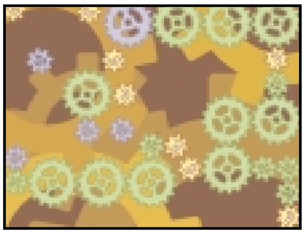
GEAR FINISHING



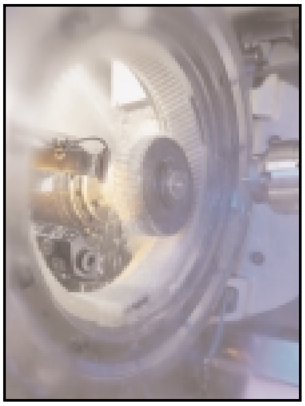
13

FEATURES

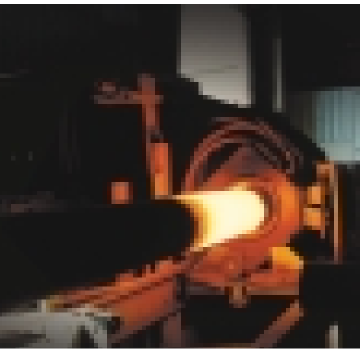
DEPARTMENTS

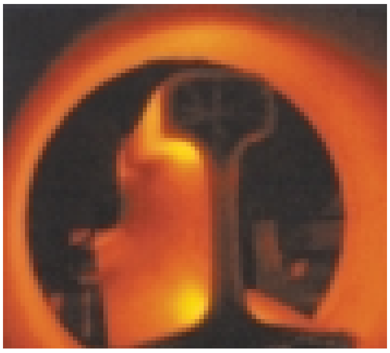


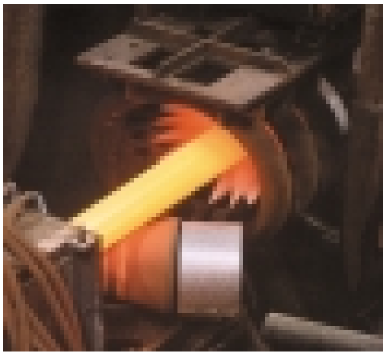
56

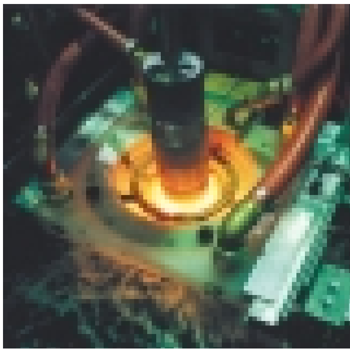


On the cover: The Gleason-Hurth ZH200 Gear Honing Machine. Courtesy of the Gleason Corp., Rochester, NY.









GEAR TECHNOLOGY

The Journal of Gear Manufacturing

EDITORIAL

Publisher & Editor-in-Chief
Michael Goldstein

Managing Editor William R. Stott

Associate Editor Joseph L. Hazelton

Assistant Editor Robin Wright

Editorial Consultant Paul R. Goldstein

Technical Editors
Robert Errichello
Don McVittie
Robert E. Smith
Dan Thurman

ART

Art Director Jean Bartz

ADVERTISING

Advertising Manager Patricia Flam

Advertising Coordinators
Cheryl Calderon, Carol Tratar

CIRCULATION

Circulation Coordinators
Cheryl Calderon, Carol Tratar

INTERNET

Web Developer Dan MacKenzie

***Gear Industry Home Page*™ Sales**
Patricia Flam

***powertransmission.com*™ Sales**
Clark Hopkins

RANDALL PUBLISHING STAFF

President Michael Goldstein
Vice President Richard Goldstein
Accounting Dianne Borg

Phone: 847-437-6604
E-mail: ***people@geartechnology.com***
Web: ***www.geartechnology.com***
www.powertransmission.com

BPA INTERNATIONAL

VOL. 20, NO. 6

GEAR TECHNOLOGY, The Journal of Gear Manufacturing (ISSN 0743-6858) is published bimonthly by Randall Publishing, Inc., 1425 Lunt Avenue, P.O. Box 1426, Elk Grove Village, IL 60007, (847) 437-6604. Cover price $5.00 U.S. Periodical postage paid at Arlington Heights, IL, and at additional mailing office (USPS No. 749-290). Randall Publishing makes every effort to ensure that the processes described in GEAR TECHNOLOGY conform to sound engineering practice. Neither the authors nor the publisher can be held responsible for injuries sustained while following the procedures described. Postmaster: Send address changes to GEAR TECHNOLOGY, The Journal of Gear Manufacturing, 1425 Lunt Avenue, P.O. Box 1426, Elk Grove Village, IL, 60007.

NEED TO CHECK GEARS?

Check Marposs For All
The Gear You Need

Looking for an easy, cost-effective way to check gears? Marposs has the solution – the M62 bench gauge system. It's accurate, flexible and right at home on the shop floor.

No more dedicated gauges

The modular M62 system is quickly re-toolable using ordinary hand tools. You'll save time and the cost of dedicated gauges.

A single-source for all of your gear inspection needs

No one has a more complete line of gear checking equipment than Marposs, so every component is guaranteed compatible. Forget mixing and matching.

If you are looking for easier, more accurate gear checking plus optional noise detection, take a look at the Marposs M62 bench gauge system. It's geared just for you.

M62 Double Flank Gear Roller

Manual loading of gear wheels and gear shafts

Measures:

- Radial composite deviation
- Radial runout
- Tooth to tooth radial composite deviation
- Tangential composite deviation
- Nicks
- Optional measurements include center distance, bore diameter and perpendicularity of bore to gear face
- Optional noise detection

All functional checks can be displayed on the rugged E9066 industrial PC system which offers a linear graphic display with full SPC functions

M62 OBD Gear Gauge

- OBD, PD and root diameter inspection
- Re-toolable
- Multiple standard capabilities
- Ball or pin contacts
- Shaft and ring-type parts
- Manual gear rollers
- Manual or automatic operation
- Statistical packages available

Gear Masters/Gauges

- Go-no go gauges
- Thread gauges
- Spline gauges
- Plain masters and master gears

MARPOSS

3300 Cross Creek Parkway
Auburn Hills, MI 48326-2758
1-888-627-7677
Fax: 248-370-0621
E-mail: marposs@us.marposs.com
www.marposs.com

POSTCARD FROM GEAR EXPO

Dear Gear Product Manufacturer:

Where were you? We were hoping to see you here at Gear Expo. We were surprised that you didn't make it. Anyway, we had a really good show, along with more than a hundred other leading companies in the gear industry who exhibited this year. It's really too bad you weren't here. You missed out on a great opportunity.

If you had any questions about gear manufacturing or were curious about how to increase your productivity, improve quality or lower cost, the answers could have been found at Gear Expo. If you were struggling with any aspect of your gear operation, coming to Columbus could have helped you. I guess everything must be running pretty smoothly, efficiently and profitably back at your place.

For four days, Gear Expo provided access to the greatest collection of knowledge and experience regarding the manufacture and processing of gears anywhere on the planet. In one building were gathered the people who design, build, sell, install and service the machines, along with manufacturers and suppliers of every other product and service used in gear manufacturing, not to mention the manufacturers of gears, gear motors and gearboxes who exhibited—a real cornucopia. There were also gear seminars by SME. Boy, you really did miss a unique event!

One gear manufacturer who was there told us how learning more about different processes and incorporating new technologies might help him remain competitive, especially in light of the pressure he's feeling from overseas competition.

I talked with another gear manufacturer who always comes to the show. He said he likes to reaffirm relationships with existing suppliers and form relationships with new suppliers. It's a quick and easy way to put faces with names of so many important suppliers.

Aside from the business of the show, there was even a little bit of fun. Segway was there with several of their "personal mobility devices," which you may have heard about. In fact, Axicon Technologies, Schafer Gear and SU America arranged to have one Segway donated for a charity raffle to support the AGMA Foundation. A lot of people had fun trying out the Segway, including yours truly, who almost took out the Balzers booth while looking for the hand brakes that weren't there. (Sorry, guys!)

We're sorry we didn't get to see you. But at least we saw some of your competitors—you know, the ones who are continually investing in new equipment and looking for solutions to make them more productive, efficient or profitable. I'm sure we'll see them again at Gear Expo 2005 in Detroit. I hope we'll see you too.

Michael

Mitch Jurek, managing director of HSW USA Inc., won *Gear Technology*'s gear clock raffle.

photo courtesy of Hans-Jürgen Geiger

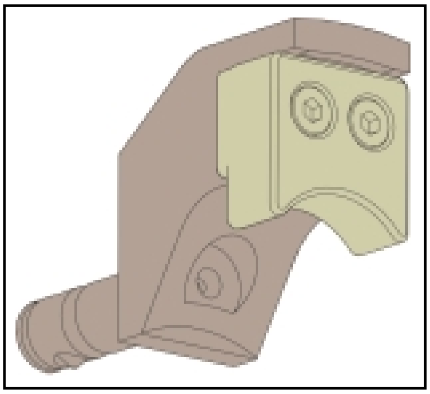

BK
BOURN&KOCH
100H Series II

Holding Gears in Place for Quick Operations

SMW Autoblok of Wheeling, IL, has a chucking solution for gear companies needing just-in-time production of small lot sizes and changing from one part to another.

"Every customer I've ever talked to says that the industry is moving in our direction. The segment of the market that's growing the most is the smaller jobs like the ones we specialize in," says Sid Roth, president of SMW.

SMW's DFR-ABS line of quick jaw-change diaphragm chucks are designed for quantities of smaller batches requiring frequent changeovers of the chuck jaws and locators.



Type A jaws can be machined for new jobs and changeovers.

The DFR-ABS chuck is guaranteed to within 2–3 microns. It's commonly used for the final machining of gears after the hardening process. The chucks can also be used in other hard turning, grinding and precision turning operations, Roth says.

An initial set-up of the chuck is required to "dial-in" the jaws with a master gear. Ordinarily this is done by SMW (not the user); it's never necessary to repeat this process, and this is what allows the quick change of the jaws. The chucks can be changed from one part to another in minutes, depending on the operator. That includes changing three jaws and the pull-down locator, which gives the part's axial location when the jaws close.

The jaws will pull the workpiece down slightly when they close and the locator provides a positive stop so the face of the gear is completely flat and parallel to the opposite side face. Therefore, when a cutting tool is run across the face of the gear, the cut is parallel to the opposite side face and the part turns out cylindrical after the gear's bore is machined.

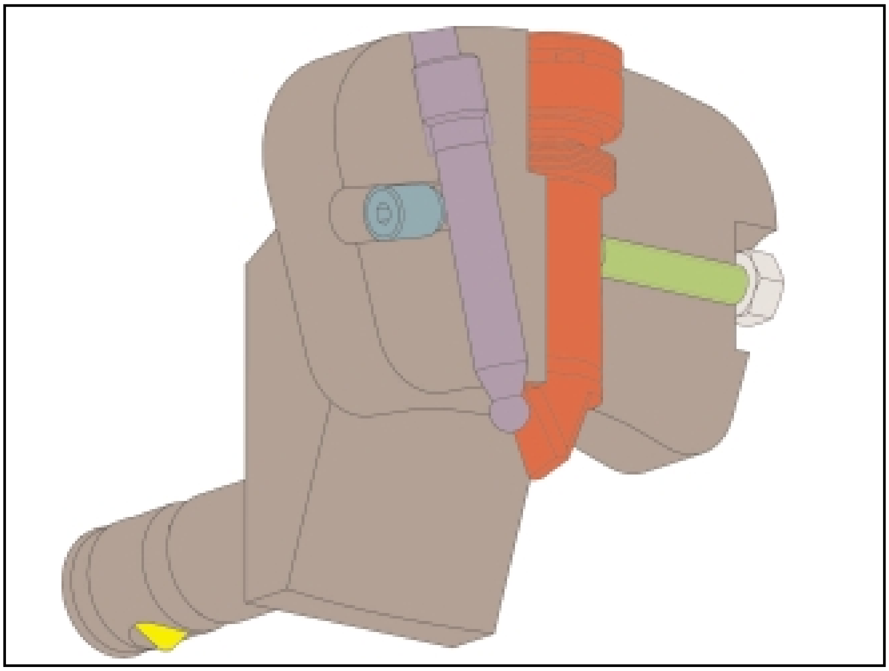
Three types of jaws are used for clamping with the DFR-ABS. Type A jaws use standard master jaws and inserts to clamp on the outside diameter of a gear. They can be machined for new jobs and changeovers. Type A's are provided with a set-up ring so the inserts can be turned to the proper diameter.

Welcome to **Revolutions**, *the column that brings you the latest, most up-to-date and easy-to-read information about the people and technology of the gear industry.* **Revolutions** *welcomes your submissions. Please send them to* **Gear Technology**, *P.O. Box 1426, Elk Grove Village, IL 60009, fax (847) 437-6618 or e-mail* **people@geartechnology.com**. *If you'd like more information about any of the articles that appear, please use Rapid Reader Response at* **www.geartechnology.com/rrr.htm.**

Type B jaws are designed with steel balls to clamp in the gear pitchline. The pin clamping jaws locate and clamp in the tooth spaces of the gear, and the clamping is only as accurate as the tolerance of the tooth spaces.

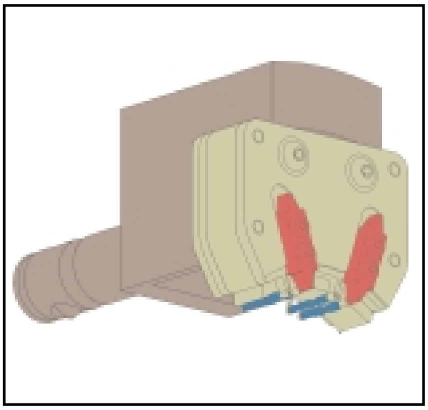
Type C jaws are designed with a single clamping pin for use in the pitchline of the gear. This type has the highest accuracy for clamping in finished gear teeth. Included in the workholding is a micrometer fine adjustment so the clamping pins can be dialed in exactly on the centerline with a master gear and a prelocator pin.

The latest version of the chuck, called the DFR-ABS KOMBI, uses both radial clamping jaws and axial swing clamps. This product is designed for thin-wall gears and for other thin-wall parts that would ordinarily be distorted by radially clamping with three jaws. When the KOMBI first clamps the gear, the jaws center the gear on the chuck. The swing



The Type C jaw from SMW is the most accurate for finish clamping gear teeth.

clamps then clamp the face of the gear, and the clamping jaws open so there is no radial force on the part during machining. The double action requires a hydraulic clamping cylinder with two independent pistons, with one piston actuating the clamping jaws and the other actuating the swing clamps.



Type B jaws can only clamp as accurately as the tolerance of the tooth spaces.

Both the DRF-ABS standard and the KOMBI versions allow either one or two media (air and coolant) to pass through the chuck. The air is a part-sensing medium that ensures the part is properly seated on the locator so that when the gear comes into contact with the airflow hole, it stops the flow of air and signals that the gear is in the proper position. The second medium comes through the spindle to a spray nozzle in the center of a part locator. This medium, either air or coolant, flushes away chips and cools the machining process.

Roth believes that SMW's quick-change chucks offer a significant advantage over traditional gear chucks.

The ITW Workholding Group, which includes NA Woodworth, Sheffer Collet, Logansport Cylinder, and SP Manufac-turing products, set the chucking standard for the gear industry decades ago by inventing the universal gear chuck.

ITW's universal gear chuck utilizes a spring-steel diaphragm to create chucking pressure on internal or external surfaces. Plain diameter and pitch-line chuck clamps range from 2–54". It's most commonly used for gears because it can hold 1/3 dimensions over wire plus 5/10 for interchanging gear pin holders.

According to ITW, part changeovers with the universal gear chuck takes several minutes, and accuracy is guaranteed within 0.0001".

"The universal gear chuck lets the customer use a modular chucking approach which allows basically a high accuracy chuck for moderate prices," says Jim McPhall, project manger at ITW Workholding.

Machine Broaches Unusual Sized Gears

To an Elmass machine, the ideal Help Wanted ad would read: Manufacturer needs small machine for production of splines, keyways, internal spur gears and other shapes. Must be able to make unusual sized spur gears, like 80 mm long teeth in a 6 mm bore. Must be broaching-type machine capable of high-volume production of keyways, but can index other parts to cut because otherwise needed for low-volume production.

That would be an ad to an Elmass vertical broaching machine. After all, that's the job it was designed to do.

And to cover several size ranges, Elmass Production of Halle, Belgium, developed three models of that vertical broaching machine. Released in July, the latest models are the P36-700 NC and the P36-500 NC. The third model is the P20-250 NC.

The largest model is the 700 version. It can cut with a force of up to 3.6 tons, and its cutters can reach 700 mm down inside a bore to create spur gear teeth. The 500 model can also cut with a force of up to 3.6 tons. Its cutters can reach 500 mm inside a bore. The smallest model, the 250, cuts with a force of up to 2.0 tons and can reach 250 mm inside a bore.

Besides maximum bore lengths, the models also have minimum bore diameters. The 250 model must have a bore diameter of at least 6 mm. Smaller than that is too small for its toolbar. The 700 model can operate in a bore as small as 24 mm in diameter.

The Elmass machine isn't a conventional broaching machine, though. A normal gear broach cuts all of a gear's teeth at the same time. The Elmass models index their parts, so they cut gear teeth one tooth space at a time.

"Compared with those broaches, our system is slow," says Martin Forrer, managing director of Elmass' Brisbane operation, Elmass (Australia) Pty. Ltd.

As an example of its broaching, the machine's 250 model cuts by lowering its guided toolbar bush into a workpiece bore. The cutter then extends out of the guide bush and begins cutting a spur gear tooth.

According to Forrer, the guide bush is what lets the cutter make long cuts in long, thin bores, like the 250's ability to cut an 80 mm long gear inside a 6 mm bore.

Forrer says the guide bush prevents deflection of the toolbar, prevents misalignment of its cutting tip and neutralizes its cutting forces, reducing vibration so the cutter can create fine tooth surfaces. Forrer adds the machine can improve gears' surface finishes because the cutters' tooth shapes are made precisely, with no side clearance, and because the guide bush reduces vibration.

"We are guided all the way through," Forrer says.

The machine can create gears as close as 15 microns to their specified dimensions. All three models cut internal spur

teeth up to H7 in quality according to DIN 3962, 3963 and 3965. Depending on gear size, H7 quality can be between Q9 to Q11 using AGMA 2000-A88.

The machine can cut spur teeth in bronze, metals, special-grade stainless steels and many industrial plastics, and they can cut them in difficult configurations, like two timed gears with different tooth depths or a long part with a short gear in its center.

As a broaching-type machine, the Elmass machine creates chips much like conventional broaching machines. During cutting, the chip curls in front of the cutting teeth. If the chip gets too long, it just breaks off and falls down.

Also like conventional gear broaches, Elmass broaches can be resharpened with a normal surface grinder. And the tools don't lose their tolerances because only the cutting interface is sharpened, not the sides.

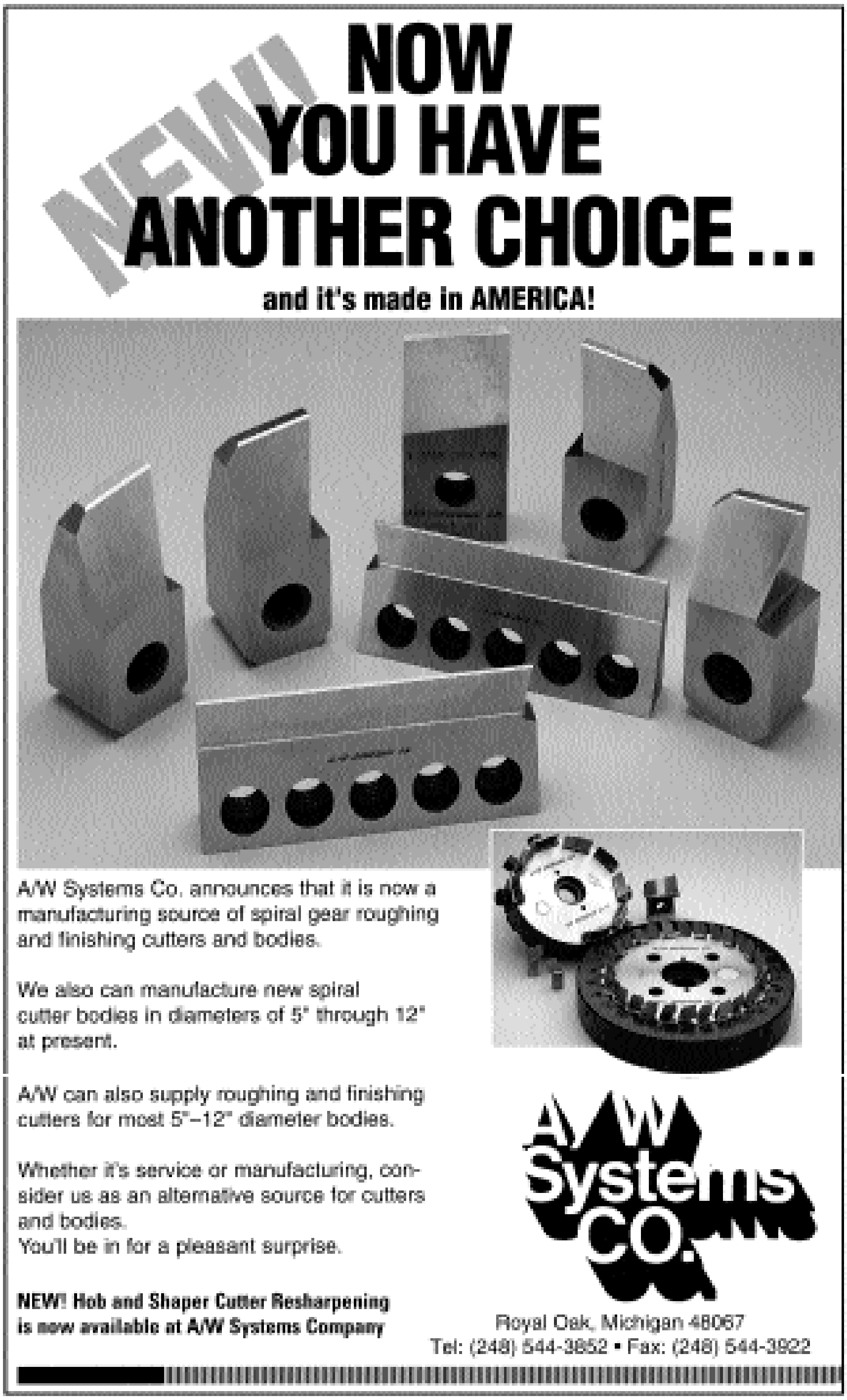
"We never touch the shape," Forrer says.

As for dimensions and weight, the 250 model is 0.65 m deep, 1.05 m wide, 2.6 m high and weighs 950 kg—a little more than a ton. The 500 and 700 models are 0.8 m deep, 2.35 m wide and weigh about 1,100 kg. The 500 model is 2.7 m high, while the 700 model is 3.05 m high. The machine's cutting speed is stepless adjustable and has an upper limit of 15 m/min.

All three models also can be programmed to use English, German, French or Dutch and are available from Elmass' Belgium headquarters and its Brisbane operation.

Forrer adds the system is flexible. By changing the cutter, the machine can be used to manufacture other shapes, including splines, keyways, hexagons, and oil grooves for vacuum pumps. And Elmass can manufacture its cutters to a variety of shapes. Also, cutters can include a chamfer, getting rid of a manufacturing step.

"It's a multipurpose machine," Forrer says. "It's use is very universal." ⚙



Do you have an idea for a Revolutions article?

Contact Joseph Hazelton,
Associate Editor, at
Gear Technology
P.O. Box 1426
Elk Grove Village, IL 60007
hazelton@geartechnology.com

Tell Us What You Think . . .
Visit *www.geartechnology.com* to
- **Rate this column**
- **Request more information**
- **Contact the people or organization mentioned**
- **Make a suggestion**

Or call (847) 437-6604 to talk to one of our editors!

Gear Grinding 2003

Joseph L. Hazelton

The benefits of ground gears are well known. They create less noise, transmit more power and have longer lives than non-ground gears. But grinding has always been thought of as an expensive process, one that was necessary only for aerospace or other high-tech gear manufacturing.

But over the past decade, much has changed in the world of gear grinding—the machines are more productive, the grinding wheels are better and the overall cost of grinding has gone down.

In the mid-1990s, gear grinding began to be incorporated on a wide scale into the operations of a wide variety of industries, including the makers of automobiles, trucks and motorcycles. That trend has continued to the point where, in many of those industries, grinding is ubiquitous.

"Virtually all Tier 1 automotive gear suppliers now have gear grinders or are being compelled to acquire gear grinders to stay competitive," says Brian Cluff, vice president of sales engineering for SU America Inc. and Star-SU Inc., both based in Hoffman Estates, Illinois.

Tom Lang, vice president/general manager of Kapp Technologies L.P. in Boulder, Colorado, agrees that gear grinding and honing are increasing in the U.S. automotive industry: "Today, all of the Big Three automotive companies have new generation automatic transmissions with hard finished transfer gears and final drive gears either in production or slated for production within the next 12–18 months."

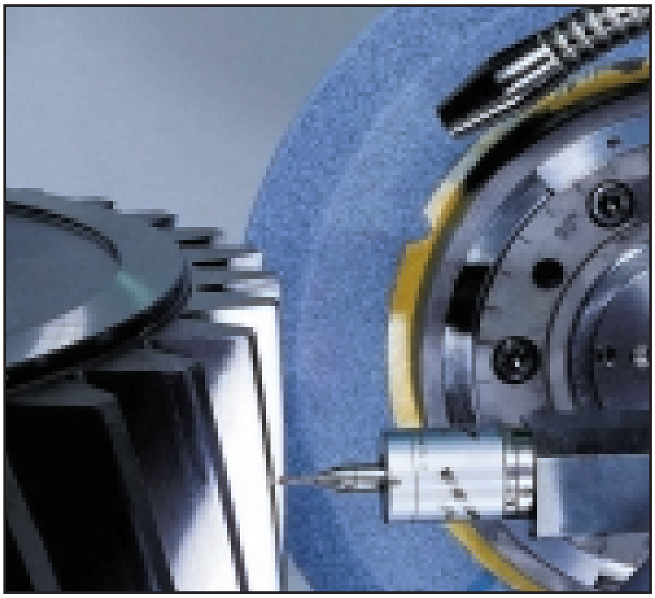
Lang predicts the auto industry will continue to be hard finishing's largest growth market for the next 2–5 years.

The auto industry is increasing its use of hard finishing so it can get rid of heat treat distortion, says Richard E. Scoda of Gleason Corp. Scoda, product manager for Gleason's gear grinding machines, says: "It's nothing to lose 2–3 gear classes [because of heat treat distortion]."

But automakers aren't the only ones grinding more today. "Gear tooth grinding has become more common in today's market," says Gary Rackley, president of Pro-Gear Co. Inc. Based in Depew, New York, Pro-Gear provides gear tooth grinding services.


Photo courtesy of Gleason Corp.

Robert Barden of Niagara Gear Corp. adds that ground gears are now commonly used in the textile, printing, power transmission and motion control industries. Barden is vice president/general manager of Niagara Gear, which is based in Buffalo, New York, and specializes in manufacturing precision ground spur, helical and pump gears.


On-board inspection has become standard on many models of gear grinding machines. Photo courtesy of Kapp Technologies.

"Gear grinding has matured and proliferated throughout the gear industry," says Loyd Koch, owner of Bourn & Koch Machine Tool Co. in Rockford, IL. "Many standard gearboxes use ground gears to better control the backlash and noise. Because standard features and the cost of these operations has continued to come down, ground gears are making their way into lower cost products."

And what industries will next start to use or increase their use of ground gears?

Cluff's answer is simple: "All transmission manufacturers."

In Barden's opinion, a growth industry for ground gears is electric power co-generation.

"This has already become one of the fastest growing segments in the marketplace and presents great potential for future growth," he says, "not only here in the U.S., but abroad."

The wind energy industry is a growth industry in Europe and the United States. In '01 and '02, the European Union installed wind turbines totaling 10,364 megawatts of new capacity, while the U.S. installed 2,106.

Barden expects several factors to promote the use of such alternative energy sources: 1.) rising energy costs, 2.) strict environmental laws, 3.) geopolitical problems in critical, oil-producing regions, 4.) greater demand for energy due to economic development in Third World countries, and 5.) the total

demand for energy surpassing the supply of fossil fuels.

"Demand for alternative energy sources should continue to grow," Barden says. "The development of newer technologies is inevitable."

Machine Tool Improvements

Today's gear grinding machines are much more productive than their counterparts of just a decade ago. This improvement doesn't stem from any one major change. However, a number of significant incremental improvements have made a big difference.

On-Machine Inspection. Many modern gear grinders come standard with on-machine inspection systems. With on-machine inspection, gears are no longer removed from a grinder and inspected elsewhere in a factory. The grinders use their inspection systems to analyze preliminary gear teeth. An operator can then compare actual parameters with specified parameters, make needed corrections and start the job.

"The gear can be checked on the machine and reground until the proper geometry is achieved," says Koch. "The controls can modify the program path using the inspection data taken as part of the grinding process."

Tom Lang agrees that on-machine inspection has been a major change in gear grinders since the mid-'90s. Such inspection speeds set-up, and faster set-ups lead to increased productivity. Lang also says integrated inspection and dressing systems have made modern gear grinders more flexible.

Some grinders also come with on-board dressing, allowing the manufacturer to redress vitrified grinding wheels without a separate device and without removing the grinding wheel from the machine.

In Buffalo, New York, Niagara Gear Corp. can use its grinders' on-board dressing for its vitrified wheels—including its CBN ones. Niagara tested vitrified CBN wheels and learned they could be used effectively, efficiently and economically in those grinders.

Direct Drives. Since the mid-'90s, there's been increased use of direct drive motors with grinding and workpiece spindles.

And the effect?

"Components used in today's machines now run at limits that were unthinkable just a decade ago," Barden says.

Barden and Lang agree the motors have contributed to increased productivity. Barden also credits direct drives with increasing gears' resulting quality.

Scoda says direct-driven spindles allow gear manufacturers to avoid transmission errors that can be present in gear trains because of tooth mesh inaccuracies.

Lang adds that the motors can combine with better vitrified abrasives and sophisticated multi-axis motion control in the dressing and grinding cycles to eliminate ghosting, biased forms, acoustic excitations and detrimental undulations.

Automatic Features. "Automatic" is more and more a word used with gear grinders, especially in serial production.

Automatic features now include parts loading, tool changers, and stock division—the synchronizing of wheel to workpiece.

Lang says automation has eliminated idle time and contributed to a 50% reduction in floor-to-floor times compared with technology from the mid-'90s.

Richmond adds that the ability to easily automate and integrate gear grinders into a factory's material handling systems has been another major change in gear grinding since the mid-'90s.

Machine Software. Windows-based software is becoming as widespread on today's gear grinders as it is on personal computers. More manufacturers are using controllers based on Windows software, Barden says, so machines have become more "adaptive" to constantly changing technologies.

"As a result," Barden says, "tomorrow's ideas can be added to today's machines."

He adds that graphical interface and algorithmic software is more operator friendly, and dressing tools and techniques now allow tooth forms to be programmed and produced in a part that previously could only be drawn on paper.

Software plays a role in another advance since the mid-'90s: self-monitoring. According to Barden, drives and ball screw configurations, scales and sensors now allow for highly accurate, monitored motion in gear grinders.

According to Loyd Koch, many newer gear grinding machines come equipped with position systems that are removed from the driving members. This provides better precision and higher thermal stability, Koch says. He adds that the latest systems use absolute scale and encoder technology connected by serial digital data wiring. The absolute technology enables faster feed rates with higher position resolution and improves the reliability of the machine, Koch says.

Machine Footprint. In some cases, today's gear grinders have smaller footprints, too. Many gear grinding machine manufacturers have redesigned their models to take up less floor space.

The smaller footprints could allow gear manufacturers to better use their current floor space, with the possible effect of "creating" more space. That space might even allow manufacturers to avoid the time and expense of "brick and mortar" work to expand their factories. As Barden notes, the money not spent on brick and mortar could then be used on more equipment.

On the other hand, some gear grinders now come with larger footprints because of the extensive cooling systems often included on the machines' backside, says Cluff.

Grinding Wheels

Just as the machine tools have become more productive over the past decade, so too have the grinding wheels used on them. Most significantly, this is seen in improved vitrified grinding wheels.

Vitrified grinding wheels are much more durable today, Barden says, because of new materials used in blended-grain compositions and because of improvements in the bonding process. They have greater toughness and form holding capability, and they have higher stock removal rates, he says. Barden says those higher rates have resulted from improved grain struc-

tures, including increased porosity. He adds that the better structures have reduced the required grinding forces and lowered the grinding temperatures.

According to Cluff, today's vitrified bonded wheels can be as productive in terms of throughput as electroplated CBN wheels.

According to Barden, the choice between electroplated CBN and vitrified wheels has been blurred by newer, cooler-grinding vitrified abrasives in conjunction with high-pressure coolant systems.

"The choice may not be as readily defined today as it was five or 10 years ago," Barden says.

Lang, however, points out that setting up electroplated CBN wheels isn't as complicated as setting up vitrified wheels, saying the setup time is shorter and there are fewer operator qualification requirements.

Possibly blurring the choice even more are the latest aluminum oxide and ceramic vitrified wheels.

In Elgin, Illinois, Dennis Richmond, vice president of Reishauer Corp., says those wheels can offer a viable, less costly alternative to vitrified CBN wheels.

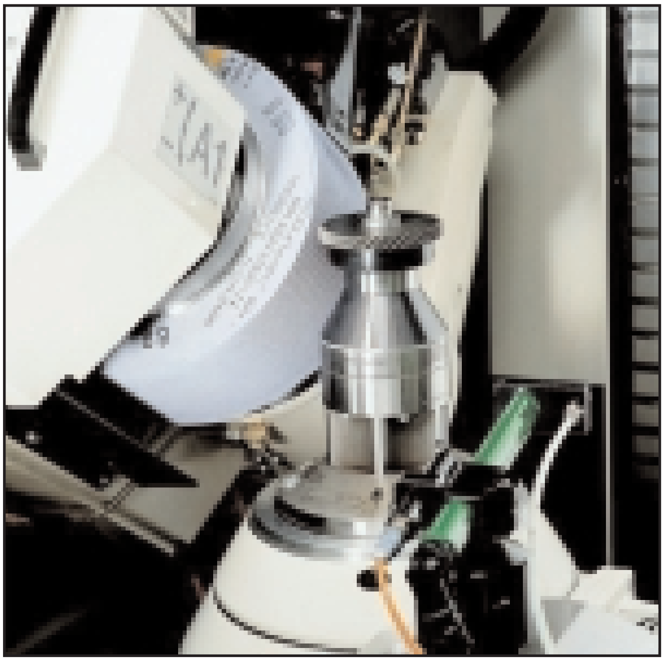
Richmond's company tested those wheels with its "cool cutting" process. Those tests led Richmond and Reishauer to several conclusions:

1) The latest aluminum oxide and ceramic wheels produce the same or less compressive stress as vitrified CBN wheels.

2.) Contrary to expectations, they were more productive than CBN wheels and had lower perishable costs.

3.) Unlike electroplated CBN wheels, they can be sharpened or refurbished by a gear manufacturer on the gear grinder. Electroplated CBN wheels have to be sent back to their manufacturer.

Richmond adds that the aluminum oxide and ceramic wheels can set new productivity standards.



Gear grinding machines and wheels are much more productive than they were a decade ago. Photo courtesy of Reishauer Corp.

Scoda echoes Richmond about ceramic's productivity. Scoda says ceramic wheels are used for maximum productivity applications, explaining ceramic wheels with multiple starts require higher surface speeds, such as 60 meters per second. He adds that the wheels have significantly longer lives than earlier wheels, such as vitrified aluminum oxide.

Scoda adds that the new wheel technology has greatly affected threaded wheel grinding of gears with diameters of 200 mm or less because gears of that size are made in high volume.

"That's where you get the biggest bang for the buck," he says.

Costs to Grind

Despite the significant gains in productivity and machine capabilities, the cost of gear grinding machines has remained constant—or in some cases even fallen—since the mid-'90s.

"The price of the equipment has remained relatively consistent since the mid-'90s," Richmond says, referring to gear grinding machines.

Lang, however, says today's gear grinders cost less—up to 30% less—through new, cost-efficient machine models based on modular design, such as common bases for grinding and honing machines and other identical parts. He also credits CNC systems and series production with helping reduce the gear grinders' cost.

Koch agrees that the cost of gear grinders has come down. "Even with all this sophistication, the machines sell for much less than the early machines," Koch says.

In addition to the cost of the machines, their greater productivity has made the cost of operating them fall as well. Richmond says the cost of grinding itself has decreased—in many cases, to less than 50 cents a gear. Richmond attributes the decrease to cycle times that can be 50–70% faster than in the past and to low costs for perishables, such as grinding wheels and diamond dressing tools.

And Barden agrees that grinding is cheaper today: "Costs have been drastically reduced."

The Future of Gear Grinding

Improvements in machine tools and cutting tools, the maturation of the technology, increased quality demands and lower overall costs point to a healthy future for gear grinding—at least that's what gear manufacturers involved in grinding seem to be saying.

"I think we are safe to go ahead and plan that next big purchase," Barden says. ⚙

Tell Us What You Think . . .
Send e-mail to *people@geartechnology.com* to
- **Rate this column**
- **Request more information**
- **Contact the companies mentioned**
- **Make a suggestion**

Or call (847) 437-6604 to talk to one of our editors!

November 4–6—Grinding Principles & Practice. TechSolve Cincinnati Headquarters, Cincinnati, OH. Attendees can understand the effects of machine power, stiffness and conditioning as well as increase troubleshooting skills, review wheel selection, design optimal grinding cycles and identify constraints. $795 for SME and TechSolve members, $895 for non-members. For more information, visit SME on the Internet at *www.sme.org*.

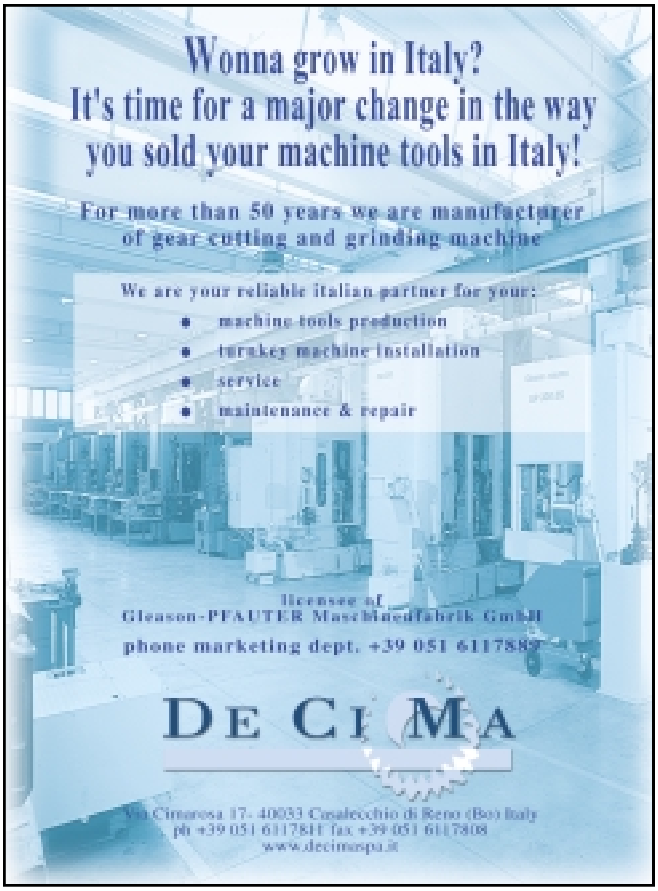
November 5–7—SMMA 2003 Fall Technical Conference for the Motors & Drives Industry. Sheraton Music City Hotel, Nashville, TN. Conference participants can expect tabletop exhibits for SMMA supplier members and speakers, plant tours, technical paper presentations, networking and break-out sessions. For SMMA members, $560 with a CD of the proceedings and $460 without the CD. For non-members, $635 with the CD, $535 without the CD. A discounted registration is available for prospective members. For more information, contact the SMMA by telephone at (508) 979-5935 or by e-mail at *info@smma.org*.

November 10–13—Introduction to Gear Cutting & Measurement. Coventry City College, Coventry, U.K. The program will cover basic involute gear theory and terms for spur and helical gearing. Other topics include gear measurement, principles of gear hobbing and shaping, selection of index and feed gears. Cost is £595 (approx. $697) for BMPTA members and £650 (approx. $741) for non-members. For more information, contact the BMPTA of Staffordshire, U.K., by e-mail at *admin@bga.org.uk*.

December 14–17—International Gear Technology Exhibition for China 2003. Shanghai Everbright Conference & Exhibition Center, Shanghai, China. Part of the larger 2003 China International Machine Components Exhibition, this conference is held alongside Bearing 2003, Machine Parts 2003, and Fastener China 2003. This event has attracted 300 manufacturers from 10 countries. Among its exhibitors are the Korea Metal Industry Cooperative as well as companies like Gleason, Mitsubishi Heavy Industries and Hamai. Attendance is free and pre-registration is required at *www.mparts.com*. For more information, contact Business & Industrial Trade Fairs Ltd. by telephone at (852) 2865-2633 or by e-mail at *enquiry@bitf.com.hk*. ✪

Tell Us What You Think . . .
Send e-mail to
***people@geartechnology.com* to**
- **Rate this column**
- **Request more information**
- **Contact the organizations mentioned**
- **Make a suggestion**

Or call (847) 437-6604 to talk to one of our editors!



Philadelphia Gear Quotes Prices Online

Potential customers can visit *www.philagear.com* to quote prices for replacement parts.

Price quotes can be provided for the company's parts and equipment as well as parts for gearboxes from other companies. According to the company's press release, this system streamlines the ordering process for the replacement parts.

For Philadelphia Gear gearboxes, customers must submit the model number, which is located on the nameplate in the box labeled "size/type." After entering this, customers gain access to a detailed technical drawing.

Non-Philadelphia Gear customers can submit their technical drawing on the Internet site as well as other product-specific information that can help identify the parts.

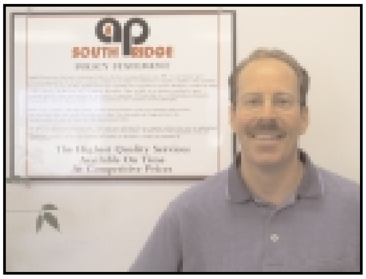
mG miniGears Granted MANA Membership

mG miniGears North America has been awarded membership in the Manufacturers' Agents National Association.

MANA, headquartered in Lake Forest, CA, is the world's largest association of manufacturing agencies.

mG miniGears, of Virginia Beach, VA, specializes in manufacturing smaller-end cut metal and powder metal gears and small gear assemblies and actuators.

New Plant Manager at Applied Process



Mark Stein

Mark Stein was named plant manager of Applied Process's heat treating facility in Elizabethtown, KY.

Previously, Stein was plant manager at Century Sun Metal Treating in Traverse City, MI, as well as metallurgical engineer at the same company.

Applied Process specializes in austempering, a high performance heat treating process for nonferrous metals.

Arrow Gear Offers In-House Design Capabilities

Arrow Gear Co. introduced a computer modeling system for use in the design of spur and helical gears.

Arrow's system uses advanced computer technology to predict the performance of a gear before a part is machined. These techniques include loaded tooth contact analysis, which is used to determine how the gear will be affected in its actual use under load. In addition, Finite Element Analysis is used to study the physical stresses on the gear under load so that engineers can modify the design to provide maximum performance.

IonBond and Cline Tool Announce Venture

IonBond of West St. Paul, MN, and Cline Tool of Newton, IA, offer full service cutting tool resharpening and recoating.

Currently, Cline Tool offers coated cutting products for the gear cutting industry. In addition, hob resharpening services include documentation of wear, serialization of hobs to monitor the number of regrinds, and inventory management.

IonBond offers full service resharpen and recoat programs for customers looking for sourcing for regrinding tooling featuring Cline Tool regrind services.

M&M Precision Receives A2LA Accreditation

The M&M Gear Calibration Laboratory of West Carrollton, OH, is now fully accredited by the American Association for Laboratory Accreditation (A2LA) for the measurement and calibration of master gears, splines, and gear artifacts.

According to the company's press release, this makes M&M the only A2LA accredited gear and spline laboratory. Accredited companies have been tested and found competent for ISO/IEC 17025:1999 (E).

The A2LA is a public service organization dedicated to the formal recognition of component testing and calibration laboratories.

AGMA/ANSI Offer Catalogs on CD-ROM

A CD with standards catalogs from ANSI, ISO, and International Electrotechnical Commission and the American Gear Manufacturers Association is now available. To obtain the CD, visit *www.agma.org*, where members can log in and nonmembers can purchase the CD online.

The ANSI and ISO standards are complimentary. Users must order the AGMA and IEC standards from the standards store. Members receive a 10% discount by entering a special code. Version 6.0 of Adobe Acrobat is required to read the standards.

In addition, ANSI has announced an electronic subscription service that allows members to stay current on standards. Subscribers annually choose the standards they want information on, and their updates arrive periodically. Prices vary depending on the package.

Send your news items to:
Robin Wright, Assistant Editor
Gear Technology
P.O. Box 1426
Elk Grove Village, IL 60007

Tell Us What You Think . . .
Send e-mail to *people@geartechnology.com* to
- **Rate this article**
- **Request more information**
- **Contact the organizations mentioned**
- **Make a suggestion**

Or call (847) 437-6604 to talk to one of our editors!

High Accurate Hobbing With Specially Designed Finishing Hobs

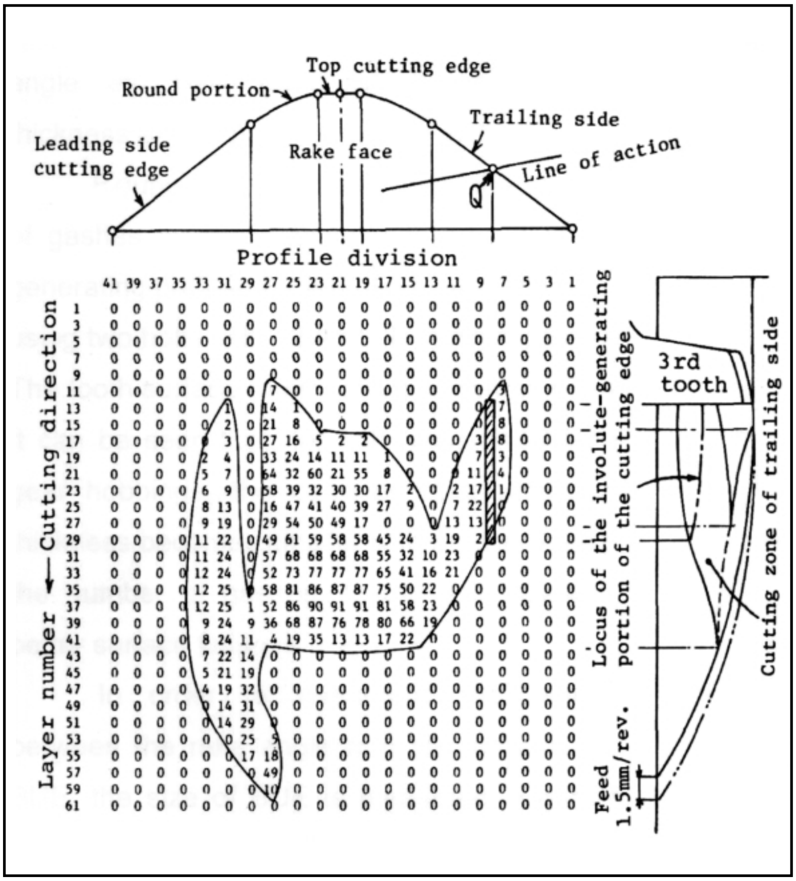
Yasutune Ariura and Yoji Umezaki

Introduction

Load-carrying capacity of gears, especially the surface durability, is influenced by their tooth surface roughness in addition to their tooth profiles and tooth traces (Refs. 1 and 2). The harder the gears are, the smoother their tooth surfaces and the more accurately their tooth profiles should be finished in order to obtain high load-carrying capacity. Through research, the relationship between the cutting thickness (undeformed chip thickness), the size of built-up edge (BUE) and the tooth surface roughness has clarified that the number of gashes and the rake angle in hobs has an effect on the cutting thickness and the BUE formation, respectively. The cermet-tipped hobs developed by Ariura and Umezaki (Ref. 4) have excellent cutting performance with respect to wear resistance, tooth accuracy of hobbed gears and roughness of their tooth surfaces for gear blanks with hardness up to about 400HBW.

For surface hardened gears (550N–800HV), some method of appropriate surface finishing is necessary for removing their distortion after heat treatment. One finishing method is skive hobbing with cemented carbide hobs, as shown by Yonekura and Ainoura (Ref. 5). However, most other finishing methods involve tooth grinding and honing (Refs. 6, 7, and 8).

In this article, the optimal finishing is investigated from a point of view of economy and productivity. This article presents finishing hobs, which are different from skiving hobs. In finishing hobs, the following characteristics are required: (1) good wear and chipping resistance, (2) smooth finishing of tooth surfaces, and (3) high accurate hobbing.



	41	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	3	0	0	0
13	0	0	0	0	0	1	0	14	1	0	0	0	0	0	0	0	0	7	0	0	0
15	0	0	0	0	0	2	0	21	8	0	0	0	0	0	0	0	0	8	0	0	0
17	0	0	0	0	0	3	0	27	16	5	2	2	0	0	0	0	3	8	0	0	0
19	0	0	0	0	2	4	0	33	24	14	11	11	1	0	0	0	7	3	0	0	0
21	0	0	0	0	5	7	0	64	32	60	21	55	8	0	0	0	11	4	0	0	0
23	0	0	0	0	6	9	0	58	39	32	30	30	17	2	0	2	17	1	0	0	0
25	0	0	0	0	8	13	0	16	47	41	40	39	27	9	0	7	22	0	0	0	0
27	0	0	0	0	9	19	0	29	54	50	49	17	0	0	0	13	13	0	0	0	0
29	0	0	0	0	11	22	0	49	61	59	58	58	45	24	3	19	2	0	0	0	0
31	0	0	0	0	11	24	0	57	68	68	68	68	55	32	10	23	0	0	0	0	0
33	0	0	0	0	12	24	0	52	73	77	77	77	65	41	16	21	0	0	0	0	0
35	0	0	0	0	12	25	0	58	81	86	87	87	75	50	22	0	0	0	0	0	0
37	0	0	0	0	12	25	1	52	86	90	91	91	81	58	23	0	0	0	0	0	0
39	0	0	0	0	9	24	9	36	68	87	76	78	80	66	19	0	0	0	0	0	0
41	0	0	0	0	8	24	11	4	19	35	13	13	17	22	0	0	0	0	0	0	0
43	0	0	0	0	7	22	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	5	21	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	4	19	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	14	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	14	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	25	5	0	0	0	0	0	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	17	18	0	0	0	0	0	0	0	0	0	0	0	0	0
57	0	0	0	0	0	0	0	49	0	0	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 1—An example of calculation of undeformed chip thickness (Ref. 9).

Finish Hobbing with High Speed Steel (HSS) Hobs

High speed steel finishing hobs with many gashes and positive rake angles can reduce the size of built-up edges because of the thinner undeformed chip thickness and the positive rake angle. They make the tooth surface smooth, resulting in a few micrometers in peak-to-valley height (*Ry*). A cutting speed of about 20 meters per minute is used for medium hardness gears (300–400HBW) to make BUE small and flank wear rate slow.

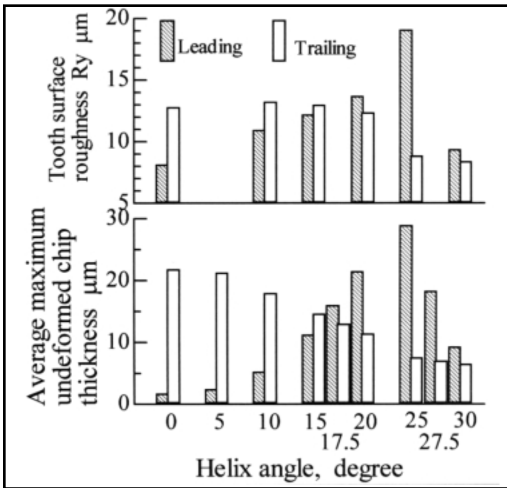
For this paper, we use AISI M35 high speed steel for our comparisons. Figure 1 shows the calculated result of undeformed chip thickness in hobbing. The vertical axis indicates divided layer numbers in vertical sections of the tooth trace. The horizontal axis indicates divided points of the hob tooth profile. The undeformed chip thickness is displayed in micrometers. When each hob tooth passes through many line segments planted in the tooth space, the length of each line segment cut is calculated and converted to an undeformed chip thickness (Ref. 9). The relationship between the maximum thickness removed by the cutting edge at the involute generating portion (Point Q) and the BUE formation is investigated.

Figure 2 shows the relationship between the maximum thickness and the tooth surface roughness in conventional hobbing of right-handed helical gears with various helix angles. The maximum thickness is an average value of the thickness removed by every cutting edge at the generating portion. It is clearly found that the difference in roughness at both flanks and for each helix angle results from the difference in the corresponding maximum thickness respectively. Specifications of the hob, such as outside diameter, number of threads, number of gashes and rake angle, etc., have great effects on the chip thickness and/or the formation of BUE.

Figure 3 shows the effect of the number of gashes on the maximum thickness at the generating portion. Experiments are carried out using two hobs with 12 and 18 straight gashes. The tooth surface roughness is shown in Figure 4. It can be seen that, for both spur and helical gear hobbing, the corresponding maximum thickness becomes smaller by increasing of the number of gashes. This results in relatively better surface finishes.

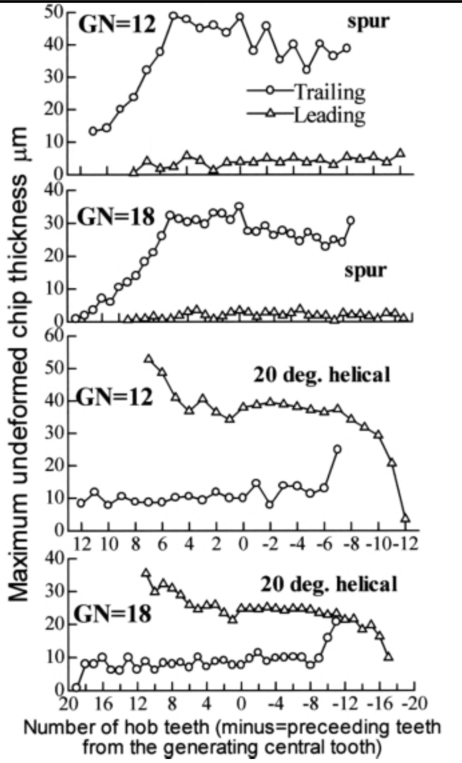
In order to investigate the relationship between the rake angle and the formation of BUE, the size of BUE is measured. Figure 5 shows the size of BUE projecting out on the rake face, which is measured at the involute generating portion of each hob tooth. These two hobs have an equal number of gashes. The maximum thickness removed by them will be about the same in both cases. Large differences in the size of BUE exist; that is, the BUE in the case of the 15° rake angle hob is smaller than that with the 0° rake angle hob. Particularily on the trailing side cutting edge, where usually large chip thicknesses would be removed during spur gear hobbing, a decrease of BUE can be seen in the case of 15° rake angle hobbing. Figure 6 shows the tooth surface roughness. This figure points out that the rake angle has a great influence on cutting with the cutting edge, which removes large chip thickness.

Recently, improving the environment and conserving resources have been needed as well as higher productivity of gear finishing. The changes have led to finish hobbing using cermet and cemented carbide hobs without cutting fluids. Coated HSS hobs are also used to finish at high speeds. However, when the rake face of the hob is not covered with the coating film after regrinding, the finished tooth surface sometimes deteriorates.



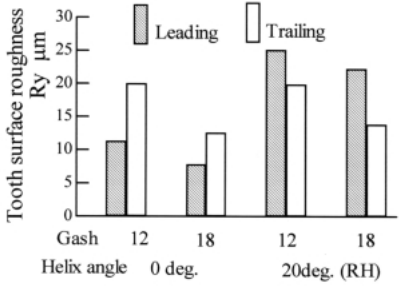
Normalized 0.35% carbon Cr-Mo steel 210HBW, module 3, equivalent no. of teeth 42, RH Helical gear/M35 (no coated HSS), ϕ80, 1-thread (RH), 12 gashes/20 m/min, feed 1.5 mm/rev., wet, conventional hobbing.

Figure 2—Relationship between the maximum thickness and the tooth surface roughness.



(Module 6, RH helical gear, 1-thread (RH) hob, conventional, equal to Fig. 4)

Figure 3—Maximum undeformed chip thickness in hobbing with 12- and 18-gash hobs.



Quenched & tempered 0.40% carbon Cr-Mo steel 320HBW, module 6, z31(Spur), 26(20 deg. RH Helical) / M35(no-coated), 1-thread(RH), ϕ115 / 20 m/min, feed 1.5 mm/rev., wet, conventional hobbing, finishing stock of one side flank 0.1–0.2 mm).

Figure 4—Tooth surface roughness in hobbing with 12- and 18-gash hobs.

Dr. Yasutune Ariura

has been a professor in the Kyushu University Department of Intelligent Machinery and Systems of of Fukuoku, Japan, since 1983. His field of study is gear manufacturing with an emphasis on finish hobbing with cermet- and CBN-tipped hobs, load carrying capacity of hardened, tempered, and surface hardened cylindrical gears as well as the manufacturing and performance of austempered ductile iron gears.

Dr. Yoji Umezaki

has been a research assistant in Kyushu University's Department of Intelligent Machinery and Systems since 1973. His areas of expertise are the analysis of gear hobbing mechanisms, the decrease of hob wear, the improvement of tooth surface roughness of hobbed gears, the analysis of the tooth profiles of hobbed gears, accurate hobbing, and finish hobbing of surface hardened gears with CBN hobs.

Table 1—Chemical compositions and mechanical properties of cermet and carbide tips.

	Chemical Compositions wt%			Mechanical Properties		
	WC	(Ti, Ta, Nb, Mo)CN	Ni, Co	HV	Specific gravity	TRS*
Cermet HTP20	16	68	16	1550	7.0	1960
Carbide HWM10	80.5	14	5.5	1730	12.9	1670

TRS*: Transverse Rupture Strength (N/mm²)

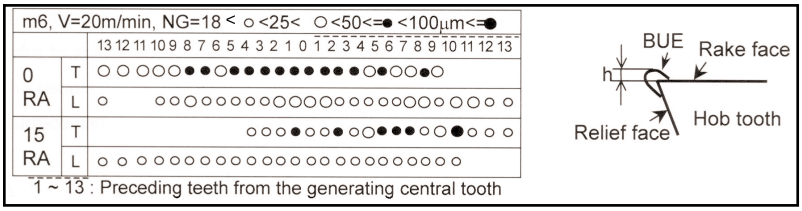
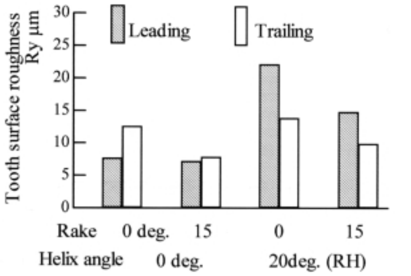
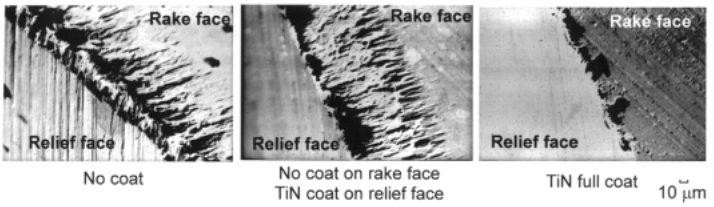


Figure 5—Size of BUE (h) projecting out on the rake face.



(Quenched & tempered 0.40% carbon Cr-Mo steel 320HBW, module 6, no. of teeth 31(Spur), 26(20 deg. RH Helical) / 1-thread(RH), 18-gashes, 115-diameter, M35 (no-coated HSS) / 20 m/min, feed 1.5 mm/rev., wet, conventional hobbing, finishing stock of one side flank 0.1–0.2mm)

Figure 6—Tooth surface roughness in hobbing with 0° and 15° rake angle hobs.



(Normalized 0.35% carbon Cr-Mo steel 210HBW, module 3, no. of teeth 42 Spur / M35 (no-coated), 80-diameter, 1-thread (RH), 12-gashes / 20 m/min, feed 1.5mm/rev., wet, conventional hobbing).

Figure 7—Back scanning electron photographs of the coated and uncoated tool edges.

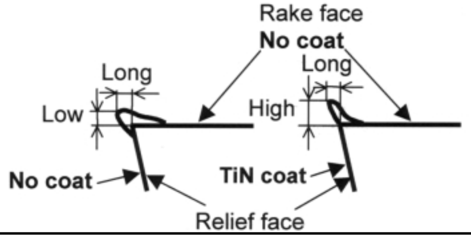
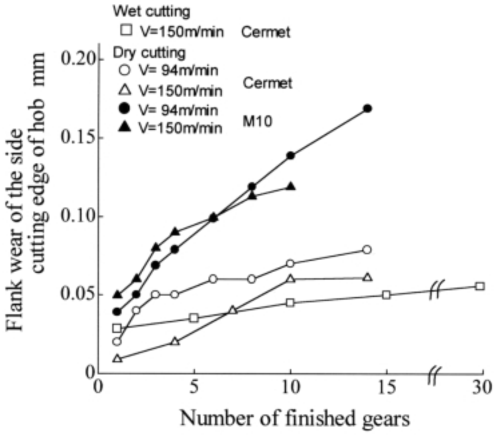


Figure 8—Illustration of the BUE on tool edge.



(Quenched & tempered 0.40% carbon Cr-Mo steel 320HBW, module 6, no. of teeth 31, Face width 55 mm / 1- thread(RH), 150-diameter, 18-gashes, Rake angle = Cemented carbide (M10) 10°, Cermet 0° / feed 1.5 mm/rev., conventional hobbing, finishing stock of one side flank 0.1–0.2 mm)

Figure 9—Wear width of cermet and cemented carbide tipped hobs.

The main cause of the degraded tooth surface is the occurrence of the built-up edge produced on the rake face and the attached fragments as shown in Figure 7. Figure 8 illustrates the adhesive fragments on the rake face. In the case of a hob with an uncoated rake face and a coated relief face, the adhesive fragments are piled higher than in the case of the usual HSS hobs. Few adhesive fragments exist as they do on coated surfaces, such as TiN, TiC, TiAlN and so on.

Finish Hobbing With Cermet-Tipped Finish Hobs

For finishing low and medium hardness gears (160–400HBW), cermet-tipped finish hobs show superior performance to cemented carbide hobs in the wear resistance and the tooth surface qualities. (See Table 1 for chemical compositions and mechanical properties of cermet and carbide tips discussed in this paper.) The cermet-tipped hobs can be applied to higher cutting speeds than the cemented carbide hobs, as the chipping resistance of cermet was recently improved via high transverse rupture strength. The cutting speed of the cermet hob is about 100–200 meters per minute, even in module 6–8 for medium hardness gears. The wear mechanism in cermet and cemented carbide hobs is mainly abrasive, and flank wear is more dominant than crater wear. The accuracy of tooth profile and normal pitch of the cermet hob has a great influence on the tooth profile of finished gears. The finished tooth profile is excellent in the case of hobbing, with the cermet hobs having cutting edges with land width less than about 0.1 mm. Cermets have low affinity with the steel, so they hardly make adhesive fragments on the cutting edges, and they do not require coatings such as TiN. The cermet hob can finish steel gear teeth very smoothly and accurately.

Figure 9 shows the changes in flank wear in finish hobbing with the cermet- and the cemented carbide-tipped hobs. The amount of wear is measured at the leading-side cutting edge and is an average value of the five most-worn teeth. The wear of the cermet finishing hob is about one-third that of the cemented carbide finishing hob when 14 gears are cut. As no chipping of the cermet finishing hob is found under any of these cutting conditions, the stability of the cermet hob for intermittent cutting is excellent. Cutting oil hardly affects the tool wear under these cutting conditions.

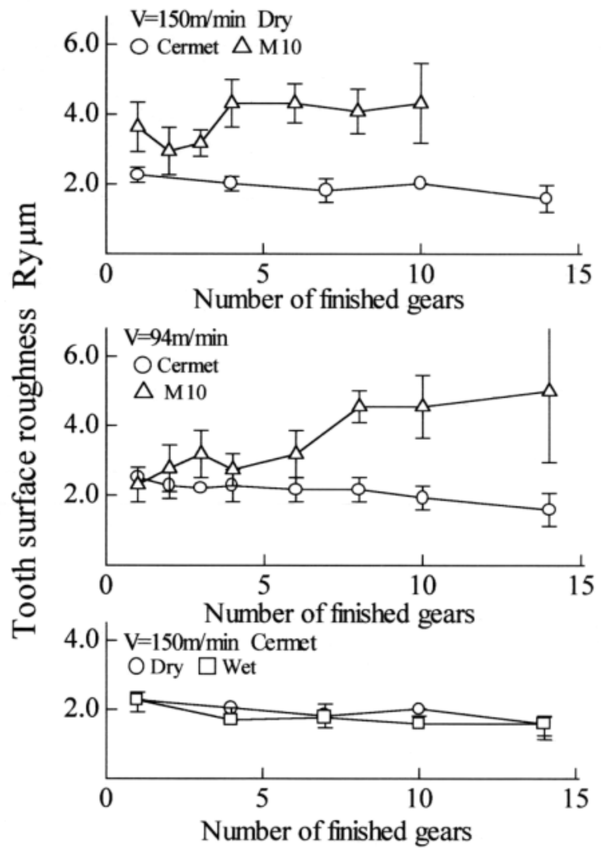
Figure 10 shows the change in tooth surface roughness with the cermet finishing hob and the cemented carbide hob in the case of cutting speeds under dry and wet conditions. The tooth surface roughness obtained by the cermet finishing hob is about half compared with that obtained by the cemented carbide hob; moreover, the variation of tooth surface roughness is very small. The difference of tooth surface roughness in dry cutting and wet cutting is hardly observed.

The roughness of the relief and rake surfaces of the cermet finishing hob are shown in Figure 11. The roughness (*Ry*, peak-to-valley height) is about 0.15 micrometers on the rake surface and about 2.0 micrometers on the relief surface. The roughness of the relief surface is much larger than that of the rake surface. As the shape of the cutting edge is influenced by the irregularity of the relief surface, the tooth surface roughness becomes the same roughness as the relief surface of the hob by transfer. The improvement of the tooth surface roughness is expected by making the relief surface of the hob smooth.

Figure 12 shows the tooth profile curves of gears finished with the cermet finishing hob. The tooth profile is very accurate (ISO class 5) and is minimally degraded because the hob wear occurs at a low rate.

Figure 13 shows photographs of tooth surfaces hobbed with cemented carbide- and cermet-tipped finish hobs. In the case of cemented carbide finish hobbing, many scratches are seen on the tooth surface, as shown in Figure 13(a). This is due to the occurrence of the phenomenon of “chip adhesion” and the formation of BUE (Ref. 4). The surfaces finished with cermet-tipped hobs are very smooth and have no scratches in dry and wet cuttings, as shown in Figure 13(b).

The land at the side cutting edge is useful for improving the hob tooth profile. Figure 14 shows the relationship between the land width and hob flank wear. This data is obtained from one side flank finishing test. In the case of land width of about 0.1 mm, the wear rate at the leading-side edge is slightly different from the case without land. When the flank wear width including the land becomes greater than about 0.25 mm, chipping and flaking occur at the land, resulting in a greater vibration of the hobbing machine and a degradation of surface finish. By attaching the land, the tooth profile error in involute helicoids of hob teeth decreases from 10 micrometers to 5 micrometers, and the pitch error decreases from 8 micrometers to 4 micrometers. The tooth surface roughness is shown in Figure 15. The roughness of the sharp edge (roughness of relief surface) without land is about 2.5 micrometers, and the finished surfaces have about the same roughness regardless



(Condition; equal to Fig. 9)

Figure 10—Tooth surface roughness in finish hobbing.

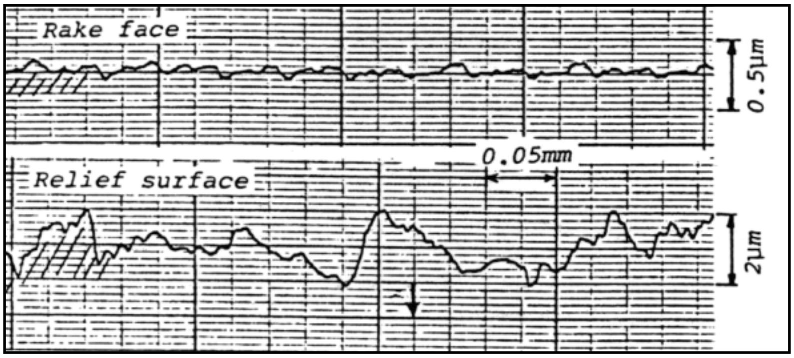


Figure 11—The relief and rake face roughness of the cermet finishing hob.

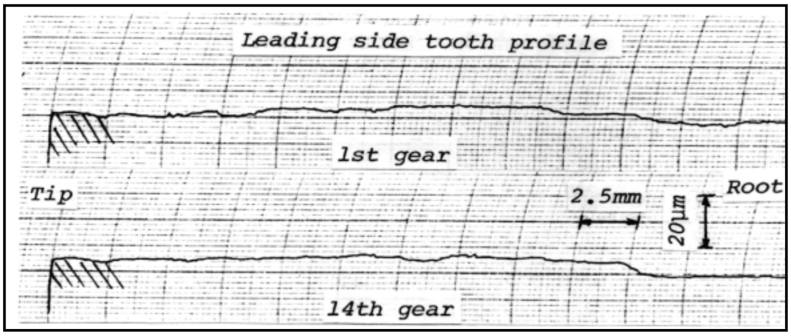


Figure 12—The tooth profile curves of finished gears with the cermet finishing hob.

of number of finished gears. However, the surface roughness becomes smoother after the wear width, which does not include the land width, is greater than 40–50 micrometers in the finishing with land. It is considered that burnishing occurs between the tooth surface and the wear land.

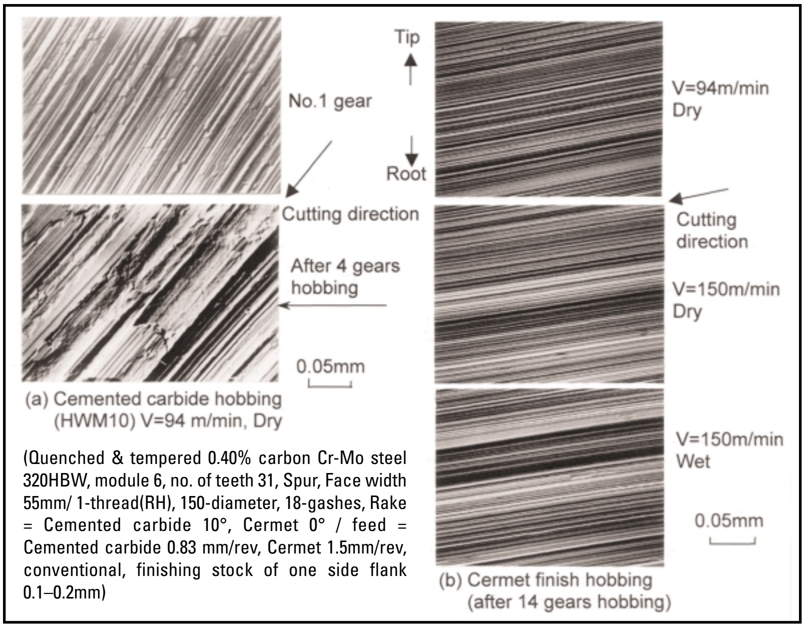
The cermet finish hob is often used for finishing annealed or normalized low carbon alloy steel, though this hob has been developed for quenched and tempered alloy steel. Figure 16 shows the combination of the roughing hob made with TiN-coated high speed steel and the cermet-tipped finishing hob. The cermet hob has a short hob length because of its low wear rate. Using this method, it is possible to omit the shaving process.

Finish Hobbing of High Hardness Gears with CBN-Tipped Hob

Skiving hobs tipped with cemented carbide are used for high hardness, case hardened gears. Skiving hobs are difficult to keep their tooth profile accurate after regrinding owing to the large negative rake angle. The authors have newly developed a CBN-tipped hob, which has many gashes and a 0° rake angle. The CBN tip has low CBN concentration of about 50% boron nitride with ceramic binders (e.g., TiN). Chipping and/or flaking are observed as a dominant wear mode. The CBN-tipped hob shows an excellent cutting performance at a high speed of 600–900 meters per minute for finishing case hardened gears. This is used sufficiently to the extent of the flank wear of 0.15 mm except chamfering width and small chipping. An important technique in manufacturing the CBN-tipped hob is to grind the cutting edges smoothly without chipping. Although CBN tips and their resharpening cost are expensive, the CBN-tipped hob has a possibility for efficiently finishing case hardened gears.

A finishing hob was manufactured for trial using a CBN tip with best wear resistance in fly-tool tests. Hobbing conditions are shown in Table 2. Test gear blanks of chrome molybdenum steel (JIS SCM415) are case hardened to 60HRC at the tooth surface and about 550HV0.1 at 1.2 mm from the surface. The cutting edges of the hob teeth are chamfered by honing with 30–50 micrometers in size on the relief surface. The shape of the CBN-tipped hob is shown in Figure 17.

Figure 18 shows a hobbing test with a CBN-tipped hob on a CNC hobbing machine at 900 meters per minute. The test cutting can be carried out smoothly in spite of spark showers. Chips are blown away by compressed air from the upper



(a) Cemented carbide hobbing (HWM10) V=94 m/min, Dry

(b) Cermet finish hobbing (after 14 gears hobbing)

(Quenched & tempered 0.40% carbon Cr-Mo steel 320HBW, module 6, no. of teeth 31, Spur, Face width 55mm/ 1-thread(RH), 150-diameter, 18-gashes, Rake = Cemented carbide 10°, Cermet 0° / feed = Cemented carbide 0.83 mm/rev, Cermet 1.5mm/rev, conventional, finishing stock of one side flank 0.1–0.2mm)

Figure 13—Back scanning electron photographs of tooth surfaces.

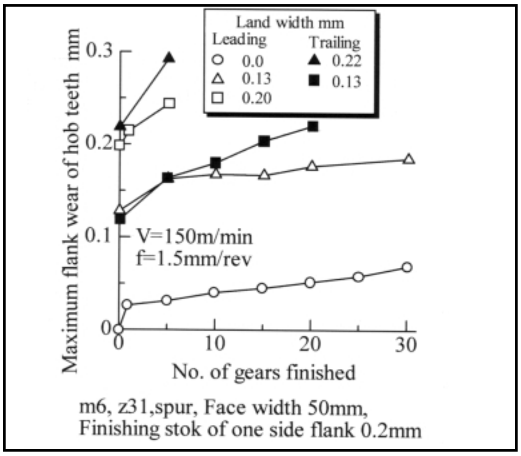


Figure 14—Flank wear of the cermet tipped hob with land width.

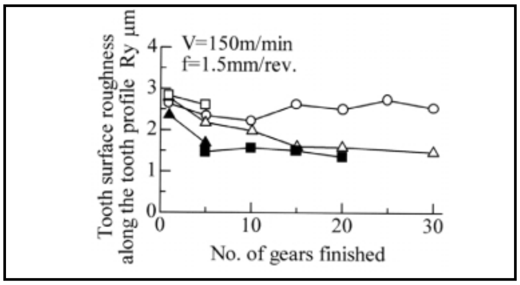


Figure 15—Tooth surface roughness finished with cermet tipped hobs with land.

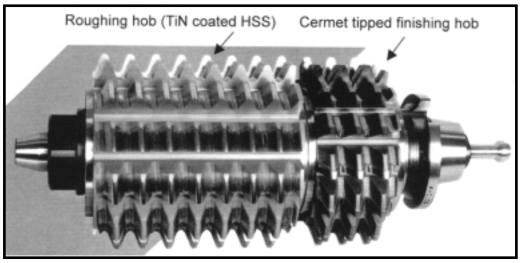


Figure 16—The combination of the roughing hob and the finishing hob.

part of the hob. Many melted chips are seen, and most of them become spheres, as shown in Figure 19. The removal of hot chips is an important problem because they can cause thermal distortion of the machines and damage the surroundings.

Figure 20 shows the wear curves of hob teeth numbers –15 through –19 which precede the central generating tooth and cut chips with relatively larger volumes than the other teeth. The sizes of wear land do not include the size of the chamfer land. In speeds less than 300 meters per minute, the wear of each tooth is small and its wear rate is low. The flank wear of the group of 600–900 meters per minute is about three times to four times as large as those of 150 and 300 meters per minute. The wear rate at 600 meters per minute is low, and the new chipping does not occur during hobbing, except the chipping by grinding when sharpening.

Photographs of these cutting edges are shown in Figure 21. The chipping is apt to occur during grinding of the hob teeth, and it remains after chamfering as shown in Figure 21(a) and (b). New chipping hardly occurs by hobbing; that is, the number and size of chippings are maintained as grinding sharpens the hob. The flaking on the cutting edge occurs just after 10 gears are hobbed at 900 meters per minute. It is seen that this flaking may occur from the –19 tooth to the –16 tooth continuously.

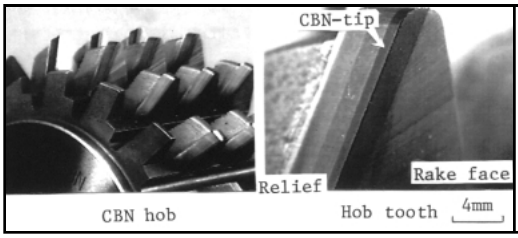
Figure 22 shows the flaking on the No. –19 tooth and its depth. The depth at the deepest point is about 23 micrometers, and it flakes along the edge in the range of about 0.75 mm. Thermal cracks are not found. The adhesive fragments are found on the edge after hobbing in the high-speed tests of 900 meters per minute. It will become an important matter that the behavior of the adhesive fragments is clarified and the method of eliminating the adhesive fragments is investigated.

Figure 23 shows the size of chipping on the relief surface including the chamfer size in tooth numbers –15, –17, –18 and –19. Micro-chippings occur on many hob teeth. The maximum size of chippings is about 0.1 mm. The chippings do not change in size and in number with respect to the number of gears hobbed.

Figure 24 shows the tooth surface roughness of hobbed gears. The roughness at the cutting speed of 300 meters per minute is about 1.0 micrometers in *Ry*, and this value is superior when compared with roughness of other conditions. The roughness remains almost constant, even as the number of gears hobbed increases,

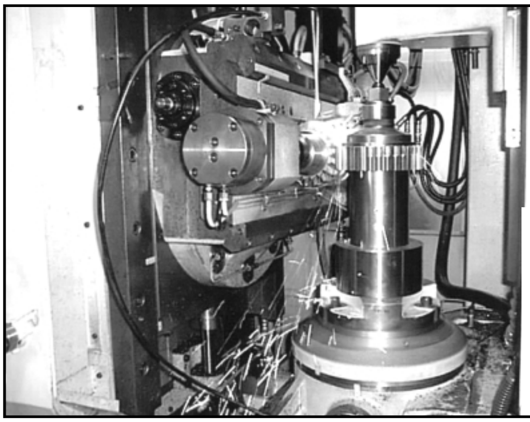
Table 2—Test conditions.

Cutting speed	150, 300, 600, 900 m/min.
Feed	1.5 mm/rev.
Finishing stock	0.1 mm/one side flank
Hobbing machine	NC machine
Hobbing method	Conventional, Dry cutting



(m6, 1-thread (RH), 150-diameter, 18-gashes, 0 deg. Rake angle)

Figure 17—CBN-tipped finishing hob.



(V=900 m/min, f=1.5 mm/rev., Dry, Conventional / m6, Spur, no. of teeth 31, 60HRC, Case-hardened SCM415(JIS) / 1- thread(RH), 150-diameter)

Figure 18—CBN finish hobbing test.

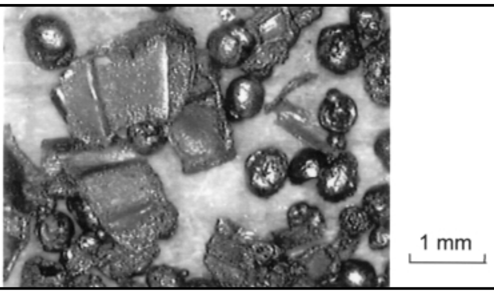
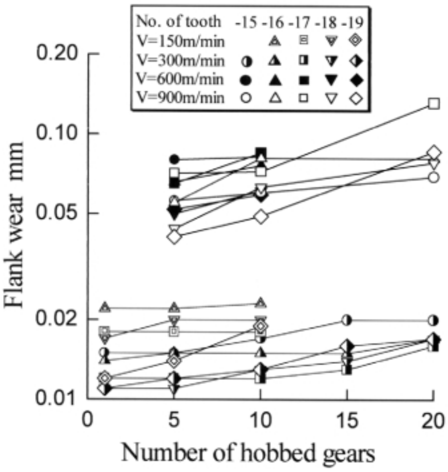


Figure 19—Chips at 900 meters per minute.



(Gear; Case-hardened 0.15% carbon Cr-Mo steel (SCM415) 60HRC, module 6, no. of teeth 31, Face width 55 mm / Hob; 150-diameter, 1-thread(RH), 18-gashes, 0° Rake / Condition; 900 m/min, 1.5 mm/rev., Dry, Conventional hobbing, finishing stock of one side flank 0.1 mm)

Figure 20—Flank wear of CBN-tipped finishing hob.

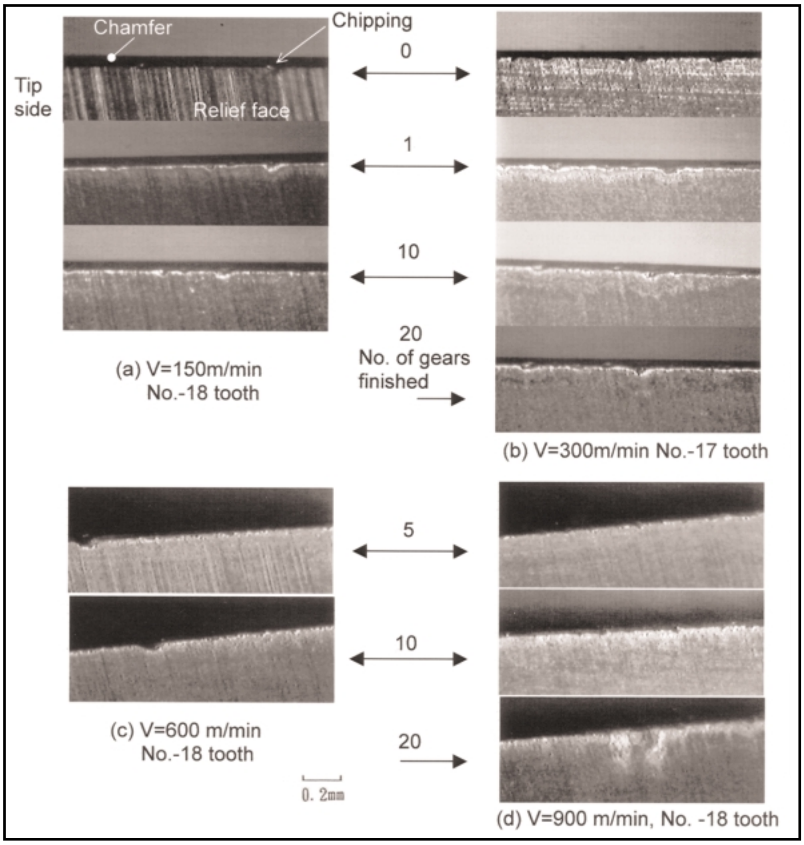


Figure 21—Photographs of flank wear and chipping.

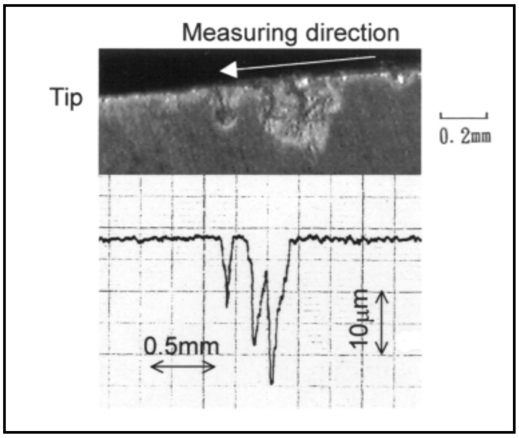


Figure 22—Flaking wear and depth.

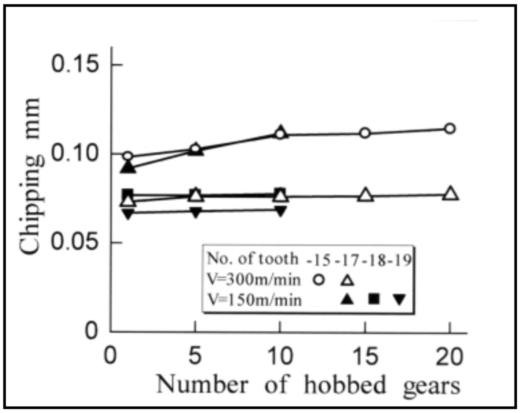


Figure 23—Chipping of CBN-tipped hob at 300 and 150 meters per minute.

and its scatter is narrow. The roughness *Ry* is 1.8–2.4 micrometers on the relief surface of the CBN-tipped hob and 0.2–0.5 micrometers on its rake surface. To finish the relief surface of CBN-tipped hobs smoothly contributes to the improvement of roughness of tooth surfaces hobbed.

Figure 25 shows the tooth profile and the tooth trace of gears hobbed (after 10 gears cut) at the cutting speed of 150 meters per minute. No scratch is found on these profiles. The tooth profile is ISO class 5, that is, about 8 micrometers. The tooth profile and the tooth trace of the trial CBN-tipped hob are about 8 and 6–8 micrometers, respectively.

Figure 26 shows the tooth profiles measured and calculated (Ref. 10) at 900 meters per minute. The tooth profile error is caused by the hob accuracy and the hob eccentricity in setting. Improving the accuracy of the CBN-tipped hob and minimizing the hob eccentricity in setting can achieve excellent accuracy of hobbed gears. The method of tooth grinding of a CBN-tipped hob is a very important factor from a point of view of the hobbed gear accuracy and surface roughness.

Conclusion

For medium hardness gears, the cermet finishing hob is superior in wear resistance and improvement of tooth surface roughness to the cemented carbide finishing hob. The cermet-tipped finish hob is now often used for not only medium module gears such as construction gears, but also small module gears such as small vehicle gears before heat treatment of case hardened steels. The following results and knowledge are obtained.

1. Higher speed cutting (near 150 meters per minute) makes the hob life longer and makes it easy to remove chips from the cutting edge.

2. The cutting edges of the hob teeth should be finished as smoothly as possible, as the irregularity of the cutting edge affects the tooth surface roughness.

3. Chips should be removed completely from the cutting edge after each cutting to improve the tooth surface roughness.

For surface hardened gear materials, CBN tips that have a low CBN concentration (about 50% wt) with ceramic binders are superior in wear and chipping resistance. The CBN-tipped hob made for the trial has excellent wear resistance. The chipping of cutting edges is apt to occur during sharpening of hob teeth, and it influences the surface roughness, though it does not progress during hobbing. Therefore, the prevention of chipping and the improvement of surface roughness in grinding of CBN-tipped hobs are considered to be very important.

The hobbing test at 900 meters per minute of case hardened steels suggests the importance of clarifying the behavior of adhesive fragments for the suppression of flaking and chipping.

Acknowledgments

The authors thank Sumitomo Electric Industries, Ltd. and Azumi Mfg. Co., Ltd. for their support of cermet and CBN tips and manufacturing for trial of cermet- and CBN-tipped hobs, respectively. (This paper was previously published by Gesselschaft Entwicklung Konstruktion Vertrieb at the International Conference on Gears, Vol. 1., VDI-Berichte 1665, Düsseldorf, VDI Verlag 2002, pp. 129–143. Printed with the friendly permission of VDI Verlag GmbH.) ✪

References

1. Ariura, Y., T. Nakanishi, T. Ueno and H. Nara. “Manufacture and Performance of Cylindrical Gears (An Application of New Finish-Hobs for Increasing Surface Durability),” *JSME International Journal*, Vol. 30, No. 267, 1987, pp. 1480–1486.
2. Ishibashi, A., S. Tanaka, and S. Ezoe. “Changes in Contact Surfaces and Surface Durability of Highly Loaded Gears with Roughnesses of 0.1 to 15 µm Rmax,” *Proceedings of the 12th Leeds-Lyon Symposium on Tribology*, 1985, pp. 339–346.
3. Ariura, Y., Y. Umezaki and H. Nara. “Finish Hobbing of Medium Hardness Gears with Cermet-Tipped Hobs,” *Proceedings of the 1989 ASME International Power Transmission and Gearing Conference*, 1989, pp. 691–696.
4. Yonekura, M. and M. Ainoura. “A Research on Finishing Hardened Gears of Large Modules,” ASME, 80-C2/DET-62, 1980.
5. König, W., L. Meijboom, and H.D. Schäfer. “Teilwälzscheiben von einsatzgehärteten Zylinderräden mit CBN Doppel kegelscheiben,” *Antriebstechnik*, 20-7/8. 1981, pp. 314–317.
6. Tsukamoto, R. and F. Haga. “CBN Gear Grinding Technologies for Automotive Gears,” *Proceedings of JSME International Conference on Motion and Power Transmission*, 1991, pp.197–202.
7. Faulstich, I. “CBN-Profile Grinding Cylindrical Gears Using Galvanically Bonded Wheels,” *Proceedings of JSME International Conference on Motion and Power Transmission*, 1991, pp. 213–218.
8. Ariura, Y., Chiu Hua and Y. Umezaki. “Improvement of Gear Accuracy in Gear Hobbing (1st Report, A Numerical Analysis of Tooth Profile Errors),” *JSME International Journal*, Vol. 30, No. 259, 1987, pp. 168–174.

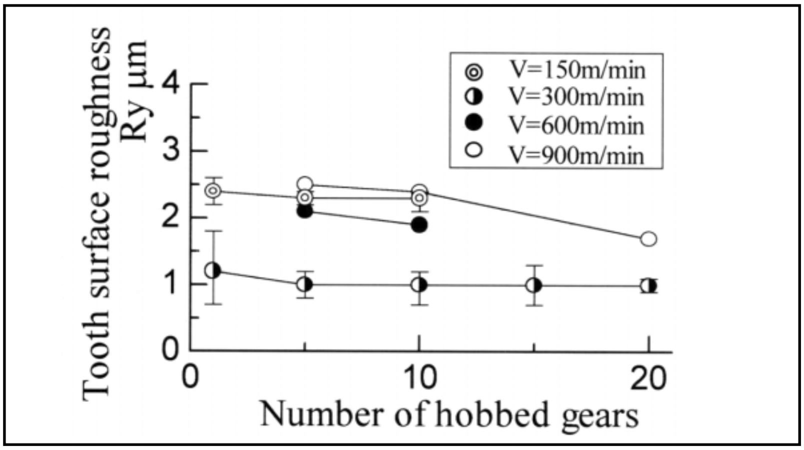


Figure 24—Tooth surface roughness after CBN-tipped hob finishing.

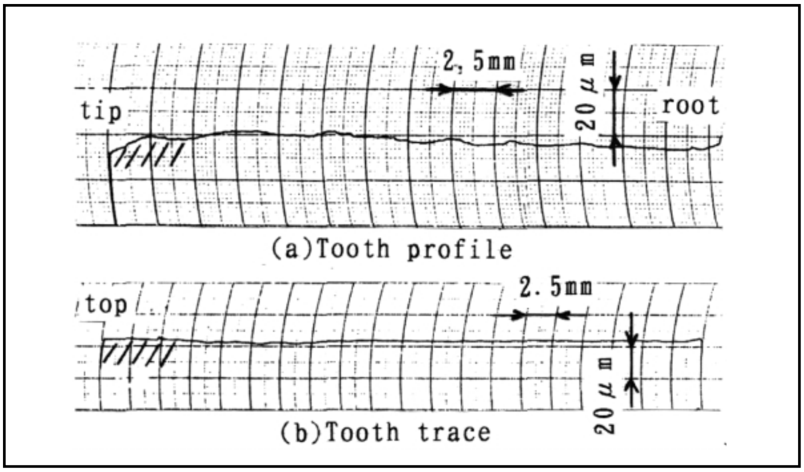


Figure 25—Tooth profile and tooth trace after 10 gears finished with CBN-tipped hob (150 meters per minute).

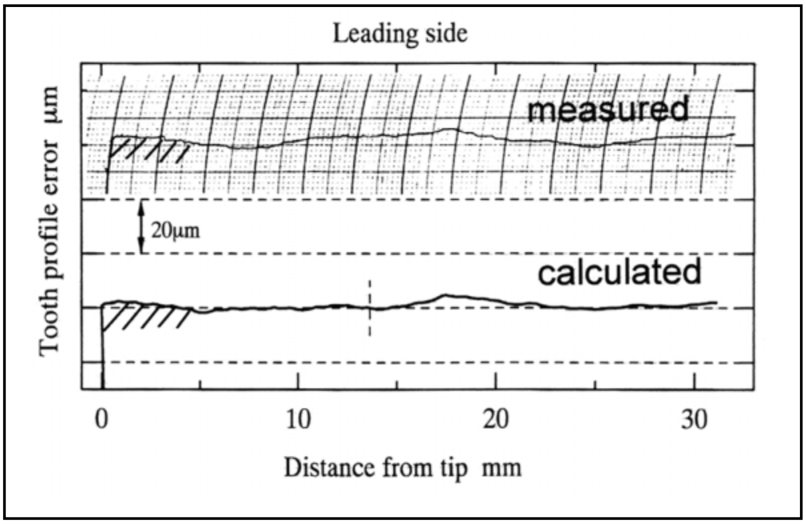


Figure 26—Tooth profile and tooth trace after 20 gears finished with CBN-tipped hob (900 meters per minute).

Superfinishing Gears—The State of the Art

Gary Sroka and Lane Winkelmann

Introduction

Superfinishing the working surfaces of gears and their root fillet regions results in performance benefits. For example, in 1987, Tanaka et al. showed that an appreciable increase in surface durability could be achieved when gear pairs were finished to a mirrorlike surface using a cubic-boron-nitride (CBN) wheel (Ref. 1). Since that time, it has been further established that superfinishing gears to a low surface roughness can reduce friction, pitting fatigue, noise, operating temperature, bending fatigue, metal debris and wear (Refs. 2–9).

Superfinishing hardened gear surfaces using conventional techniques, such as grinding and/or honing, however, has several serious drawbacks. Not only are such processes costly and time consuming, but there is always the risk of permanently damaging the gear by either destroying the tooth profile or introducing grind burn. In addition, such superfinishing methods can routinely achieve a roughness average (R_a) of only 6.0–12 μin., whereas there is technical data strongly supporting that a smoother surface is even more beneficial (Refs. 1–8).

For the past several years, chemically accelerated vibratory finishing has been used to successfully superfinish high quality gears to a roughness average (R_a) between 1.0 and 3.0 μin. The aim of this article is to identify and dispel two common misconceptions about this technique.

Figure 1—SEM images of test specimens superfinished with ceramic (top) and plastic (bottom) non-abrasive media.

Description of the Superfinishing Process

Before proceeding further, it is important to explain how this process works and how it is radically different from conventional machining. The following is a brief overview of the chemically accelerated vibratory finishing process using high density, non-abrasive ceramic media.

Vibratory machines. The process is carried out in vibratory finishing bowls or tubs. These relatively inexpensive and durable machines are basically unchanged in design since their introduction more than 40 years ago. Vibratory finishing machines are available in sizes from 0.5 to 250 cubic feet of working capacity. This means gears can be finished ranging in size from less than two inches in diameter to more than six feet in diameter and quantities from one to thousands at a time.

High density, non-abrasive ceramic media. **(Ref. 10)** The process utilizes high density, non-abrasive ceramic media in the vibratory finishing machine. It is considered non-abrasive since it does not contain discrete abrasive particles and alone is unable to abrade material from the hardened surface of the gears being processed. The media is selected from a range of shapes and sizes best suited for maintaining the geometry of the gears. No finishing occurs on a surface where media is unable to contact and rub. By selecting a media that has a uniform probability of contact across all surfaces, especially across the tooth flanks, the tooth profile and lead are not adversely affected, even with AGMA Q12 gears (Ref. 11). One important advantage of the high-density ceramic media is that it has essentially no attrition during usage. The process is consistent for thousands of hours of production because the size and the shape of the media remains constant.

Process chemistry. The unique and significant feature of the process is the surface leveling/smoothing mechanism utilized to achieve the surface finish. A reactive chemistry is used in the vibratory machine in conjunction with the media. When introduced into the machine, this chemistry produces a stable, soft conversion coating across the asperities (peaks and valleys) of the gears.

The rubbing motion across the gears developed by the machine and media effectively wipes the soft conversion coating off the "peaks" of the gear's surfaces, thereby removing a micro-layer of metal. The "valleys" are left untouched since the media bridges over them and cannot wipe the conversion coating. The conversion coating is continually re-formed and wiped off during this stage, producing a surface leveling/smoothing mechanism. This mechanism is continued in the vibratory machine until the surfaces of the gears are free of asperities. At this point, the reactive chemistry is rinsed from the machine with a neutral soap. The conversion coating is wiped off the gears one final time to produce the mirrorlike surface.

It is important to note that the reactive chemistry producing the conversion coating is only mildly acidic, having a nominal pH of 5.5, and the process is normally carried out at ambient temperature. Thus there is no possibility of hydrogen embrittlement or grind burn, as is common with mechanical grinding or honing operations.

When a number of gears are processed simultaneously, all are exposed to the same mechanical and chemical environment such that every tooth of every gear is processed identically. This eliminates the need for 100% final inspection.

Depending on the choice and concentration of the active chemistry, the process can be controlled to remove stock at a rate of 0.00005 to 0.00040 in./hr. Therefore, aerospace gears with an AGMA quality of Q12 or greater and an initial R_a of 12 µin. or OEM automotive gears with an initial R_a of 60 µin. can be superfinished to a low surface roughness in approximately 1.0 hour.

Health, safety and environmental considerations. The chemicals used to produce the superfinished gears of alloy steels are non-toxic and are classified as non-hazardous by 49CFR (Federal Hazardous Material Transportation Law). Such products have been supplied to a wide variety of industries for more than 15 years without any health or safety incident.

The waste produced by the process is classified as non-hazardous according to the Environmental Protection Agency (EPA), but the waste may require standard metals precipitation to meet local and state discharge regulations.

Gear Industry Acceptance

As with any new technology, initially there were some serious technical questions that needed answering. This was especially true for gears used in aerospace or military applications where any failure could be catastrophic.

Metallurgists had apprehensions that gear alloys exposed to an acidic chemistry would produce hydrogen embrittlement and/or intergrannular attack. Both in-house and outside testing quickly dispelled such fears and demonstrated that this process is metallurgically safe. The results have been presented elsewhere, and these concerns no longer seem to be an issue (Refs. 8–9).

However, other misconceptions about the process have surfaced from time to time. It is the purpose of this article to identify and explain two common misconceptions.

Misconceptions

Misconception No. 1. Gear teeth having a mirrorlike surface will not have the proper lubrication properties. Residual machine lines or a dimpled surface are required for oil retention.

Two basic facts are known about the correlation between surface roughness and tribological properties:

1.) If two mating surfaces are too rough, boundary or mixed lubrication occurs. The resulting metal-to-metal contact produces a higher operating temperature, increased friction and increased wear.

2.) On the other hand, if the two mating surfaces are too smooth,

Table 1—Specifications of Scuffing Specimens.

Property	Specification
Material	AMS 6260 (SAE 9310 Air Melt)
Heat Treatment	Carburized
Surface Finish after Grind (RMS)	16 µin. max.
Hardness (HRC)	60–63
Effective Case Depth (in.)	0.036–0.042
Core Hardness (HRC)	36–41
Diameter	3.0 in.
Crowning radius of disks with transverse radius of curvature	12.0 in.

Table 2—Testing Parameters of Two-Disk Apparatus.

Peripheral Velocity of Fast Shaft (ft./sec.)	65.62
Peripheral Velocity of Slow Shaft (ft./sec.)	16.21
Mean Entraining Velocity (ft./sec.)	42.49
Sliding Velocity (ft./sec.)	52.49

Table 3—Number of Test Specimens Finished in Each Type Of Media.

Media Type	No. of Specimen Sets
Non-abrasive ceramic	3
Non-abrasive plastic	2

Table 4—Results of Scuffing Tests.

Test	Ground	Ceramic			Plastic	
Scuffing Load (lbs.)	522	933*	933*	933*	776	776

* No scuffing occurred at maximum testing load and 30 minutes hold time.

Table 5—Specifications of SAE 8620 Carburized Rolling/Sliding Contact Fatigue Specimens.

Property	
Material	SAE 8620
Hardness (HRC)	60–61
Roughness Average (R_a) (µin.)	26

Gary J. Sroka
is research & development manager for REM Research Group Inc., located in Brenham, Texas. He holds a doctorate in physical chemistry. His research interests include development of new products and processes for superfinishing gear and bearing alloys using chemically accelerated vibratory finishing.

Lane Winkelmann
is a senior research associate at REM Research Group. He has developed proprietary products and processes for the superfinishing of stainless steels, brass, and carbon steel alloys and has published several gear-related technical articles.

then adhesive forces become appreciable, again resulting in high friction and wear. Anyone who has held two clean, highly polished flat steel surfaces together knows just how strong this force can be.

There is no argument among gear designers that removing the peaks from the working surfaces of gears is beneficial. After all, if the peaks are left in place, there must be a traditional run-in period when friction and operating temperature are high, and metal debris is generated, which causes further damage to the lubricant, gears, bearings, or all three.

In addition, since these peaks are fractured or sheared from the surface during the traditional run-in, initiation sites for future contact fatigue are seeded. So the question arises: What type of surface is needed to obtain optimum performance?

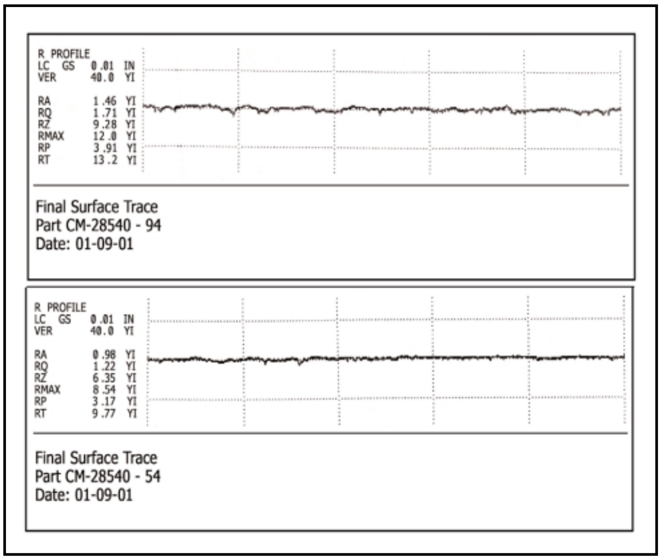


Figure 2—Surface roughness profiles of test specimens superfinished with ceramic (top) and plastic (bottom) non-abrasive media.

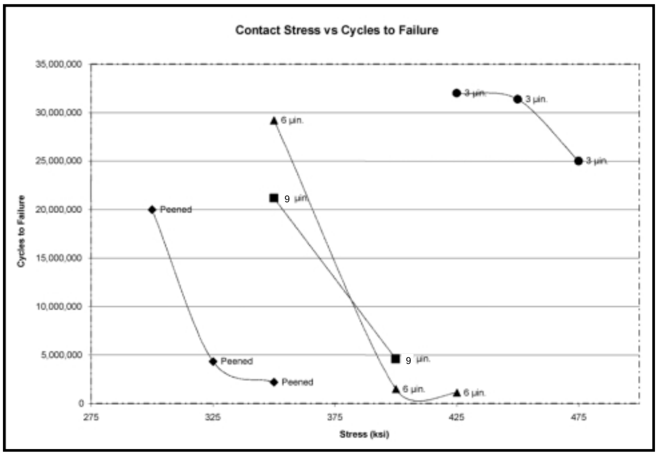


Figure 3—Results of rolling/sliding contact fatigue testing.

Table 6—Surface Treatment of Specimens Tested.

	R_a (µin.)	Surface Treatment
Baseline	22	Shotpeened, 230 Hard Cast Shot, 0.012–0.015 Almen "A," 200%
Group I	8.8	Superfinished using chemically accelerated vibratory finishing in non-abrasive ceramic media
Group II	5.9	
Group III	2.6	

In an attempt to answer this question, two experiments were conducted by independent gear research laboratories: Cardiff University's engineering school in Wales, U.K., and The Pennsylvania State University's Gear Research Institute in State College, Pennsylvania, U.S.A.

Scuffing. At Cardiff University, scuffing specimens and testing were provided by the engineering school's R.W. Snidle. The specifications of the specimens are given in Table 1.

A special two-disk machine was used for the testing with the aim of simulating gas turbine gearing conditions as closely as possible. The ratio of the speeds of the two shafts may be preset from unity (pure rolling) up to a value of almost five. In the work reported here, the ratio for the speeds was 4.24, which gives a slide/roll ratio of 1.24. One shaft is supported on fixed bearings, and the second shaft is mounted on a swinging yoke.

Scuffing is caused by running the disks at constant speed and increasing the load between them at 3-minute intervals. The maximum load that is normally applied to the contact is 933 lbs., which produces a corresponding maximum Hertzian pressure of 247 ksi. The testing parameters are given in Table 2.

Two groups of scuffing specimens were superfinished using chemically accelerated vibratory finishing. One group was processed using non-abrasive ceramic media, while the other was processed using non-abrasive plastic media. Table 3 lists the number of test specimen sets finished in each type of media.

The two surfaces are both mirrorlike in appearance to the naked eye, but the Scanning Electron Micrograph (SEM) images at 500X clearly show that the surfaces are quite different (see Fig. 1). Typical profilometer traces along with the surface measurement parameters for these surfaces are shown in Figure 2 and are consistent with the SEM images. The ceramic media causes scratches and dings on the surface, while the plastic media produces a very smooth surface. Prior to testing, it was anticipated that the surface processed using the plastic media would significantly outperform that produced with the ceramic media.

The surface formed with the ceramic media is typical of the isotropic surface produced with non-abrasive ceramic media. This surface has undergone thorough evaluation over the past several years and has demonstrated that it can increase performance, resulting in reduced friction, lower operating temperature, better contact fatigue resistance and less wear (Refs. 8, 12–13).

Scuffing test results. The results of the testing are summarized in Table 4. Surprisingly the more highly textured surface using the non-abrasive ceramic media was vastly superior to the ultra-smooth surface of the non-abrasive plastic media with regards to scuffing. Even more remarkable is the fact that the highly textured surface did not scuff even at the maximum loading of the test and even after the test was allowed to continue for an additional 30 minutes.

Therefore, it is now evident that two mirrorlike surfaces with low R_a's can perform quite differently. As predicted, too smooth of a surface without microtexture does not perform as well as the smooth but textured surface. The microtexture created by the non-abrasive ceramic media is essential to obtaining optimum performance benefits from surface finishing.

Rolling/sliding contact fatigue. At The Pennsylvania State University, rolling/sliding contact fatigue tests were performed at the Gear Research Institute and were sponsored by the institute's Vehicle Bloc.

Case carburized SAE 8620 rolling/sliding contact fatigue specimens were fabricated without any grinding/honing after carburization. The specification of these specimens is given in Table 5. The baseline specimens were shotpeened after carburization. Two sets of seven specimens each and a third set of four specimens were finished using chemically accelerated vibratory finishing with high density, non-abrasive ceramic media. The sets were processed after carburization to a low, medium and high level of surface finish (see Table 6).

The rolling/sliding contact fatigue testing was done under the conditions shown in Table 7. The results are listed in Table 8 and are shown graphically in Figure 3.

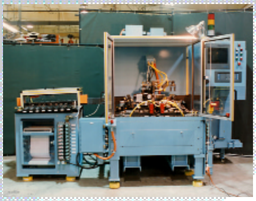
In this study of SAE 8620 specimens, the maximum benefit for performance is achieved by refining to a line-free, isotropic condition with an $R_a < 3.0$ µin. It is postulated that this process not only improves performance because it removes the peaks from the working surface and creates a microtexturing, but it also removes any damage to the metal surface caused by grinding, honing or carburization.

Another interesting observation is that even the partially finished specimens still well outperformed the baseline shot-peened specimens. Specimens receiving the full finish (i.e., line-free with an $R_a < 3.0$ µin.) performed as well as aerospace specimens from an earlier study manufactured from SAE 9310. In that study, the aerospace specimens were ground/honed after heat treatment and then superfinished. It should also be mentioned that there were three other sets of specimens superfinished to an $R_a < 3.0$ µin. and tested by rolling/sliding contact fatigue over a two-year period. All had extremely good contact fatigue and wear resistance (Ref. 14).

In conclusion, the most desirable surface has an $R_a < 3.0$ µin. and has microtexturing to facilitate lubrication, as shown in Figure 1's top image. This microtexturing, with its extremely shallow dings and random scratch pattern, is inherent to chemically accelerated vibratory finishing using high density, non-abrasive ceramic media. Residual machine lines or deep dimples are not essential, and in fact are detrimental insofar as these can contain damaged metal or act as stress raisers leading to contact and/or bending fatigue.

Misconception No. 2. The relationship between surface roughness parameters and component functionality is not well understood and requires advanced mathematics and sophisticated software. Therefore, there is no simple method of determining what surface will give the desired performance benefit.

This misconception arises because of the extreme difficulty to characterize a surface. Today there are about 57 different surface roughness parameters described in current standards for 2-D pro-



filometry and 14 parameters for 3-D topographic analysis. This being the case, it would be difficult to predict the performance of a given surface.

In the previous section, it was found that a surface having an $R_a < 3.0$ μin. generated by chemically accelerated vibratory finishing using high density, non-abrasive ceramic media gave excellent performance on test rigs designed to simulate gear performance. This again is attributed to the fact that the non-abrasive ceramic media consistently gives the microtextured surface that facilitates lubricant retention.

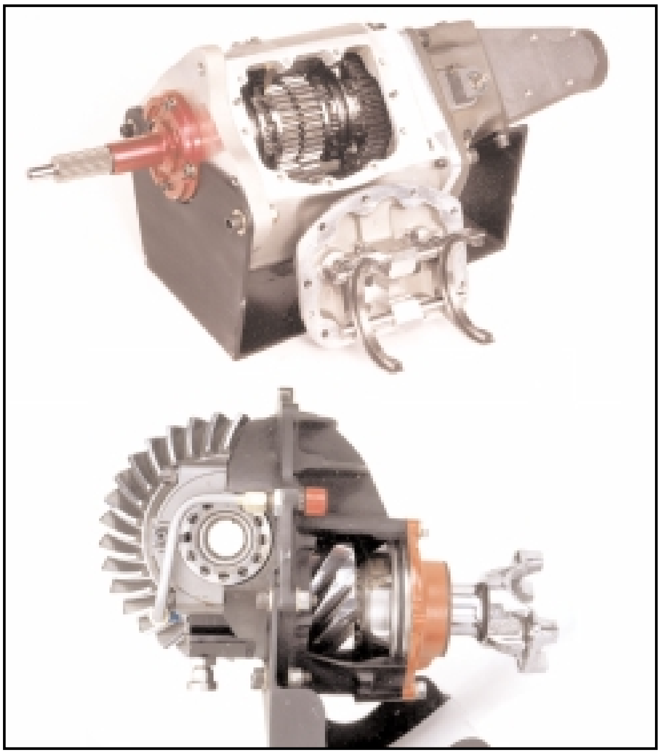


Figure 4—NASCAR transmission and differential that are superfinished with chemically accelerated vibratory finishing using high density, non-abrasive media. Courtesy of Tex Racing.

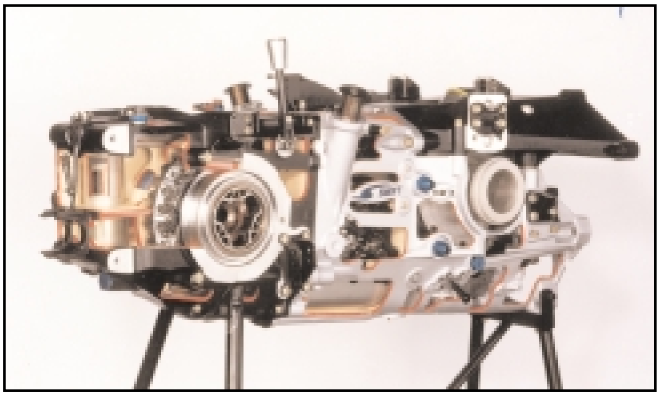


Figure 5—IndyCar™ transmission that is superfinished with chemically accelerated vibratory finishing using high density, non-abrasive media. Courtesy of Swift Racing Technologies.

Table 7—Parameters of Rolling/Sliding Contact Fatigue Testing.

Testing Parameters	
RPM of Test Rig	1,330
Runout (cycles)	30×10^6
Negative Sliding (%)	43
Temperature (°F)	200

Field performance using this superfinishing process over the last five years supports the validity of the test rig data and the use of only roughness average as the measurement parameter to ensure proper finishing. Various job shop facilities across the country routinely use this superfinishing process on transmission and differential gears for the automotive racing industry.

For example, all NASCAR racing teams use this process as well as many of the IndyCar™ series teams. Figure 4 is an example of a NASCAR transmission and differential superfinished by this process. Note the mirrorlike surface of the tooth flanks.

Figure 5 is an example of an IndyCar transmission superfinished by this process. The superfinished gears can be glimpsed through an opening beneath the Swift logo. In Europe, the process is used by several Formula 1 cars. No transmission or differential problems have been attributed to this process. In fact, post-race inspections of the gears show little to no indications of usual wear or pitting patterns. An example of this is shown in Figure 6.

The standard finished (ground) gear has been run for 500 miles in a typical race transmission. The contact pattern is clearly marked by pitting and wear. The superfinished gear, on the other hand, shows no contact pattern, wear or micropitting at all after being run for the same 500 miles in the same transmission.

Similarly, gears finished for aerospace companies such as Westland Helicopters Ltd., Sikorsky Aircraft Corp., and Rolls-Royce Gear Systems and for automotive companies such as DANA Corp., Ford Motor Co. and GM Powertrain have all shown performance improvements after superfinishing with this process using only the R_a as a criterion for proper finishing (Refs. 15–17).

A few examples of these improvements reported by aerospace companies are: sustained operating temperature reductions of 5°F while using an external oil cooler, reductions in vibro-acoustic noise of up to 7 dB, increases in bending fatigue resistance of approximately 10 percent and significant increases in contact fatigue resistance. Improvements reported by automotive companies include elimination of the initial run-in temperature spike followed by a reduction of the sustained operating temperature by up to 50°F, significantly less wear and much lower coefficients of friction.

Summary

Superfinishing gears using chemically accelerated vibratory finishing with high density, non-abrasive ceramic media brings about a surface textured property that facilitates lubrication. The superfinished surface will be free of stress raisers, damaged metal and peak asperities, all of which reduce the life of the gears. These gears will experience reduced friction, lower operating temperature, less wear, better scuffing resistance, and better contact fatigue resistance. Laboratory and field testing supports the conclusion that only the R_a needs to be monitored during the process to attain proper surface finishing. An R_a of < 3.0 μin. will ensure optimum performance benefits (Refs. 6–9, 12–17).

References

1. Tanaka S., A. Ishibashi and S. Ezoe. “Appreciable Increases in Surface Durability of Gear Pairs With Mirror-Like Finish,” ASME Publication 84-DET-223, ASME, New York, NY, 1984.
2. Patching M.J., H.P. Evans, R.W. Snidle. “Micro EHL Analysis of Ground and Superfinished Steel Discs Used to Simulate Gear Tooth Contacts,” *Tribology Transactions*, Vol. 39, Issue 3, 1996, pp. 595–602.
3. Britton, R.D., C.D. Elcoate, M.P. Alanou, H.P. Evans, and R.W. Snidle. “Effect of Surface Finish on Gear Tooth Friction,” *Proceedings of STLE/ASME Tribology Conference*, Orlando, FL, 1999.
4. Krantz, T.L., M.P. Alanou, H.P. Evans, R.W. Snidle. “Surface Fatigue Lives of Case-Carburized Gears With an Improved Surface Finish,” NASA/TM-2000-210044, 2000.
5. Patching, M.J., C.C. Kweh, H.P. Evans, R.W. Snidle. “Conditions for Scuffing Failure of Ground and Superfinished Steel Disks at High Sliding Speeds Using a Gas Turbine Engine Oil,” Transactions ASME *Journal of Tribology*, Vol.117, July 1995, pp. 482–489.
6. Manesh, A. “Surface Enhancement for Increasing Load Bearing Density,” *Proceedings of Defense Manufacturing Conference 2000*, Foundation for Global Security, Tampa, FL, Nov. 27–30, 2000.
7. Swiglo, A. A. “Enhanced Surface Protection of Precision Gears,” INFAC Program, IIT Research Institute, 2001, Sponsored by the U.S. Army Aviation and Missile Command (AMCOM), Contract DAAJ09-95-C-5046.
8. Winkelmann, L., M. Michaud, G. Sroka, A. Swiglo, and D. Mahan. “Chemically Accelerated Vibratory Finishing for the Virtual Elimination of Wear and Pitting for Steel Gears,” 01FTM7, AGMA Fall Technical Meeting, Detroit, MI, October 2001.
9. Winkelmann, L., M. Michaud, G. Sroka, and A. Swiglo. “Impact of Isotropic Superfinishing on Contact and Bending Fatigue of Carburized Steel,” Paper No. 2002-01-1391, *Advances in Surface Engineering, SAE International Off-Highway Congress*, Las Vegas, NV, March 19–21, 2002.
10. Michaud, M. U.S. Patent 4,818,333, “Metal Surface Refinement Using Dense Alumina-Based Media,” 1989.
11. Arvin, J., A. Manesh, M. Michaud, G. Sroka, and L. Winkelmann. “The Effect of Chemically Accelerated Vibratory Finishing on Gear Metrology,” 02FTM1, AGMA Fall Technical Meeting, St. Louis, MO, October 2002.
12. Nebiolo, W.P. “Isotropic Finishing of Helicopter & Turboprop Gearbox Components,” AESF 2001 Aerospace/Airline Plating & Metal Finishing Forum, Portland, OR, March 27–29, 2001.
13. Niskanen, P., A. Manesh, R. Morgan. “Reducing Wear with Superfinishing Technology,” *The AMPTIAC Quarterly*, Vol. 7, No. 1, 2003, pp. 3–9.
14. The Gear Research Institute, The Pennsylvania State University, Aerospace Bloc, Privileged data accessible to members only, 2000–2003.
15. Hanson, B. M. Salerno, L. Winkelmann. “Isotropic Superfinishing of S-76 Main Transmission Gears,” SAE Aerospace Manufacturing Technology Conference, Montreal, Quebec, Canada, September 2003.
16. Development Programs for the Joint Strike Fighter (JSF) and the Global Hawk UAV.
17. Gangopadhyay, A., E.A. Soltis, M.D. Johnson. “Valvetrain Friction and Wear: Influence of Surface Engineering and Lubricants,” Presented at Society of Tribologists and Lubrication Engineers (STLE) Annual Meeting, Houston, TX, May 19-23, 2002.

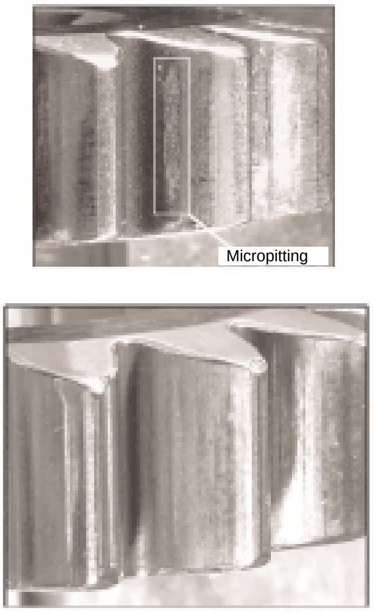


Figure 6—Two gears that each completed 500 miles of use in an automotive racing transmission. The top gear had the standard ground finish while the bottom gear had been superfinished with chemically accelerated vibratory finishing with high density, non-abrasive ceramic media. Note there is no wear or micropitting at the contact area on the superfinished gear.

Table 8—Rolling/Sliding Contact Fatigue Results for Various Levels of Surface Finish.

Surface Finish	Contact Stress (ksi)	Cycles to Failure (10^6)	Mean (10^6)
Shotpeened $R_a \approx 22$ μin.	300	12.0	20.0
	300	28.0	
	325	3.1	4.3
	325	3.7	
	325	6.2	
	350	2.2	2.2
$R_a \approx 8.8$ μin.	350	5.6	21.2
	350	26.0	
	350	31.9	
	400	1.4	4.6
	400	2.8	
	400	4.1	
	400	10.0	
$R_a \approx 5.9$ μin.	350	25.0	29.2
	350	32.4	
	350	30.2	
	400	1.2	1.5
	400	1.7	
	425	0.9	1.1
	425	1.4	
$R_a \approx 2.6$ μin.	425	32.0	32.0
	450	31.3	31.3
	450	31.5	
	475	25.0	25.0

Application of Statistical Stability and Capability for Gear Cutting Machine Acceptance Criteria

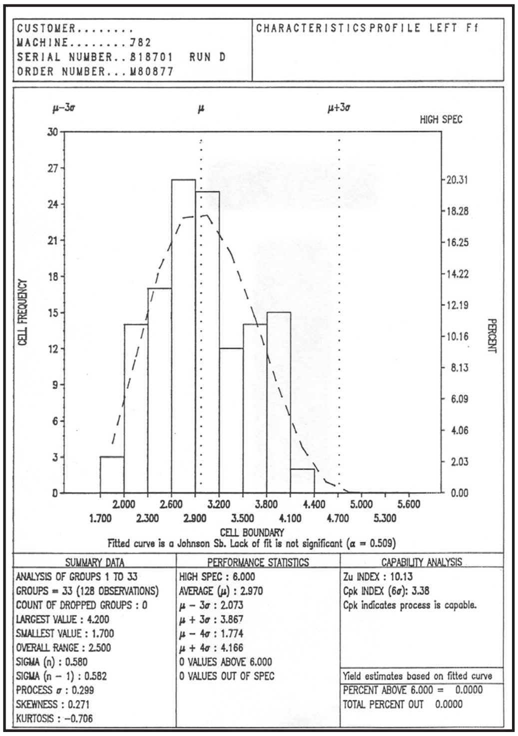
Thomas J. "Buzz" Maiuri

Printed with permission of the copyright holder, the American Gear Manufacturers Association, 500 Montgomery Street, Suite 350, Alexandria, Virginia, 22314-1560. Statements presented in this paper are those of the author and may not represent the position or opinion of the American Gear Manufacturers Association.

Introduction

Machine tool manufacturers supplying machines to the gearing world have been in existence for many years. The machines have changed, and so has the acceptance criteria for the machines. Before the 1980s, the criteria for virtually all machine acceptance was either a supplier's standard test job or the supplier producing one or two of the customer's parts to within a print tolerance.

It wasn't until about 1984 that The Gleason Works of Rochester, NY, was required to perform a capability analysis for machine acceptance on a cylindrical hobbing machine. Capability requirements for bevel machine acceptance did not occur until several years after that. Today virtually every customer requires a capability study on at least one parameter for at least one type of part.



CUSTOMER........
MACHINE........782
SERIAL NUMBER..818701 RUN D
ORDER NUMBER...M80877

CHARACTERISTICSPROFILE LEFT Ff

Fitted curve is a Johnson Sb. Lack of fit is not significant (α = 0.509)

SUMMARY DATA
ANALYSIS OF GROUPS 1 TO 33
GROUPS = 33 (128 OBSERVATIONS)
COUNT OF DROPPED GROUPS : 0
LARGEST VALUE : 4.200
SMALLEST VALUE : 1.700
OVERALL RANGE : 2.500
SIGMA (n) : 0.580
SIGMA (n − 1) : 0.582
PROCESS σ : 0.299
SKEWNESS : 0.271
KURTOSIS : −0.706

PERFORMANCE STATISTICS
HIGH SPEC : 6.000
AVERAGE (μ) : 2.970
μ − 3σ : 2.073
μ + 3σ : 3.867
μ − 4σ : 1.774
μ + 4σ : 4.166
0 VALUES ABOVE 6.000
0 VALUES OUT OF SPEC

CAPABILITY ANALYSIS
Zu INDEX : 10.13
Cpk INDEX (6σ): 3.38
Cpk indicates process is capable.

Yield estimates based on fitted curve
PERCENT ABOVE 6.000 = 0.0000
TOTAL PERCENT OUT 0.0000

Figure 1—Histogram and distribution.

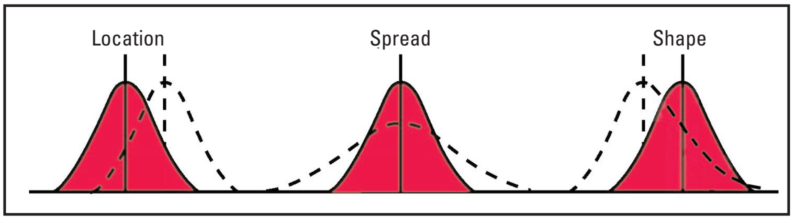


Figure 2—Distributions.

Since the introduction of capability requirements for machine acceptance, we have seen the goal post move. Initially the requirement was for a Cp or Cpk of 1.33 using a 6-sigma analysis. Now we have seen requirements of a 1.67 or 2.0 Cp or Cpk with a 6-, 8- or 10-sigma analysis on tolerances that have been tightened from the original tolerance!

This can cause some real headaches for the machine tool supplier, and that is why it is very important for the supplier to understand true machine and process capability before agreeing to any capability requirement.

In 1991, the quality and supplier assessment staffs at Chrysler, Ford and General Motors worked under the auspices of the Automotive Division of the American Society for Quality Control (ASQC) Supplier Quality Requirements Task Force in collaboration with the Automotive Industry Action Group (AIAG) to put together the *Statistical Process Control (SPC) Reference Manual* (Ref. 1).

The same group developed the *Measurement Systems Analysis (MSA) Reference Manual* (Ref. 2). Many companies, such as Delphi Automotive Systems, have developed their own statistical qualification requirements based on both the SPC and MSA reference manuals.

This paper will reference the SPC and MSA manuals and the Delphi Specification SD-002 for much of the material presented.

With this paper, we hope to review some of the basics of Statistical Process Control (SPC) and provide a better understanding of its application as it relates to a machine runoff.

Customer Agreement, Data Collection & Distributions

Before conducting a machine runoff that has a capability study tied to it, it is very important that both the customer and the machine tool supplier agree on the parameters to be measured and on what the tolerance and capability requirement is for machine acceptance.

Once these are established, the parts are usually produced on the machine in a continuous run without interruption under the conditions agreed to. The parts are then inspected on equipment that has passed a GR&R study (more on GR&R later) and the resultant data analyzed.

There are a number of tools that are used today to analyze the data collected, from spreadsheet software that can be tailored using built-in statistical functions to software designed specifically for statistical analysis, such as the popular MINITAB package.

Once collected, the data can be organized, analyzed, interpreted and presented (Fig. 1). Besides the average, range and the data's other statistics, the standard deviation can be calculated.

Think of the standard deviation as the statistical spread or dispersion from the mean of the data collected. There are several methods that can be used to calculate the standard deviation, designated by the Greek letter σ (sigma). One method is to use the individual values of a process characteristic, and another method estimates the standard deviation using the average range from a subgroup analysis and a factor, designated as d_2. (See below for further discussions on subgroups.)

No two parts are exactly alike because every process contains some source of variability. While individual values may be different, as a group they can form a pattern that can be described as a distribution.

Distributions are characterized by a location (the typical value), a spread (the span of values) and a shape (the pattern of variation). See Figure 2.

The causes of variation in a distribution are referred to as either "common causes" or "special causes." The term "assignable causes" is often used in place of "special causes."

The type of variation preferred in any distribution is that of common causes. When common causes exist (also referred to as random variations), the process is said to be "in control" and the process's output is stable and predictable over time, as depicted in Figure 3.

Distributions with special or assignable causes of variation are not stable over time. When present, assignable causes will produce changes in the distribution, and if they are not removed, the process output cannot be predicted (Fig. 4).

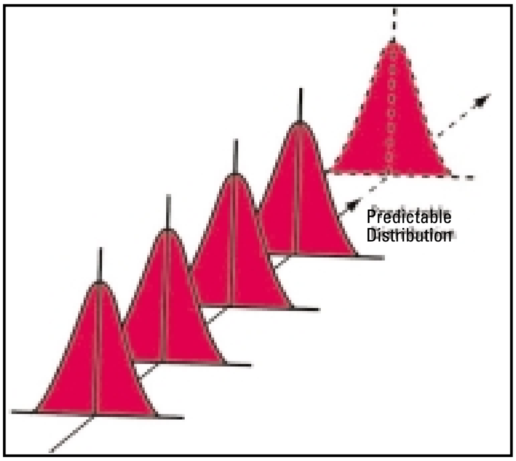


Figure 3—Predictable distribution.

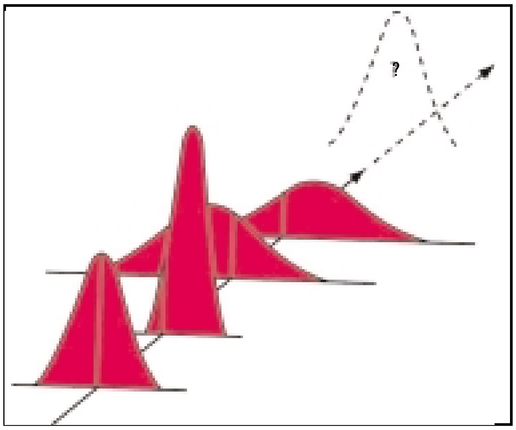


Figure 4—Unpredictable distribution.

If a process is in control (a predictable distribution), the number of in-specification parts can be estimated. As long as the process remains stable and the distribution does not change in location, spread or shape, it will continue to produce the same distribution of in-specification parts.

Control Charts: $\bar{X}$ and R Charts

In the 1920s, Dr. Walter Shewhart of Bell Laboratories developed what is known as the control chart to make the distinction between controlled and uncontrolled variation due to common (random) and special (assignable) causes. Control charts for variables are powerful tools that can explain process data in terms of both spread (piece-to-piece variability) and location (process average).

Control charts should be prepared and analyzed in pairs, most commonly the $\bar{X}$ and R charts. $\bar{X}$, the average of the values in subgroups, describes the location of the data. R, the range of the values within each subgroup, measures the data spread.

A sample subgroup table or data block is shown in Figure 5. The table consists of a defined number of subgroups and includes data from each subgroup. Each subgroup has a total, an average ($\bar{X}$) and a range (R).

Generally, there are three to five individual parts per subgroup and 25 or more subgroups in the analysis. The frequency of the data collection

T.J. "Buzz" Maiuri

is Director–Gear Technology for The Gleason Works of Rochester, New York. A mechanical engineer, he is responsible for application engineering, training and specialized gear services. Maiuri has been a Gleason Works employee for more than 37 years and has been involved with capability studies of machine runoffs for more than 20 years. His involvement includes working with customers to define machine runoffs and troubleshooting during the runoffs.

Data and Control Charts for Capability Study

Sub-Group #	1	2	3	4	5	6	7	8	9	10
Data From Each Sub-Group	30.5	30.4	37.3	35.7	37.9	37.0	32.6	35.0	33.5	34.8
	34.3	36.2	36.6	30.3	31.1	30.8	30.6	34.1	31.3	35.7
	36.7	31.3	36.3	37.0	31.2	34.9	34.8	36.1	30.6	37.7
	37.6	35.6	34.3	34.9	32.6	31.5	35.3	31.5	32.9	33.4
	37.5	37.5	37.0	33.1	36.9	33.9	30.8	34.5	34.7	32.9
Total	176.60	171.00	181.50	171.00	169.70	168.10	164.10	171.20	163.00	174.50
Average (x-bar)	35.32	34.20	36.30	34.20	33.94	33.62	32.82	34.24	32.60	34.90
Range (R)	7.1	7.1	3	6.7	6.8	6.2	4.7	4.6	4.1	4.8

Figure 5—Data table for a control chart.

Table 1—Factors For Control Chart Control Limits.

n	2	3	4	5	6	7	8	9	10
D_4	3.27	2.57	2.28	2.11	2.00	1.92	1.86	1.82	1.78
D_3	*	*	*	*	*	0.08	0.14	0.18	0.22
d_2	1.13	1.69	2.06	2.33	2.53	2.7	2.85	2.97	3.08
A_2	1.88	1.02	0.73	0.58	0.48	0.42	0.37	0.34	0.31

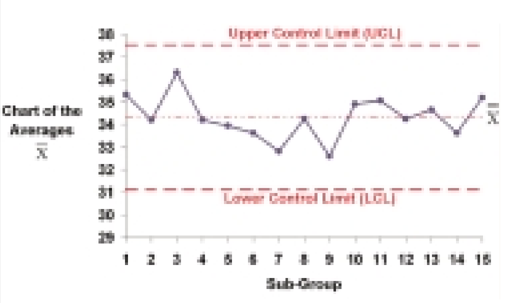


Figure 6—Control chart for averages.

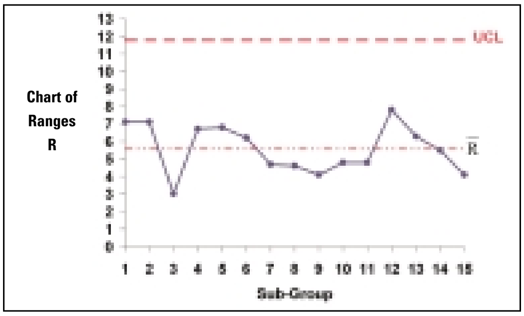


Figure 7—Control chart for ranges.

for the subgroups is determined to detect changes in the process over time. During an initial study, the frequency can be over a short period of time, or even taken with consecutive parts. This is generally the case during a machine qualification study because of the availability of parts and the time allotted to the machine runoff. In a production environment, the frequency can be hourly, several times per shift, or any feasible time frame.

From the data collected, the average range ($\overline{R}$) and the process average ($\overline{X}$) are calculated simply by averaging the subgroup ranges and averages. The next step in the process of creating the control charts is to calculate the control limits. Control limits are used to show the extent by which the subgroup averages and ranges would vary if only common (random) causes of variation were present. They are based on the subgroup sample size and the amount of "within" subgroup variability reflected in the ranges. The formulas for the upper control limit (UCL) and lower control limit (LCL) for the $\overline{X}$ and R charts follow:

$$UCL_R = D_4\overline{R}$$
$$LCL_R = D_3\overline{R}$$
$$UCL_{\overline{X}} = \overline{\overline{X}} + A_2\overline{R}$$
$$LCL_{\overline{X}} = \overline{\overline{X}} - A_2\overline{R}$$

The factors A_2, D_3 and D_4 are constants based on subgroup size N taken from the chart shown in Table 1. Note that for subgroup sizes of less than seven, there is no lower control limit for the range chart, only an upper control limit. An interesting point to keep in mind is that the control limits have absolutely nothing to do with the tolerance of the parameter being evaluated.

Now the $\overline{X}$ and R charts can be created with the calculated control limits by plotting the $\overline{X}$ for each subgroup on one chart (Figure 6) and the range R for each subgroup on another chart (Figure 7). Very often, the two charts are combined.

Stability

Now that we have the data and charts, what do we do with them?

Basically, if the process variability and average were to remain constant, the subgroup ranges and averages would vary by chance only and would not exceed the control limits. In theory, there would be no runs or trends in the data, and the subgroups would be positioned randomly around the centerline. If all of the above were the case, the process would be "in control" and stable.

To summarize, there are several criteria that can be used to determine if a process is "out of control":

1.) Data points outside the control limits (Figure 8),
2.) Runs within the control limits (Figure 9)—seven consecutive points above or below the centerline,
3.) Trends (Figure 10)—seven points consistently increasing or decreasing, and
4.) To be stable and in control, two-thirds of the points must be within the middle one-third of the chart. The chart's one-third band is determined by dividing the difference of the UCL – LCL by three (Figure 11).

The criteria for stability may vary depending on the customer's specifications. There may be changes in the number of points that determine a trend or a run, i.e. six instead of seven, or the number of subgroups specified to be within the middle third of the chart, etc. As stated earlier, agreement with the customer should be reached and understood before any trial begins.

If the process is shown to be out of control, the assignable cause or causes must be identified and eliminated. The process of troubleshooting and correcting the assignable causes in the gear manufacturing process is a subject in itself and will not be addressed in this paper.

The important point is that the process must be in control and stable before determining the process capability.

Capability

Process capability is a measure of how well the process output meets the specified requirements (tolerances). Every process can be classified as falling into one of four cases as shown in Table 2.

The preferred situation is to have a Case 1 condition where the process is both in control and capable. As often occurs in the case of machine qualifications, a customer will allow a Case 3 condition where the process may not be in control, but is capable. For the most part, it is not a case of the process being out of control, but the fact that you do not know if the process is in control or out of control. This is generally due to the fact that not enough parts are available from the customer to perform a true stability study. If this is the case, only a test for capability is conducted at the supplier's facility.

The capability indices that are used today are Cp, Pp and Cpk, Ppk. Cp and Pp are indices of process variation that are relative only to a specification. Cpk and Ppk are indices that combine process variation and process centering (location) relative to a specification. As you will see below, the equation for Cp and Pp is the same, except for the method of calculation used for the standard deviation in the equation.

As with Cp and Pp, Cpk and Ppk also have the same equation except for the method of calculation for the standard deviation. Cp and Cpk use the standard deviation ($\hat{\sigma}_{R/d_2}$) estimated from subgroups using the average range ($\bar{R}$) and the d_2 factor from the chart in Table 1:

$$\hat{\sigma}_{R/d_2} = \bar{R}/d_2$$

Pp and Ppk use the sample standard deviation ($\hat{\sigma}_S$) calculated from the individual values of the characteristic:

$$\hat{\sigma}_S = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{n-1}}$$

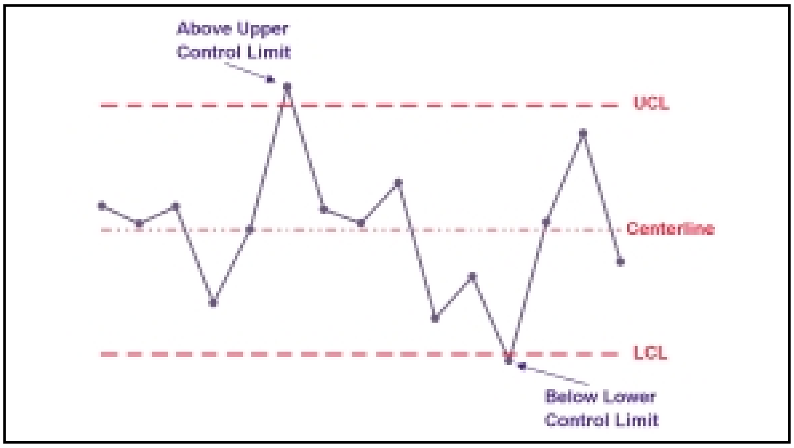


Figure 8—Subgroups outside the control limits.

Figure 9—Consecutive points above or below centerline.

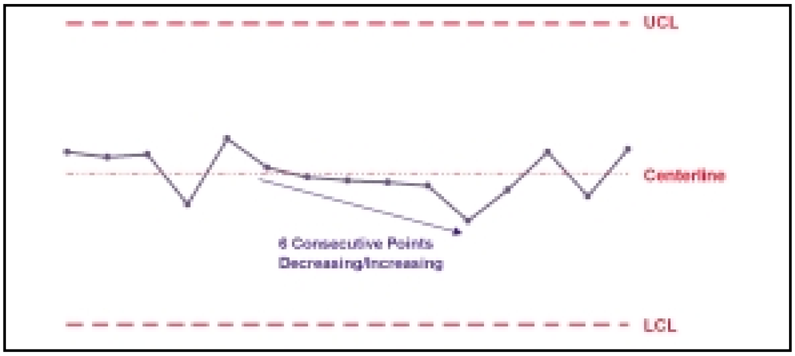


Figure 10—Consecutive points moving up or down.

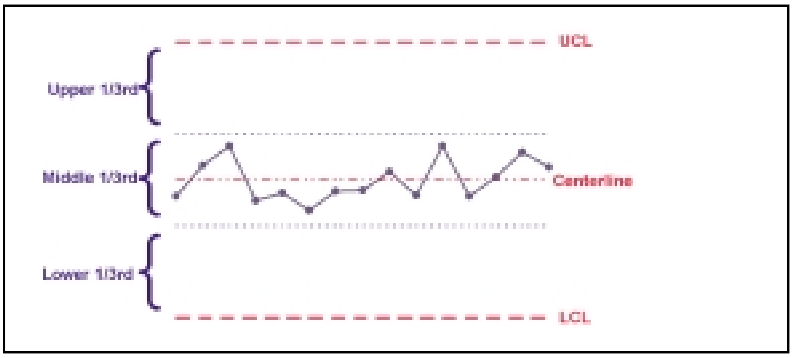


Figure 11—Subgroups within the middle third of the chart.

Table 2—Process Classifications.

Meeting Requirements	In Control	Not In Control
Acceptable (Capable)	Case 1	Case 3
Not Acceptable (Not Capable)	Case 2	Case 4

where x_i is the individual value, $\bar{x}$ is the average, and n is the total number of individuals sampled.

Cp is the capability index defined as the tolerance width divided by the process capability, irrespective of process centering (location):

$$Cp = \frac{(USL - LSL)}{6\hat{\sigma}_{\bar{R}/d_2}}$$

where USL is the upper specification limit and LSL is the lower specification limit.

Pp is the performance index defined as the tolerance width divided by the process performance, irrespective of process centering (location). Pp should be used only to compare to or with Cp and Cpk and to measure and prioritize improvement over time.

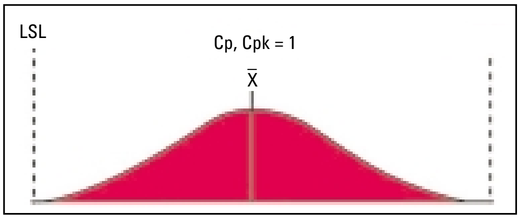


Figure 12—Data spread using all the tolerance.

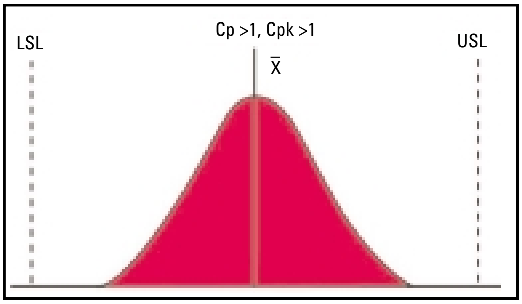


Figure 13—Distribution spread is less than the tolerance.

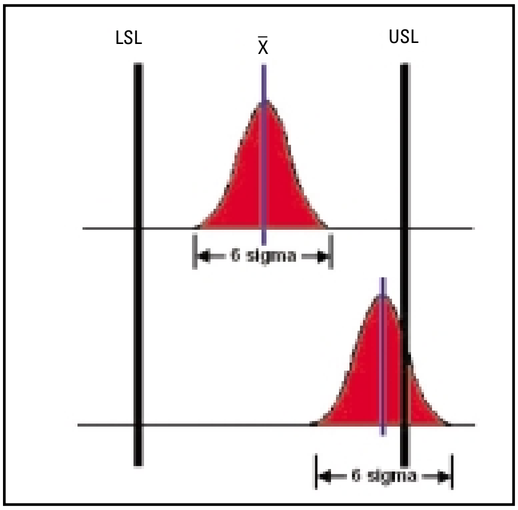


Figure 14—Cp is the same for both distributions.

$$Pp = \frac{(USL - LSL)}{6\hat{\sigma}_S}$$

CPU is the upper capability index and is defined as the upper tolerance spread divided by the actual upper process spread.

$$CPU = \frac{(USL - \bar{\bar{X}})}{3\hat{\sigma}_{\bar{R}/d_2}}$$

CPL is the lower capability index and is defined as the lower tolerance spread divided by the actual lower process spread.

$$CPL = \frac{(\bar{\bar{X}} - LSL)}{3\hat{\sigma}_{\bar{R}/d_2}}$$

Cpk is the capability index that accounts for process centering and is defined as the minimum of CPU or CPL. Cpk relates the distance between the process mean and the closest specification limit to half the total process spread.

Ppk is the performance index that accounts for process centering (location) and is defined as the minimum of:

$$\frac{(USL - \bar{\bar{X}})}{3\hat{\sigma}_S} \quad \text{or} \quad \frac{(\bar{\bar{X}} - LSL)}{3\hat{\sigma}_S}$$

As with Pp, it should be used only to compare to or with Cp and Cpk and to measure and prioritize improvement over time.

Capability can also be expressed in terms of a ratio. CR is the capability ratio equal to the reciprocal of Cp. The performance ratio PR is equal to the reciprocal of Pp.

The following graphical examples may make the concept of the capability indices easier to understand.

Figure 12 depicts a Cp of 1, since the statistical spread is equal to the tolerance. Also, since the average is exactly in the middle of the tolerance, the Cpk = 1

Figure 13 depicts a Cp greater than 1, since the statistical spread is less than the tolerance. Since the average is exactly in the middle of the tolerance, the Cpk value will be equal to the Cp value.

Figure 14 depicts the same distribution in two different locations relative to the specification limits. In the top distribution, Cp and Cpk are both greater than one since the 6-sigma spread is less than the tolerance. Cp and Cpk are also equal to each other since the average is at the middle of the tolerance. In the distribution on the bottom, the Cp value is exactly the same as the top distribution, but the Cpk is some value less than 1 since part of the distribution falls outside the USL. With the mean of the distribution located where it is, some percentage of parts will fall outside the USL.

Double-Sided and Single-Sided Tolerances

Double-sided tolerances or bilateral tolerances are those which define a nominal dimension along with a plus or minus tolerance. Bilateral tolerances tend to generate distributions that are normal. Typically a gear size over pins, wires or balls would be bilateral.

Single-sided or unilateral tolerances have a single limit tolerance. A zero-based dimension unilateral tolerance has zero as the inherent target value. Typically gear runout, pitch variation, etc. are unilateral tolerances. Unilateral tolerances by nature tend to generate distributions that have a visible amount of skewness or non-normality. Single-sided tolerances are calculated using the Cpk or Ppk indices as described above.

Some customers use different methods in handling the data to calculate the capability index for unilateral tolerances. One example is demonstrated in the Delphi specification SD-002 (Ref. 3). A mirror image transformation is used to “normalize” the data set. The data is ordered from the smallest values to the largest values. When there is an odd number of data points, the median is the middle value of the ordered data. When there is an even number of data points, the median is the average of the two middle values of the ordered data set. The transformation is made by first removing all the data points that fall above the median for a minimum specification and below the median for a maximum specification. For each remaining data value, a corresponding value is created equally distant from the median on the median’s opposite side. Standard techniques are then used to calculate a “trial” standard deviation from the mirrored data set.

Using σ_{trial}, all values that exceed the (median + $3\sigma_{trial}$) are excluded and $\overline{R}$, $\hat{\sigma}$ and σ are recalculated using the modified data set.

Gage Repeatability and Reproducibility

Every parameter that is subjected to a capability study will require some type of gage or instrument to measure the value of the parameter. How do we know the value we are measuring is actually what the gage says it is? How do we know the gage is good enough to make the measurement so we can rely on the reading and use the result in the capability analysis? Gage repeatability and reproducibility (GR&R) procedures have been developed to assess the statistical properties of gages. Before a gage is used for a capability study, it should be evaluated to determine its performance.

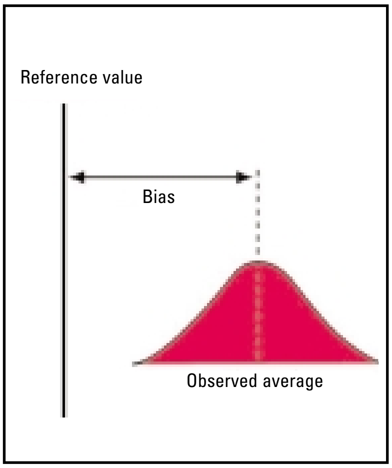


Figure 15—Gage bias.

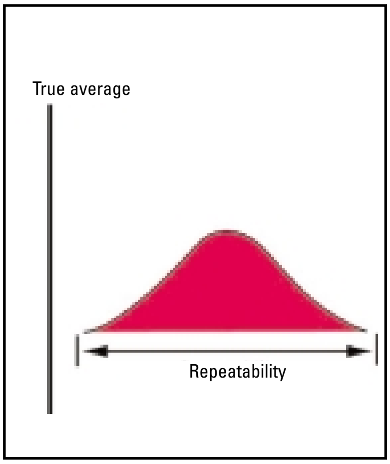


Figure 16—Gage repeatability.

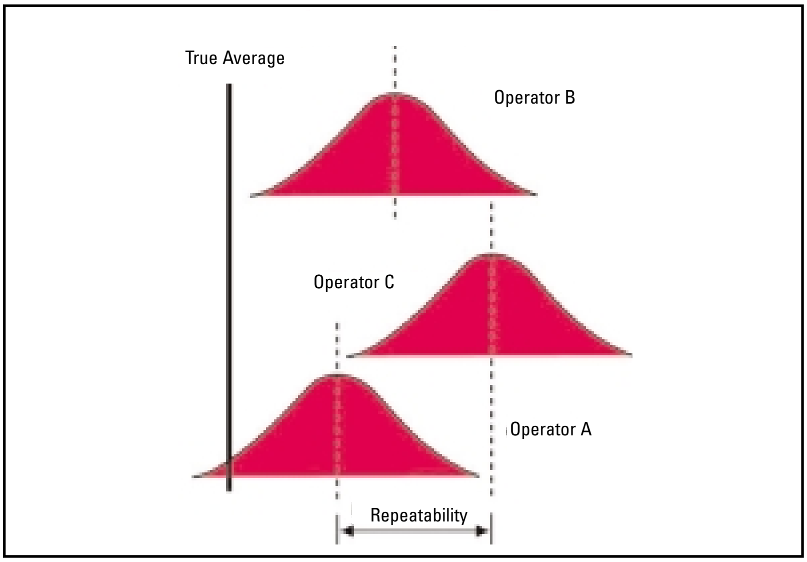


Figure 17—Gage reproducibility.

Before we discuss the different methods of conducting a GR&R, the following are definitions of a number of characteristics of any gage system.

Gage bias (Figure 15) is the difference between the observed average and the reference value. Bias is sometimes referred to as accuracy, but the term accuracy is not recommended as an alternative to bias.

Gage repeatability (Figure 16) is the variation in measurements obtained with one measurement instrument when used several times by one operator measuring the identical characteristic on the same part.

Gage reproducibility (Figure 17) is the variation in the average of the measurements made by different operators (appraisers) using the same gage when measuring identical characteristics of the same part.

Gage stability (Figure 18) or drift is the total variation in the measurements obtained with a measurement system on the same parts when measuring a single characteristic over an extended time period.

Gage linearity (Figure 19) is the difference in the bias values through the gage's expected operating range.

Table 3—d_2 Values for the Distribution of the Average Range.

Parts	Number of Operators			
	2	3	4	5
1	1.41	1.91	2.24	2.48
2	1.28	1.81	2.15	2.40
3	1.23	1.77	2.12	2.38
4	1.21	1.75	2.11	2.37
5	1.19	1.74	2.10	2.36
6	1.18	1.73	2.09	2.35
7	1.17	1.73	2.09	2.35
8	1.17	1.72	2.08	2.35
9	1.16	1.72	2.08	2.34
10	1.16	1.72	2.08	2.34

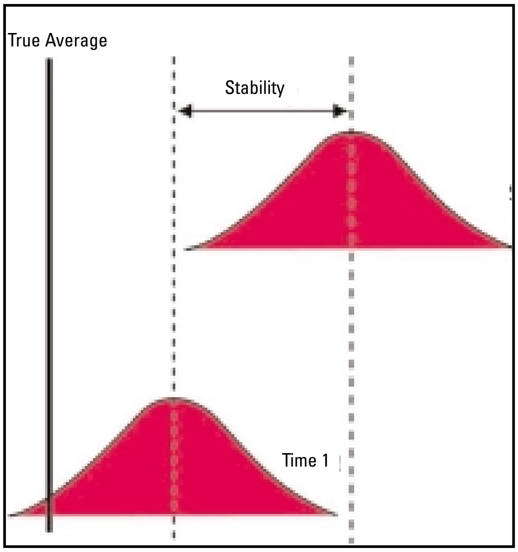


Figure 18—Gage Stability.

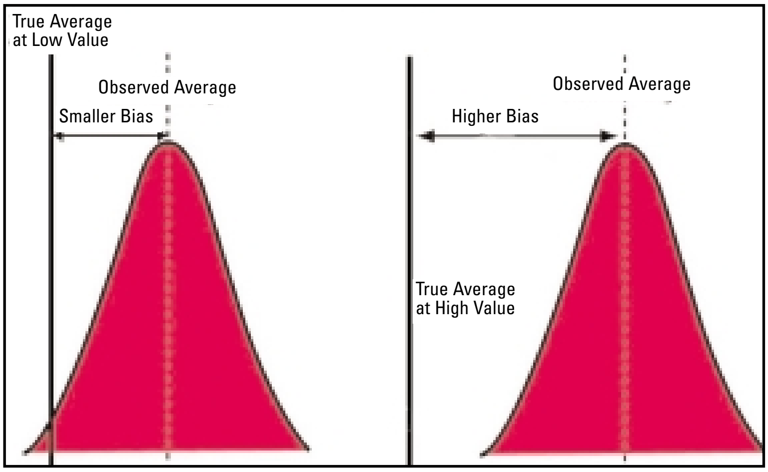


Figure 19—Gage Linearity.

GR&R Techniques—Long and Short Studies

There are several techniques that can be used to perform a gage study. The two most widely used are the range method (short study) and the average and range method (long study).

The range method or short study will provide a quick approximation of the gage variability. It will not distinguish the variability between repeatability (equipment variation) and reproducibility (appraiser variation), but only provide an overall picture of the measurement system.

Typically, the short study will require only two operators (appraisers) and five parts. Each operator measures each part once. The range for each part is the absolute difference between the measurements obtained by the operators. The sum of the ranges found and the average range R is calculated. The total measurement variability is found by multiplying the average range by $5.15/d_2$. The d_2 factor can be found in a table for the distribution of the average range for two trials and five parts (Table 3). It is interesting to note that there are some tables where d_2 values are based on the number of parts times the number of appraisers, where other tables use only the number of parts.

The long study (average and range method) will provide an estimate of both the repeatability (equipment variation) and reproducibility (appraiser variation) for a measurement system.

The number of appraisers, trials and parts may vary, but typically 10 parts that represent the actual or expected range of process variation are numbered and used with three appraisers. Each appraiser checks the 10 parts in random order two or three times each.

For the short study, the calculated GR&R value is generally expressed as a percentage of the tolerance of the parameter being measured. It can also be expressed as a percentage of the process variation, if it is known. For the long study, the GR&R value can be expressed as a percentage of the total variation measured in addition to the tolerance or process variation.

The information in Table 4 can be used as a general guide for acceptance criteria of a percentage GR&R study. Generally speaking, if the percentage GR&R is 10% or less, the gage will be acceptable. If it is 10% to 30%, the gage may be acceptable based on the importance of the application. If the GR&R is more than 30%, the gage is determined to be unacceptable.

It should be noted that it is an acceptable practice to factor out the gage error when making the capability calculation. The calculated standard deviation is actually made up of the process standard deviation and the standard deviation of the gage. They are related by the following formula:

$$\sigma^2 \text{ process \& gage} = \sigma^2 \text{ gage} + \sigma^2 \text{ process}$$

Since we know the total standard deviation (consisting of the process and the gage) and we know the gage standard deviation, we can solve for the process standard deviation and use the process standard deviation in the capability calculations:

$$\sigma_{\text{process}} = \sqrt{\sigma^2 \text{ (process \& gage)} - \sigma^2 \text{ gage}}$$

The appendix contains a sample of a short study and a long study GR&R. The long study sample uses a spreadsheet set up to follow the example in the MSA reference manual.

Summary

The understanding and application of the SPC and GR&R techniques presented in this paper is essential for a successful machine runoff. When properly applied, much can be learned about the process and machine.

As you may have already concluded, the techniques described in this paper are not limited to just gear cutting machines. They can be applied to any parameter for any process.

To demonstrate the techniques, case studies from actual machine runoffs for cylindrical and bevel gear cutting machines are provided.

Case Studies

For cylindrical gear applications, the parameter most often measured and evaluated is the tooth size, usually by measurement over pins or wires. Equipment such as the Mahr Diamar and Unite-A-Matic tooth size checkers are preferred over using hand micrometers because the tooth checkers have a much better GR&R than that of micrometers. Other parameters that have been evaluated are lead and profile average, lead and profile variation, runout and spacing parameters.

For bevel gear applications, the parameter most often measured and evaluated is also the tooth size, usually by measurement with a dinging ball gage supplied by the customer. Other parameters inspected are flank form errors, runout and spacing parameters.

A typical machine runoff today generally consists of a 10-part mini-run prior to any extended runs. The mini-run serves to verify targeting of the size and verify that all other parameters are within specifications.

Table 4—Guidelines for GR&R Percentages.

GR&R Percentage	Measurement System
Less than 10%	Acceptable
10% to 30%	May be acceptable based on importance of application, gage cost, etc.
More than 30%	Unacceptable—measurement system needs improvement

Often a customer will require mini-run results prior to his visit for the machine runoff. If possible, a full run is made producing the required number of parts prior to the customer's visit under the exact conditions requested by the customer. This helps to eliminate any surprises that might occur during a run that would take place for the first time in the customer's presence.

Most machines have some type of temperature compensation system to allow for machine growth as the machine warms up. The extended runs allow an opportunity to verify that the correct temperature compensation factor is being used.

As stated previously in the paper, although technically required to show stability before capability, most customers will specify a run of anywhere from 25 to 125 continuous parts without stoppage for a machine runoff and only the capability is calculated from the inspection results. It is not uncommon to repeat the capability study in the customer's facility after the machine is shipped.

Appendix 1: Subgroup Stability—X-Bar and R-Bar Charts

The case study in Appendix 1 is a hobbing machine runoff with a requirement to prove stability, then capability, on the tooth size parameter for a plastic worm gear. The data is shown in a spreadsheet created to analyze the specific customer requirements with respect to stability and capability. The size over balls was measured with a special gage provided by the customer. Prior to using the gage, a GR&R was conducted and it was found to be acceptable for use.

The customer required the hobbing machine to be warmed up by rotating the spindles for 8 hours prior to beginning the run. The size was targeted to within 0.005 mm of nominal, and a total of 654 worm gears were run continuously in automatic mode without interruption.

Twenty subgroups of three parts per subgroup were selected for analysis throughout the run. There were 18 cycles with cutting between each three-piece subgroup. In other words, three out of every 21 parts were selected for the analysis.

Offsets to the size were allowed during the run, but could not be made on two consecutive subgroups. Note that only the last four digits of the gage measurement were entered in the spreadsheet. The results for stability and capability are summarized in the top table of Appendix 1. Note the cells in the right-hand column indicating a "Pass" or "Fail." The X-bar and R-bar charts for the data are also shown in the appendix. In the X-bar chart, note the relationship between the actual specification limits and the control limits.

Appendix 2: Pp and Ppk Capability Data

Appendix 2 data is presented in another spreadsheet created to analyze basic statistical data with respect to a capability analysis. The table provided shows 11 of the 15 parameters that were required for the analysis. The data is from an actual bevel gear cutting machine runoff for a truck application requiring face-hob-cutting of a 41-tooth gear.

The parameters evaluated were tooth size, spacing (Fp and fp) on both the concave and convex flanks, runout (Fr) on both flanks, and the errors (measured in microinches) on the four corners of the tooth flank. The corners are designated as Toe Top, Toe Root, Heel Top and Heel Root. All data, including the tooth flank form error, were taken from the output of a CMM inspection machine.

The data presented for the tooth form error was measured to a master gear with zero error on the corners. Note that the flank form corner data for the convex side of the tooth is not shown in the table in order to cut down on the data presented.

The run of 35 gears was made without stoppage on a warm machine. Verification of process stability was not required for the runoff. Note that the spreadsheet is set up to enter the specification limits, the type of tolerance (unilateral or bilateral), and the Pp and/or Ppk requirement. In addition to calculating the capability results, the spreadsheet also reports a "Pass" or "Fail." The spreadsheet is also set up to yield a run chart for each of the parameters. The run charts for the accumulated pitch (Fp) and the runout (Fr) are shown in the appendix. Both the data from the concave and convex sides are shown on one chart. Run charts are an excellent visual for comparing the data to the tolerance, and any irregularities—such as flyers, trends, runs, etc.—can be seen immediately.

Appendix 3: Short Study GR&R

The range method or short study GR&R shown in Appendix 3 is presented in a spreadsheet. The data provided is from a machine runoff of a CNC test machine, measuring the first harmonic of mesh in arc seconds of a set of automotive bevel gears. Two operators (appraisers) and five parts were used for the short study. Each operator measured each part once, and the range for each part (the absolute difference between the measurements obtained by the operators) was calculated.

The sum of the ranges (0.24) and the average range, $\overline{R}$, (0.048) is calculated. The total measurement variability or GR&R (0.2078) is found by multiplying the average range (0.048) by 5.15/1.19, where 1.19 is the d_2 factor for five parts, two operators. The GR&R expressed as a percent of the 5 arc second tolerance yields a GR&R percentage of 4.2%, which is an excellent result.

As stated previously, the short study provides a quick approximation of the gage variability, and it does not distinguish the variability between repeatability (equipment variation) and reproducibility (appraiser variation), but only provides an overall picture of the measurement system.

Appendix 4: Long Study GR&R

The long study (average and range methods) shown in Appendix 4 is also presented in a spreadsheet set up to duplicate the sample provided in the MSA reference manual. The data provided is from a machine runoff of a CNC test machine, measuring the first harmonic of mesh in arc seconds of a set of automotive bevel gears. Three operators (appraisers) and 10 parts were used for the long study. Each operator inspected each of the 10 parts three different times.

The spreadsheet shows each of the operators' measurements, and the results are displayed in the last several rows of the spreadsheet. The resultant GR&R is 0.44648. As stated earlier, the long study also yields the estimate for the repeatability or equipment variation (0.44108) and the reproducibility or appraiser variation (0.06294). The results of this study are also expressed as a percentage of the total part variation (5.19602), yielding a GR&R percentage of 8.59%, which passes the criteria for a good gage. The results also could have been expressed as a percentage of the tolerance or of the process variation. ⚙

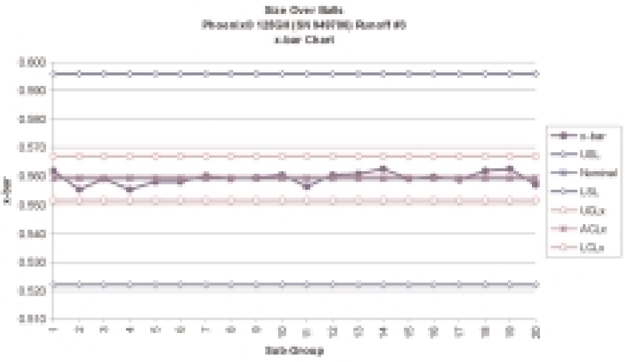
References

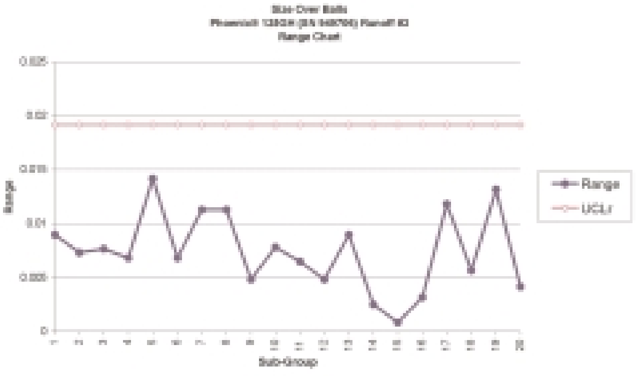
1. Chrysler Corp., Ford Motor Co. and General Motors Corp. *Statistical Process Control—SPC—Reference Manual*, 1992.
2. Chrysler Corp., Ford Motor Co., and General Motors Corp., *Measurement Systems Analysis—MSA—Reference Manual*, 1992.
3. Delphi Saginaw Steering Manufacturing Equipment Statistical Qualification Requirements SD-002, *Saginaw Steering Systems,* Issued 1 March 1993, Revised 7 January 2002.
4. Juran, J.M., and Frank M. Gryna, Jr. *Quality Planning and Analysis*, McGraw Hill, 1980.
5. Juran, J.M. *Quality Control Handbook*, 3rd Edition, McGraw Hill, 1979.

Appendix 1—Subgroup stability data.

Size over Balls	Tolerances	Requirement	Value	Pass/Fail
Upper Limit	0.596	Cpk > 1.33	2.78	Pass
Lower Limit	0.522	Ppk > 1.33	2.96	Pass
Cpk	1.33	100% in CL's	100%	Pass
Ppk	1.33	> 66% in Center 1/3	70%	Pass
		No Runs (7 on one side)	0	Pass
Setup Info		No Trends (6 incr./decr.)	0	Pass
Sub-Group Size	3			
# of Blank Cycles	18		x-bar-bar	R-bar
# of Sub-Groups	20		0.55930	0.00744
Measurements/Piece	3			

Sub-Group	Piece #	Meas. #1	Meas. #2	Meas. #3	Avg. Meas.	Sub-Group Average (x-bar)	Sub-Group Range (R)
1.1	188	0.5480	0.5750	0.5610	0.56133	0.56178	0.00900
1.2	189	0.5610	0.5660	0.5725	0.56650		
1.3	190	0.5685	0.5485	0.5555	0.55750		
2.1	209	0.5670	0.5645	0.5350	0.55550	0.55528	0.00733
2.2	210	0.5600	0.5455	0.5490	0.55150		
2.3	211	0.5330	0.5660	0.5775	0.55883		
3.1	230	0.5630	0.5410	0.5705	0.55817	0.55928	0.00767
3.2	231	0.5550	0.5730	0.5630	0.56367		
3.3	232	0.5545	0.5760	0.5375	0.55600		
4.1	251	0.5565	0.5430	0.5710	0.55683	0.55522	0.00683
4.2	252	0.5610	0.5610	0.5515	0.55783		
4.3	253	0.5505	0.5715	0.5310	0.55100		
5.1	272	0.5695	0.5545	0.5515	0.55850	0.55811	0.01417
5.2	273	0.5470	0.5615	0.5440	0.55083		
5.3	274	0.5795	0.5465	0.5690	0.56500		
6.1	293	0.5665	0.5680	0.5440	0.55950	0.55822	0.00683
6.2	294	0.5700	0.5555	0.5575	0.56100		
6.3	295	0.5410	0.5480	0.5735	0.55417		
7.1	314	0.5605	0.5670	0.5360	0.55450	0.56006	0.01133
7.2	315	0.5650	0.5430	0.5715	0.55983		
7.3	316	0.5770	0.5525	0.5680	0.56583		
8.1	335	0.5650	0.5365	0.5545	0.55200	0.55906	0.01133
8.2	336	0.5805	0.5575	0.5475	0.56183		
8.3	337	0.5660	0.5555	0.5685	0.56333		
9.1	356	0.5555	0.5810	0.5480	0.56150	0.55939	0.00483
9.2	357	0.5630	0.5475	0.5695	0.56000		
9.3	358	0.5545	0.5525	0.5630	0.55667		
10.1	377	0.5515	0.5815	0.5390	0.55733	0.56039	0.00783
10.2	378	0.5390	0.5750	0.5620	0.55867		
10.3	379	0.5735	0.5645	0.5575	0.56517		
11.1	398	0.5760	0.5460	0.5540	0.55867	0.55639	0.00650
11.2	399	0.5490	0.5685	0.5575	0.55833		
11.3	400	0.5555	0.5575	0.5435	0.55217		
12.1	419	0.5705	0.5500	0.5530	0.55783	0.56039	0.00483
12.2	420	0.5435	0.5615	0.5830	0.56267		
12.3	421	0.5505	0.5705	0.5610	0.56067		
13.1	440	0.5595	0.5690	0.5510	0.55983	0.56083	0.00900
13.2	441	0.5730	0.5780	0.5465	0.56583		
13.3	442	0.5790	0.5505	0.5410	0.55683		
14.1	461	0.5600	0.5610	0.5690	0.56333	0.56250	0.00250
14.2	462	0.5675	0.5785	0.5440	0.56333		
14.3	463	0.5510	0.5785	0.5530	0.56083		
15.1	482	0.5545	0.5585	0.5660	0.55967	0.55911	0.00083
15.2	483	0.5735	0.5465	0.5565	0.55883		
15.3	484	0.5745	0.5580	0.5440	0.55883		
16.1	503	0.5645	0.5555	0.5555	0.55850	0.55972	0.00317
16.2	504	0.5645	0.5865	0.5340	0.56167		
16.3	505	0.5365	0.5805	0.5600	0.55900		
17.1	524	0.5505	0.5600	0.5575	0.55600	0.55872	0.01183
17.2	525	0.5345	0.5610	0.5670	0.55417		
17.3	526	0.5780	0.5700	0.5500	0.56600		
18.1	545	0.5595	0.5680	0.5480	0.55850	0.56189	0.00567
18.2	546	0.5430	0.5630	0.5830	0.56300		
18.3	547	0.5685	0.5475	0.5765	0.56417		
19.1	566	0.5595	0.5595	0.5450	0.55467	0.56261	0.01317
19.2	567	0.5860	0.5455	0.5720	0.56783		
19.3	568	0.5590	0.5535	0.5835	0.56533		
20.1	587	0.5690	0.5480	0.5505	0.55583	0.55711	0.00417
20.2	588	0.5665	0.5775	0.5355	0.55983		
20.3	589	0.5545	0.5365	0.5760	0.55567		

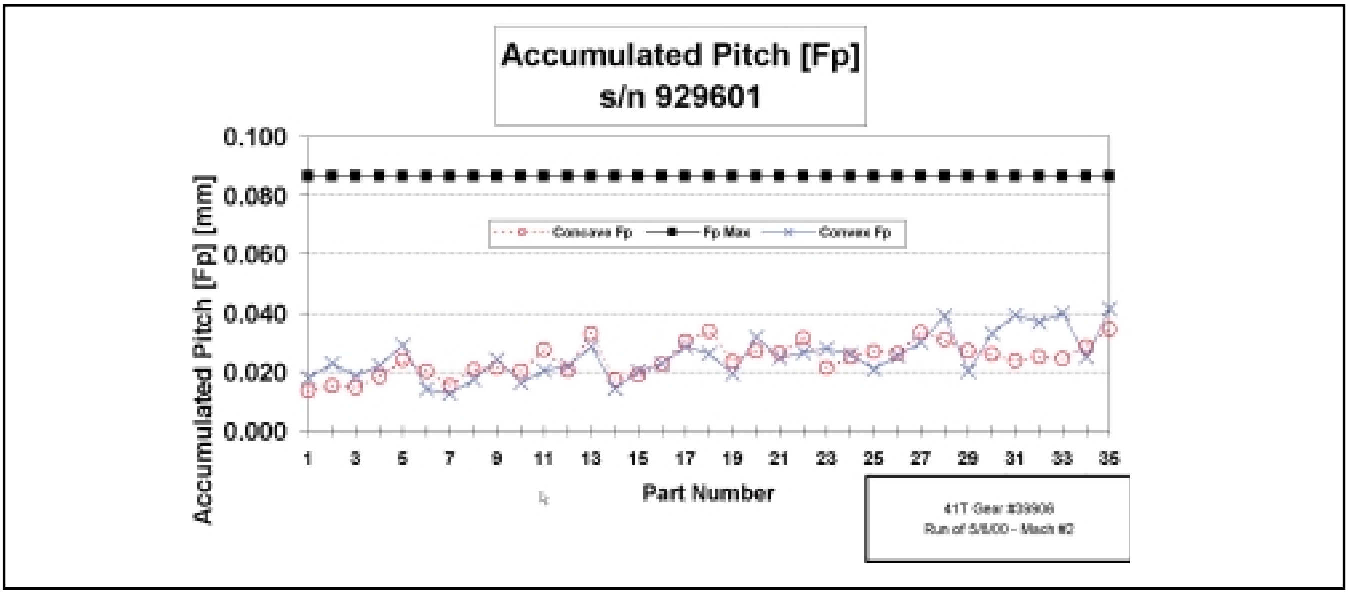


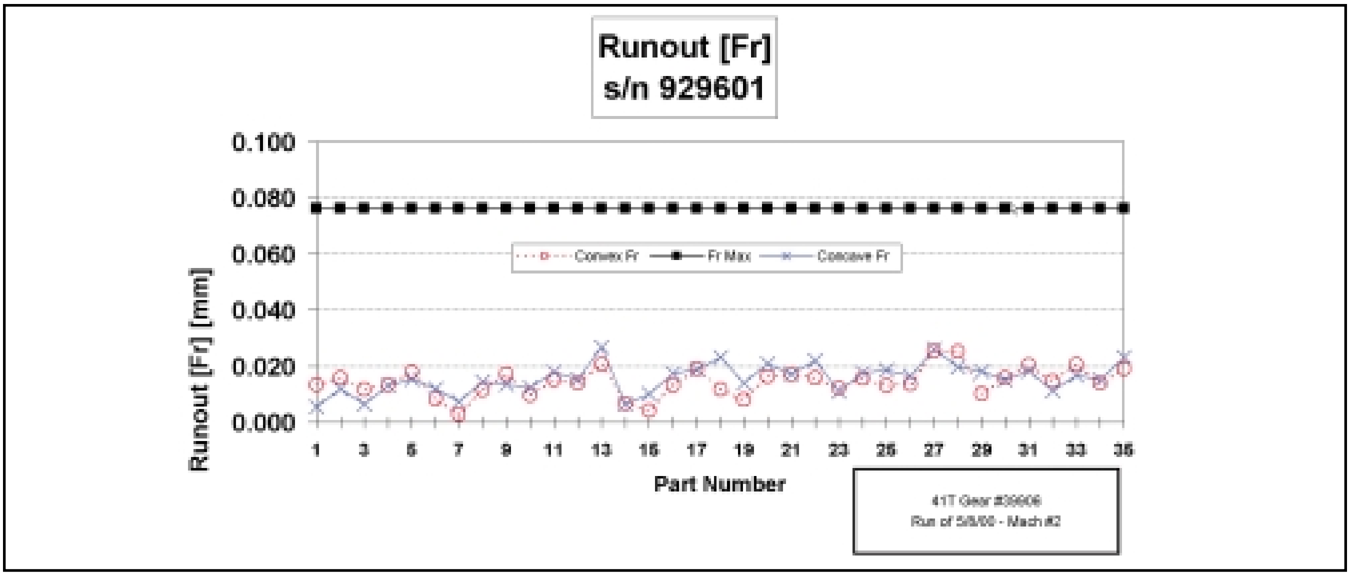


Appendix 2—Pp and Ppk capability data.

Customer:					1000HC	36654	#39906				
Date:		May 9, 00		929601	Mach #2	41 Gear					
	side 2	side 1	side2	side 1	side 2	side 1					
	B	C	D	E	F	G	H			Conv = Concave	
Part ID	Conv Fp	Conx Fp	Conv fp	Conx fp	Conv Fr	Conx Fr	Size	ToeTop	ToeRoot	HeelTop	HeelRoot
1	0.0136	0.0178	0.0056	0.0064	0.0056	0.0132	–0.0090	–1.6	5.5	–7.4	–4.2
2	0.0152	0.0229	0.0083	0.0092	0.0118	0.0158	–0.0160	–0.8	5.4	–4.6	–4.1
3	0.0146	0.0186	0.0079	0.0107	0.0064	0.0116	–0.0160	–1.7	6.2	–4.5	–0.6
4	0.0183	0.0223	0.0062	0.0095	0.0130	0.0132	–0.0140	–0.9	5.3	–5.3	–2.5
5	0.0241	0.0290	0.0081	0.0091	0.0153	0.0178	–0.0160	–3.4	3.9	–5.7	–2.2
6	0.0202	0.0143	0.0069	0.0109	0.0118	0.0082	–0.0160	–1.8	5.8	–7.5	–1.2
7	0.0153	0.0127	0.0059	0.0079	0.0074	0.0028	–0.0180	–2.6	7.3	–3.7	–1.4
8	0.0208	0.0175	0.0074	0.0075	0.0145	0.0115	–0.0110	–4.5	3.8	–7.9	–2.7
9	0.0214	0.0242	0.0064	0.0099	0.0135	0.0172	–0.0230	–2.5	4.0	–5.4	2.2
10	0.0204	0.0164	0.0063	0.0071	0.0124	0.0097	–0.0230	–0.9	4.4	–5.8	2.3
11	0.0275	0.0205	0.0108	0.0092	0.0179	0.0150	–0.0220	–9.3	–0.4	–6.4	–3.0
12	0.0206	0.0220	0.0066	0.0095	0.0153	0.0140	–0.0220	–1.5	7.0	–4.1	2.8
13	0.0330	0.0285	0.0112	0.0121	0.0268	0.0207	–0.0190	–2.6	3.8	–5.8	2.5
14	0.0174	0.0144	0.0084	0.0077	0.0065	0.0067	–0.0230	–7.6	1.3	–3.6	2.7
15	0.0189	0.0204	0.0059	0.0149	0.0101	0.0041	–0.0180	–5.6	1.9	–4.5	3.8
16	0.0226	0.0230	0.0085	0.0135	0.0173	0.0131	–0.0180	–6.2	2.0	–4.0	1.3
17	0.0304	0.0285	0.0087	0.0130	0.0187	0.0191	–0.0190	–8.2	0.8	–5.5	0.9
18	0.0339	0.0263	0.0096	0.0139	0.0230	0.0117	–0.0200	–8.6	–0.7	–4.2	1.4
19	0.0235	0.0195	0.0133	0.0137	0.0139	0.0079	–0.0270	–4.4	3.1	–3.5	4.1
20	0.0271	0.0319	0.0070	0.0164	0.0208	0.0163	–0.0270	–2.9	5.4	–4.4	3.9
21	0.0264	0.0249	0.0091	0.0127	0.0172	0.0170	–0.0260	–5.6	2.1	–4.5	1.2
22	0.0315	0.0266	0.0101	0.0141	0.0220	0.0158	–0.0260	–5.7	3.2	–3.1	5.4
23	0.0215	0.0279	0.0102	0.0171	0.0109	0.0122	–0.0240	–6.0	2.0	–3.3	3.0
24	0.0251	0.0259	0.0090	0.0151	0.0176	0.0155	–0.0300	–4.2	2.6	–1.6	7.2
25	0.0269	0.0210	0.0079	0.0145	0.0185	0.0130	–0.0340	–2.7	5.1	–4.0	4.1
26	0.0263	0.0255	0.0110	0.0130	0.0164	0.0136	–0.0220	–7.6	0.4	1.0	8.0
27	0.0334	0.0301	0.0084	0.0098	0.0260	0.0253	–0.0230	–6.5	–1.5	0.5	8.1
28	0.0311	0.039	0.0096	0.0131	0.0196	0.0251	–0.032	–8.3	3	0.6	8.7
29	0.027	0.0204	0.0095	0.0134	0.018	0.0101	–0.033	–6.6	1.6	–2.9	4.4
30	0.026	0.0332	0.0114	0.0174	0.0152	0.0158	–0.031	–7.8	1.8	–2.9	5
31	0.0237	0.0394	0.011	0.0216	0.0183	0.0203	–0.035	–3.6	4.3	0	7.3
32	0.0252	0.037	0.0166	0.0237	0.0113	0.0147	–0.032	–10	1.5	–5.4	6.7
33	0.0244	0.04	0.0123	0.0247	0.0166	0.0205	–0.023	–5.9	0.7	–3.2	5.7
34	0.0285	0.0251	0.0138	0.0171	0.0152	0.0139	–0.035	–2.9	6.2	2.7	12.6
35	0.0344	0.0415	0.0107	0.0194	0.023	0.0191	–0.027	–5.9	2.5	–1.8	4.8

	Conv Fp	Conx Fp	Conv fp	Conx fp	Conv Fr	Conx Fr	Size	ToeTop	ToeRoot	HeelTop	HeelRoot
Count	35	35	35	35	35	35	35	35	35	35	35
Min.	0.0136	0.0127	0.0056	0.0064	0.0056	0.0028	–0.035	–10.000	–1.500	–7.900	–4.200
Max.	0.0344	0.0415	0.0166	0.0247	0.0268	0.0253	–0.009	–0.800	7.300	2.700	12.600
Range	0.0208	0.0288	0.0110	0.0183	0.0212	0.0225	0.026	9.200	8.800	10.600	16.800
Average	0.0243	0.0254	0.0091	0.0131	0.0157	0.0143	–0.023	-4.769	3.180	–3.763	2.806
SD	0.00572	0.00761	0.00250	0.00455	0.00524	0.00510	0.00683	2.66235	2.24458	2.45022	3.99588
3*SD	0.01717	0.02284	0.00749	0.01366	0.01573	0.01529	0.02049	7.98705	6.73373	7.35066	11.98763
6*SD	0.03434	0.04567	0.01499	0.02733	0.03146	0.03059	0.04098	15.97409	13.46745	14.70132	23.97526
Upper Lim	0.0864	0.0864	0.0193	0.0193	0.076	0.076	0.076	30.000	30.000	30.000	30.000
Lower Lim	0.000	0.000	0.000	0.000	0.000	0.000	–0.076	–30.000	–30.000	–30.000	–30.000
Tolerance	0.0864	0.0864	0.0193	0.0193	0.076	0.076	0.152	60	60	60	60
Toler Type	Uni	Uni	Uni	Uni	Uni	Uni	Bi	Bi	Bi	Bi	Bi
Pp Spec							1.67	1.67	1.67	1.67	1.67
Ppk Spec	1.33	1.33	1.33	1.33	1.33	1.33	1.67	1.67	1.67	1.67	1.67
Bilat Pp							3.71	3.76	4.46	4.08	2.50
Bilat Ppk							2.58	3.16	3.98	3.57	2.27
Unilat Ppk	3.62	2.67	1.36	0.45	3.84	4.03					
Bilat Pp							PASS	PASS	PASS	PASS	PASS
Bilat Ppk							PASS	PASS	PASS	PASS	PASS





Appendix 3—Short study GR&R, range method.

Machine S/N 951104

DATE: March 12, 2002

Short Study GR&R Coast Side
Results in Arc Seconds

	5 parts	10 parts
d2	1.19	1.16

Reading	Operator A	Operator B	Delta
1	1.01000	1.09000	0.08000
2	2.63000	2.65000	0.02000
3	3.29000	3.24000	0.05000
4	2.62000	2.64000	0.02000
5	2.10000	2.17000	0.07000
		Sum	0.24000
		Avg. R	0.04800

Tolerance: 5 Arc Seconds

GRR 0.20784 (5.15 x Avg. R /1.19)
GRR% 4.2 (100 x GRR / 5)

GRR Sigma = 0.04034 (GRR/(1.19 x 4.33))

Appendix 4—Long study GR&R, average and range method.

Phoenix 500HCT GR&R Study—8.8–3.73
Customer:
Machine Serial Number: 951104
Study Date: March 6, 2002
Study Conducted By: Andrew DeSantis
Operator 1: S.G.
Operator 2: S.Z.
Operator 3: J.Z.

Side: Coast
Units: arc sec.
Apprais.:3
Trials: 3
Sets: 10

	Operator #1					Operator #2				
Set #	**1/A**	**1/B**	**1/C**	**Avg.**	**Range**	**2/A**	**2/B**	**2/C**	**Avg.**	**Range**
1	1.06	1.17	1.24	1.16	0.18	1.18	1.19	1.30	1.22	0.12
2	3.02	3.08	3.05	3.05	0.06	3.05	3.12	3.01	3.06	0.11
3	3.54	3.62	3.62	3.59	0.08	3.59	3.65	3.67	3.64	0.08
4	3.07	3.16	3.17	3.13	0.10	3.14	3.35	3.20	3.23	0.21
5	2.56	2.64	2.68	2.63	0.12	2.73	2.71	2.64	2.69	0.09
6	2.50	2.63	2.70	2.61	0.20	2.60	2.59	2.71	2.63	0.12
7	4.34	4.37	4.39	4.37	0.05	4.36	4.43	4.35	4.38	0.08
8	1.66	1.89	1.93	1.83	0.27	1.72	1.93	1.91	1.85	0.21
9	3.00	3.24	3.23	3.16	0.24	3.11	3.05	3.21	3.12	0.16
10	3.03	3.03	3.21	3.09	0.18	2.93	3.10	3.09	3.04	0.17
Totals	27.78	28.83	29.22	28.61	1.48	28.41	29.12	29.09	28.87	1.35
Avgs.	2.78	2.88	2.92	2.86	0.15	2.84	2.91	2.91	2.89	0.14

	Operator #3					Sample	Sample	Sample	Sample
Set #	**3/A**	**3/B**	**3/C**	**Avg.**	**Range**	**Avg.**	**Max.**	**Min.**	**Range**
1	1.17	1.15	1.26	1.19	0.11	1.19	1.30	1.06	0.24
2	2.96	3.12	3.20	3.09	0.24	3.07	3.20	2.96	0.24
3	3.54	3.63	3.70	3.62	0.16	3.62	3.70	3.54	0.16
4	3.17	3.31	3.39	3.29	0.22	3.22	3.39	3.07	0.32
5	2.59	2.66	2.80	2.68	0.21	2.67	2.80	2.56	0.24
6	2.62	2.57	2.64	2.61	0.07	2.62	2.71	2.50	0.21
7	4.39	4.42	4.43	4.41	0.04	4.39	4.43	4.34	0.09
8	1.81	1.88	1.92	1.87	0.11	1.85	1.93	1.66	0.27
9	3.11	3.14	3.00	3.08	0.14	3.12	3.24	3.00	0.24
10	3.06	3.28	3.09	3.14	0.22	3.09	3.28	2.93	0.35
Totals	28.42	29.16	29.43	29.00	1.52	Rsubp			
Avgs.	2.84	2.92	2.94	2.90	0.15	3.20			

BarA	2.86100	Trials	3
RBarA	0.14800	Dsub4	2.58
XBarB	2.88733	UCLr	0.374100
RBarB	0.13500	LCLr	0
XBarC	2.90033	Ksub1	3.0419
RBarC	0.15200	Operators	3
Rp	3.19556	Ksub2	2.7
RBarBar	0.14500	Ksub3	1.62
XBarDiff	0.03933	Parts	10

EV	0.44108	Repeatability - Equipment Variation (EV)
AV	0.06924	Reproducibility - Appraiser Variation (AV)
R&R	0.44648	Repeatability & Reproducibility (R&R)
PV	5.17680	Part Variation (PV)
TV	5.19602	Total Variation (TV)
%EV	8.49%	
%AV	1.33%	
%R&R	8.59%	
%PV	99.63%	

EV = RBarBar * Ksub1
AV = SQRT((XBarDiff * KSub2)^2 – (EV^2/nr))
R&R = SQRT(EV^2 + AV^2)
PV = Rp * Ksub3
TV = SQRT(R&R^2 + PV^2)
%EV = 100 *(EV/TV)
%AV = 100 *(AV/TV)
%R&R = 100 * (R&R/TV)
%PV = 100 * (PV/TV)

Appendix 5—Useful definitions from the SPC reference manual and Delphi specification SD-002.

analysis of variance (ANOVA)—statistical method to evaluate the data from a designed experiment.

apparent resolution—the size of the least increment on the measurement instrument, this value is typically used in literature as advertisement to classify the measurement instrument; the number of data categories can be determined by dividing the size into the expected process distribution spread (6σ).

appraiser variation—variation due to difference in appraiser method, calculated as variation due to the inability of one appraiser to reproduce the measurements of another appraiser; appraiser variation is referred to as "reproducibility" in the calculation worksheets.

assignable cause—sometimes referred to as a special cause, a source of variation that is intermittent, often unpredictable, and unstable.

average (x)—the sum of the numerical values in a sample divided by the number of observations.

bias—difference between the observed average of measurements and the master average of the same parts using precision instruments.

bilateral specification—bilateral tolerances are those that define a nominal dimension along with a ± allowance.

center line—the horizontal line in the middle of a control chart that shows the average value of the items being plotted.

common cause—a source of variation that affects all the individual values of the process variation.

control chart—a chart that shows the plotted values, a central line and one or two control limits that are used to monitor a process over time; the types of control charts used are:

X chart—a control chart where the average of a subgroup of data is monitored over a period of time.

R chart—a chart used to monitor the range of a subgroup of data over a period of time.

p chart—used for data that consists of the ratio of the number of occurrences of an event to total occurrences, generally used to report the fraction non-conforming or defective; p charts can have a variable sample size.

control limit—a dashed line or lines on a control chart used as a basis for judging the significance of variation from subgroup to subgroup. Variation beyond a control limit shows that special causes may be affecting the process. Control limits are calculated from process data and are not to be confused with engineering specifications.

Cpk—the capability index for a stable process, typically defined as the minimum of CpkU or CpkL.

CR—capability ratio.

data—variable data: measurements of a sampled part. attribute data: qualities and pass/fail test results of a sampled part.

designed experiment—a plan to conduct tests that involves all of the prework that must be accomplished before any tests are conducted. Prework requirements are: questions be written; data collection sheets be prepared; analysis of data be laid out; and the limitations of the test be known.

discrimination—discrimination is the larger of the apparent and effective resolutions for single reading systems. The number of data categories is often referred to as the discrimination ratio since it describes how many classifications can be reliably distinguished given the observed process variation.

distribution—a way of describing the output of a natural cause system of variation, in which individual values are not predictable but in which the outcomes as a group form a pattern that can be described in terms of its location, spread and shape. Location is commonly expressed by the mean or average, or by the median; spread is expressed in terms of the standard deviation or the range of a sample; shape involves many characteristics such as symmetry and peakedness, but these are often summarized by using the name of a common distribution, such as the normal, binomial, or Poisson.

effective resolution—the size of the data category when the total measurement system variation is considered is the effective resolution. This size is determined by the length of the confidence interval based on the measurement system variation. The number of data categories can be determined by dividing the size into the expected process distribution spread. For the effective resolution, a standard estimate of this (at the 97% confidence level) is 1.41 [PV/R&R].

finish tool—any tool that generates a part feature being evaluated (final or in-process).

gage—any device used to obtain measurements, frequently used to refer specifically to the devices used on the shop floor, includes go/no-go devices.

gage repeatability & reproducibility (GR&R)—a statistical method of determining the accuracy, repeatability, and the relative ease of use of a gaging system.

histogram—a bar chart that represents data in cells of equal width. The height of each cell is determined by the number of observations that occur in each cell.

in control—state of a process when it exhibits only random variations (as opposed to systematic variations and/or variations with assignable sources).

in-process dimensions—dimensions that occur on the process routings but usually not on the part print. Normally they are intermediate dimensions of a complex process.

interaction—found in GR&R. Non-additivity between appraiser and part. Appraiser differences depend on the part being measured.

key control characteristic (KCC)—a process parameter for which variation must be controlled around some target value to ensure that variation in a KPC is maintained around its target value during manufacturing and assembly. A method for adjusting the KPC to its target value is required.

key product characteristic (KPC)—a product characteristic for which reasonably anticipated variation could significantly affect the product's safety or compliance with government standards or regulations, or is likely to significantly affect customer satisfaction with a product.

linearity—difference in the bias values of a gage through the expected operating range of the gage.

long term capability—statistical measure of the within-subgroup variation exhibited by a process over a long period of time. This differs from performance because it does not include the between-subgroup variation.

mean—the average of values in a group of measurements.

median—the middle value of a group of measurements, when arranged from lowest to highest, if the number of values is odd. By convention, if the number of values is even, the average of the middle two values is the median.

measurement system—the collection of operations, procedures, gages and other equipment, software and personnel used to assign a number to the characteristic being measured; the complete process used to obtain measurements. The actual gages or measurement devices utilized to monitor a process.

measurement system error—the combination of gage bias, repeatability, reproducibility, stability and linearity.

normal distribution—a continuous, symmetrical, Gaussian-bell-shaped frequency distribution for variable data that underlies the control charts for variables. When measurements have a normal distribution, about 68.26%, 95.44%, 99.73% of all individuals lie within plus and minus one, two, and three standard deviations from the mean, respectively. These percentages are the basis for control limits and control charts analysis.

out-of-control—condition describing a process from which all special causes of variation have not been eliminated. This condition is evident on a control chart by the presence of points beyond the control limits or by patterns that are not random within the control limits.

Ppk—the performance index for a stable process, typically defined as the minimum of PpkU or PpkL.

PR—performance ratio.

probability—set of conditions or causes working together to produce an outcome.

process—the combination of people, machines and equipment, raw materials, methods and environment that produces a given product or service.

process capability—the total range of a stable process's inherent variation ($6\hat{\sigma}_{R/d_2}$)

process performance—the total range of a stable process's total variation ($6\sigma_s$).

process routings—the documents that describe the processes required to produce a product.

range (R)—the difference between the highest and lowest values in a subgroup.

reference value—**1**. a value that serves as an agreed upon reference for comparison. It may be a theoretical or established value based on scientific principles; an assigned value based on some national or international organization; a consensus value based on collaborative experimental work under the auspices of a scientific or engineering group; or for a specific application, an agreed upon value obtained using an accepted reference method. **2**. a value attributed to a specific quantity and accepted, sometimes by convention, as appropriate for a given purpose. **3**. a value consistent with the definition of a specific quantity and accepted, sometimes by convention, as appropriate for a given purpose.

regression analysis—a calculation to define the mathematical relationship between two or more variables.

repeatability—variation in measurements obtained with one gage when used several times by one appraiser while measuring a characteristic on one part.

reproducibility—variation in the average of the measurements made by different appraisers using the same gage when measuring a characteristic on one part.

resolution—the capability of the measurement system to detect and faithfully indicate even small changes of the measured characteristic; see also discrimination.

scatter diagram—a plot of two variables, one against the other, to display trends.

sigma (σ)—the measure of variability, or dispersion, that indicates how data spreads out from the mean. It gives information about the variation in a process.

stability—the condition describing a process from which all special causes of variation have been eliminated, and only common causes remain; evidenced by the absence of points beyond the control limits and by the absence of non-random patterns or trends within the control limits.

standard deviation—see sigma.

statistical process control—the use of statistical methods and techniques, such as control charts, to analyze a process or its output so as to take appropriate actions to achieve and maintain a state of statistical control and continue improvement of process variability.

subgroup—one or more events or measures used to analyze the performance of a process. Rational subgroups are chosen so that the variation represented within each subgroup is as small as feasible.

tolerance—allowable deviation from standard. That is, the permitted range of variation about a nominal value. The permitted tolerance is the difference between the upper and lower specification limits. Specification limits should not be confused with control limits.

unilateral specification—unilateral tolerances are those which have only a single limit, e.g. must not exceed 1,000 lbs. or hardness to be 60 Rockwell or less.

variation—the inevitable differences among individual outputs of a process; the source of variation can be grouped into two major classes: common causes and assignable (special) causes.

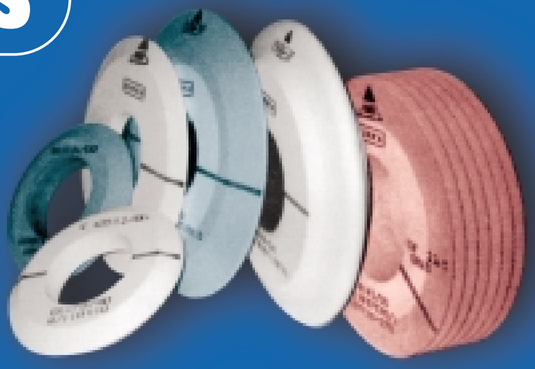
$\bar{X}$ and R chart—see control chart.

zero based dimensions—these dimensions have a value of zero as their inherent target value, e.g. roundness, concentricity, and surface finish. They usually generate distributions that have a visible amount of skewness or non-normality.

BURKA-KOSMOS

Gear Tooth Grinding Wheels

Burka-Kosmos has been manufacturing grinding wheels since 1890. They have specialized in grinding wheels for gear grinding since 1980 and now over 95% of their production is for gear grinding applications. They manufacture wheels for profile grinding, generative grinding and thread grinding. They offer both aluminum oxide and ceramic. JRM International, Inc. is the exclusive North American partner of Burka-Kosmos. We stock wheels for all applications in a variety of sizes. We are also available to assist you in optimizing your grinding process.



- ***Available unprofiled or pre-profiled***
- ***Standard wheels in stock***

JRM International, Inc.

5701 Industrial Avenue • Rockford, IL 61111
815-282-9330 • Fax: 815-282-9150
E-Mail: jrmsales@jrminternational.com
www.jrminternational.com

Gear Production Specialists

• Gear Shapers • Gear Hobbers • Gear Grinders •

- **Full Remanufacture:**
  - A brand new machine on highly stable, naturally aged castings.
- **CNC Retrofit** for total process control. Max performance with minimal operator intervention:
  - Up to 6-Axis of CNC machine control.
  - Thermal Compensation
  - Closed loop auto compensation from post process and/or tool gages.
- **Application Engineering:**
  - Process development and cycle optimization.
- **Field Service and Preventive Maintenance Plans**

NO RISK – RESULTS GUARANTEED

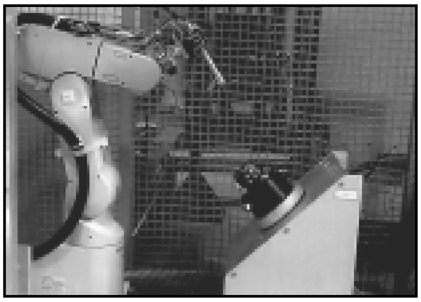
- **Statistical run-off to your specifications.**
- **2 Year warranty, *best in the industry.***

VERMONT MACHINE TOOL®

802-885-4521
www.vermontmachinetool.com

Quality, Experience and Craftsmanship for over 20 years
Springfield, Vermont USA

Products for the Gear Industry



Gear Inspection System from American Stress Technologies

The Gear Scan Inspection System from American Stress Technololgies is an off-line audit system that monitors residual stress from manufacturing processes and detects grinding damage.

According to the company's press release, spur, helical and spiral bevel gears can all be tested by programming the robotic arm for that specific gear. The unit requires manual loading and unloading of the test piece. A sensor scans the ground surface and sends test information to a ROLL SCAN central unit.

For more information, contact American Stress Technologies of Pittsburgh, PA, by telephone at (412) 963-0676 or on the Internet at *www.ASTresstech.com.*

New Hobbing Machine from Bourn & Koch

The 100H Series II Hobbing Machine from Bourn & Koch incorporates the features of the 200H/400H Series II machines.

Standard features include six-axis CNC controls, radial in-feed, axial feed, hob shift, hob spindle, work spindle, and hob swivel.

New features include 6" of hob shift, standard NUM 1050 CNC controller containing NUM digital drives with absolute encoders, conversational software, 2,000 rpm hob spindle with 5 continuous hp and 10 maximum peak hp, a full machine enclosure with stainless steel sloped guarding for wet or dry cutting capabilities, no hydraulics, an easy placement tail center assembly with adjustable clamping force up to 500 lbs. and 3" stroke live center.

According to the company's press release, the 100H accommodates parts with a maximum swing diameter of 10" and a cutting diameter of 4.5".

For more information, contact Bourn & Koch of Rockford, IL, on the Internet at *www.bourn-koch.com* or by e-mail at *bournkoch@att.net.*

New Hobbing Machine from Liebherr

The LC 120 hobbing machine from Liebherr is a new generation series based on components of other successful hobbers.

According to the company's press release, the redesigned cutting head represents the core of the machine evolution. Speed and torque of 6,000 rpm at 18 kW are realized by means of new direct drives that enable the use of both HSS and hard metal tools in wet and dry processes.

In addition, a new bed design guarantees virtually complete swarf removal during dry processing by means of an integrated worm conveyor. Cutting speeds for cermet tools reach 1,000 m/minute.

This machine can be enhanced and become multi-functional through use of an add-on unit for the pressure deburring of gears during mass production.

For more information, contact Liebherr by e-mail at *amontag@klingelnberg.com* or on the Internet at *www.lvt.liebherr.com.*

Carbide Burs from TJT Sales

The Aggressor carbide burs from Grobet File Co. have been redesigned for use in the gear industry.

Double-cut burs were engineered for

heavy duty applications with a unique tooth design to remove more material per hour, according to the company's press release.

Burs are more durable and resistant to chipping because of the width and depth of the teeth. Wider teeth make longer chips that break up easily, and the tooth profile is less prone to filling up with those chips.

For more information, contact Grobet's distributor TJT Sales of Cathedral City, CA, by telephone at (760) 322-5279 or by e-mail at *thomas-saccuci@cs.com.*

Florida Drives & Gearmotors Expands Facility, Product Line

Florida Drives & Gearmotors is expanding its gear parts division with the purchase of a facility to offer new, used and obsolete replacement parts and components for manufacturers of reducers, gearmotors, adjustable speed drives and related products.

According to the company's press release, they are also expanding their product line through the purchase of Hauser Development Corp.'s right angle bevel gear drives line. Used primarily in agricultural, marine and heavy construction industries, this line has units available in two, three, and four shaft arrangements at 45° and 90° assemblies. Drives are available with or without flanges and with spline or standard shafts.

For more information, contact Florida Drives & Gearmotors of Tampa, FL, by telephone at (800) 940-GEAR or on the Internet at *www.herculesgear.com.*

New Whirling Machine from Leistritz

The PWM 200 whirling machine from Leistritz is designed for quick set up and change-over times.

According to the company's press release, features include a simple operation with interactive programming, a compact design, central lubrication system for ball screws and guideways, a vertical bed arrangement for chip removal, and automatic loading and unloading systems.

In addition, the patented tooling system includes screw-mounted inserts and a positive stop insert location. CBN inserts for cutting hard material are available up to 65 HRc. Regrindable carbide and CBN inserts are available, and these inserts can be reground up to 15–20 times.

For more information, contact Lestritz Corp. of Allendale, NJ, by telephone at (201) 934-8262 or on the Internet at *www.leistritz.com.*

New Hobbing Machines from Mitsubishi

The new GE line of hobbing machines from Mitsubishi allows for dry hobbing on a vertical platform.

According to the company's newsletter, this product converts from dry to wet cutting by the flip of a switch. Other features include a modular floor plan and easily adapted automation, among other high-speed features.

For more information, contact Mitsubishi Gear Center of Wixom, MI, by telephone at (248) 669-6136 or by visiting the company's website at *www.mitsubishigearcenter.com*.

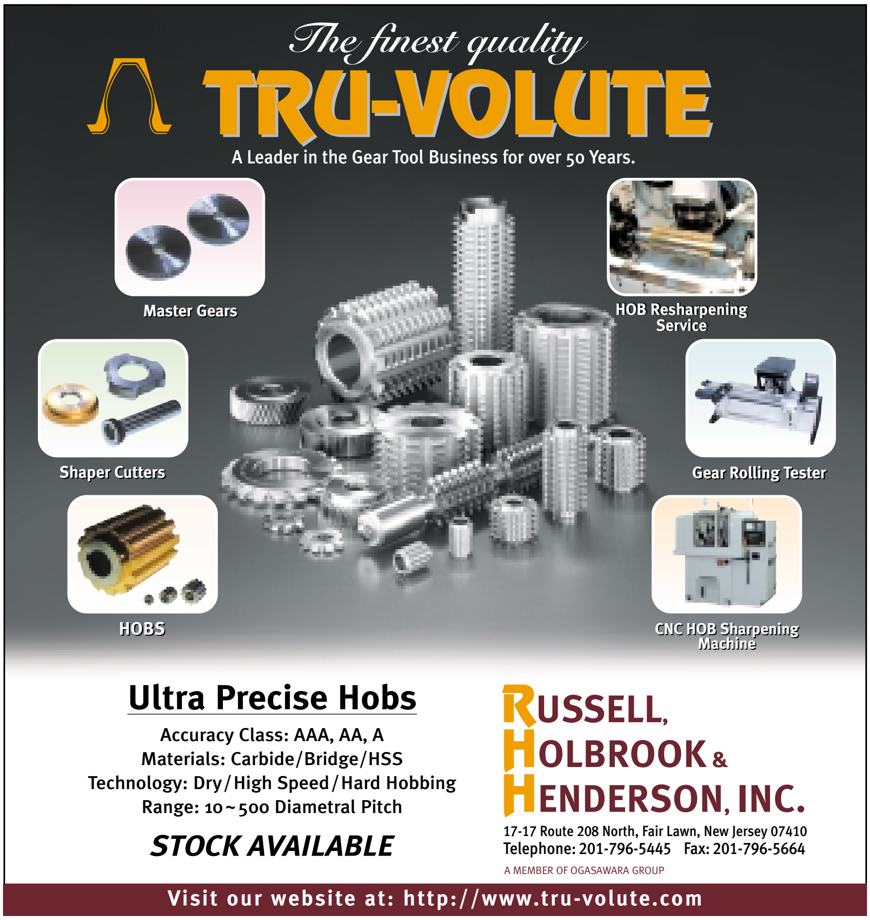
New Blade Profile Grinder from Gleason

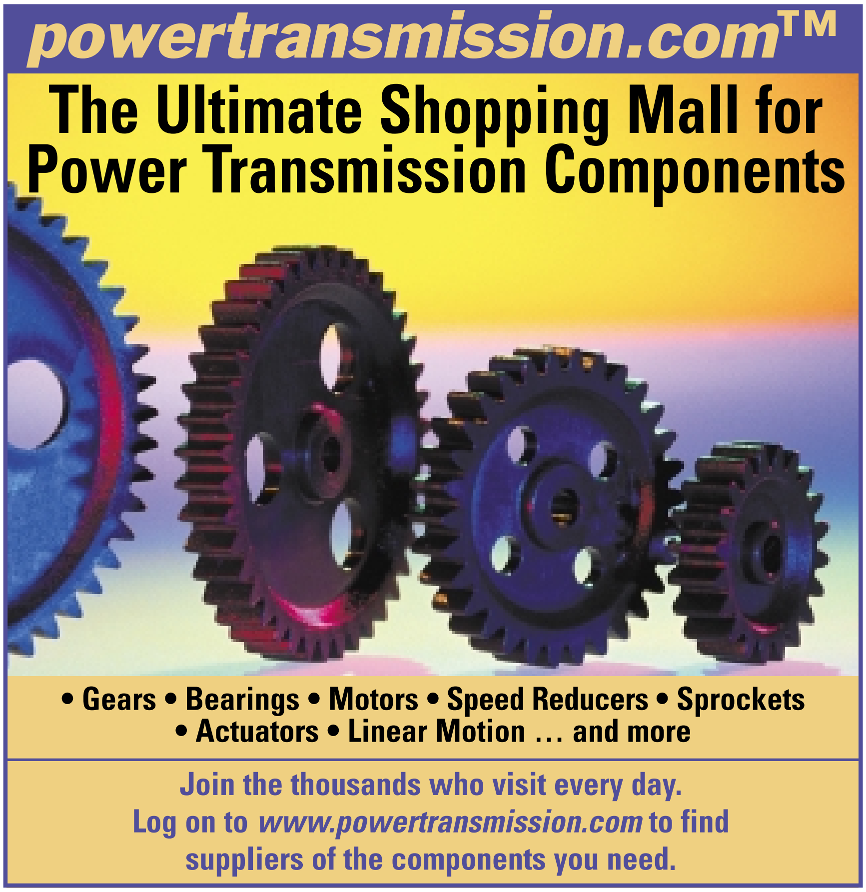
The new BPG blade profile grinder from Gleason improves sharpening operations on bevel cutter blades though reduced cycle times and ease of use, according to the company's press release.

By combining Gleason's Quickedge grinding process with high speed, flexible automation, the BPG is designed to reduce floor-to-floor times and the cost of blade resharpening. The process features faster stock removal rates while reducing wheel wear. According to the company's press release, the process also offers fast and repeatable results for stick-type blades of high-speed steel and carbide materials.

In addition, machine thoroughput is improved by faster automation. Other features include a double gripper gantry system for automation of blade load and unload as well as a direct drive grinding wheel spindle and an on-machine unit that dresses wheels in one minute or less.

For more information, contact Gleason Corp. of Rochester, NY, by telephone at (585) 473-1000 or on the Internet at *www.gleason.com*.





ADVERTISER INDEX

USE RAPID READER RESPONSE to contact any advertiser in this issue
www.geartechnology.com/rrr.htm
Rapid Reader Response: It's FAST! It's EASY! It's ONLY ONLINE!

Advertiser	Page	Phone	E-mail	Internet
Ajax Tocco Magnethermic	3	(800) 547-1527		www.ajaxtocco.com
Allen Adams Shaper Services Inc.	54	(802) 259-2937	adams@vermontel.net	
American Metal Treating Co.	54	(216) 431-4492	bruce@americanmetaltreating.com	www.americanmetaltreating.com
Arrow Gear Co.	4	(630) 969-7640	bevels@arrowgear.com	www.arrowgear.com
A/W Systems Co.	12, 53	(248) 544-3852		
B&R Machine and Gear Corp.	14	(800) 238-0651	inquirygt@brgear.com	www.brgear.com
Barit International Corp.	4	(847) 272-8128	people@barit.com	www.barit.com
Bourn & Koch Machine Tool Co.	8, 54	(815) 965-4013	bournkoch@worldnet.att.net	www.bourn-koch.com
Clydesdale Forge Co.	14	(44) (1384) 252587	sales@clydesdale-forge.co.uk	www.clydesdale-forge.co.uk
De.Ci.Ma SpA	18	(39)(051) 611-7889	info@decimaspa.it	www.decimaspa.it
Dr. Kaiser (S.L. Munson)	50	(800) 775-1390	info@slmunson.com	
Gear Motions Inc.	55	(315) 488-0100	ronwri@nixongear.com	www.gearmotions.com
Gear Technology magazine	54	(847) 437-6604	jbartz@geartechnology.com	www.geartechnology.com
The Gear Works–Seattle Inc.	53	(206) 762-3333	sales@thegearworks.com	www.thegearworks.com
Gleason Corp.	IFC, 55	(585) 473-1000	dmelton@gleason.com	www.gleason.com
Gleason Cutting Tools Corp.	1, 53, 55	(815) 877-8900	dmelton@gleason.com	www.gleason.com
The Gleason Works	53	(585) 473-1000	dmelton@gleason.com	www.gleason.com
Insco Corp.	31	(978) 448-6368	sales@inscocorp.com	www.inscocorp.com
Interstate Tool Corp.	54	(216) 671-1077		www.interstatetoolcor.com
ITW Heartland	31	(320) 762-8782	itwgears@rea-alp.com	www.itwgears.com
JRM International Inc.	48	(815) 282-9330	jrmsales@jrminternational.com	www.jrminternational.com
Koro Sharpening Service	54	(763) 425-5247	steve@koroind.com	www.koroind.com
Liebherr Gear Technology Co.	5	(734) 429-7225	info@lgt.liebherr.com	www.liebherr.com
LMT-Fette	17	(800) 225-0852	lmtfette@lmtfette.com	www.lmtfette.com
Marposs Corp.	6	(888) 627-7677, (248) 370-0404	marposs@us.marposs.com	www.marposs.com
mG miniGears North America	15	(757) 627-4554	mg_usa@minigears.com	www.minigears.com
Midwest Gear Corp.	54	(330) 425-4419	sales@mwgear.com	www.mwgear.com
Midwest Gear & Tool Inc.	19	(586) 754-8923	rosscr@attglobal.net	
Mosey Manufacturing Co. Inc.	54	(765) 983-8800	samosey@aol.com	www.moseymanufacturing.com
Nachi Machining Technology Co.	11, 53	(586) 263-0100	sales@nachimtc.com	www.nachimtc.com
Niagara Gear Corp.	53	(800) 447-2392, (716) 874-3131	info@niagaragear.com	www.niagaragear.com
Perry Technology Corp.	IBC	(860) 738-2525	sales@perrygear.com	www.perrygear.com
Precision Gage Co. Inc.	19	(630) 655-2121		www.precisiongageco.com
Process Gear/Bengal Industries	49	(847) 671-1631	jhertl@processgear.com	www.processgear.com
The Purdy Corp.	10	(860) 649-0000	sales@purdytransmissions.com	www.purdytransmissions.com
Quality Transmission Components	18	(516) 437-6700	support@qtcgears.com	www.qtcgears.com
Russell, Holbrook & Henderson Inc.	51	(201) 796-5445	sales@tru-volute.com	www.tru-volute.com
Star-SU Inc.	54, OBC	(847) 649-1450	sales@star-su.com	www.star-su.com
Vermont Machine Tool Co.	48	(802) 885-4521	info@vermontmachinetool.com	www.vermontmachinetool.com

CLASSIFIEDS

SERVICE

- CONTRACT METROLOGY SERVICES
- CURVIC COUPLING GRINDING & INSPECTION
- BEVEL & CYLINDRICAL DEVELOPMENTS & PROTOTYPES
- APPLICATION ENGINEERING SUPPORT & DESIGN SERVICES
- HEAT TREATMENT
- REPLACEMENT HELICAL GUIDES FOR SHAPERS, INCLUDING FELLOWS

SPECIALIZED GEAR SERVICES

The Gleason Works

1000 University Ave., P.O. Box 22970
Rochester, NY 14692-2970 U.S.A.
Phone: 585/473-1000
Fax: 585/461-4348
E-mail: sales@gleason.com

www.gleason.com

- BROACH SHARPENING
- HOB SHARPENING
- SHAVING CUTTER GRINDING
- THIN FILM COATING
- CUSTOM HEAT TREAT SERVICE
- REPLACEMENT HELICAL GUIDES FOR SHAPERS, INCLUDING FELLOWS

PICK UP AND DELIVERY IN MANY AREAS

Gleason Cutting Tools
CORPORATION

1351 Windsor Road
Loves Park, IL 61111 U.S.A.
Phone: 815/877-8900
Fax: 815/877-0264
E-mail: gctc@gleason.com

www.gleason.com

NACHi
NACHI MACHINING TECHNOLOGY CO.

Now offering the following services for:
Broaching Machines
Gear Shaving Machines
Rack Rolling Machines

- Repair Services in-plant
- Redesign & Retool
- Replacement Parts for Red Ring, National Broach and Nachi Products
- Repair Services for most gear and spline-making machines

Contact:
service@nachimtc.com
ph: 586.263.0100
fx: 586.263.4571

www.nachimtc.com

Reconditioned Cutter Bodies
$ Guaranteed Cost Savings $

A/W Systems can recondition A/W Spiral Bevel Cutter Bodies to 100% like-new condition.

A/W Systems can sharpen Spiral Bevel and Straight Bevel Cutter Blades. Hob and Shaper Cutter sharpening service also available.

PCD and CBN Inserts reconditioned and retipped available.

Rapid turnaround time.
Most sizes available.

For information and quote,
please contact us at the following:

A/W Systems Company
612 E. Harrison Ave., Royal Oak, MI 48067
Phone: (248) 544-3852 • Fax: (248) 544-3922

WHEN IT HAS TO BE RIGHT

- Gear Grinding to 94"
- Industrial Gears to 250"
- Turbo Compressor Gears
- Custom Drives
- Spline Broaching
- Gear Metrology
- Stock Planetary Speed Reducers

THE GEAR WORKS

GEARBOX REPAIR

Custom Gear Services Since 1946

ISO-9001

www.thegearworks.com

The Gear Works—Seattle, Inc.
500 S. Portland Street
Seattle, WA 98108-0886
Phone: (206) 762-3333
Fax: (206) 762-3704
E-mail: sales@thegearworks.com

PRECISION GROUND GEARS

- Spur, Helical and Pump Gears to AGMA Class 15
- Featuring the latest grinding and CNC technology including:
  - Reishauer RZ300E Electronic Gear Grinders
  - Gleason TAG 400 CNC, 8-axis High Production Gear Grinder
  - Full CNC Multi-axis Cylindrical Grinding (Internal and External)
  - High Performance CNC Hobbing
- Continuous Process Improvement Utilizing SPC and Quality Planning
- JIT Delivery using Innovative Stocking Programs

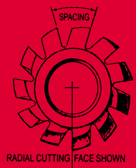
800-447-2392
Fax: 716-874-9003
www.niagaragear.com
email:info@niagaragear.com

NIAGARA
GEAR CORPORATION

Rates—Line Classified: 1" minimum, $325. Additional lines $45 per line (8 lines per inch). Display Classified: 3" minimum: **1X**—$735, **3X**—$685 per insertion, **6X**—$645 per insertion. Additional per inch: **1X**—$255, **3X**—$235 per insertion, **6X**—$225 per insertion. **Color Classified:** Add $150 per insertion for color. *Gear Technology* will set type to advertiser's layout or design a classified ad at no extra charge. **Payment:** Full payment must accompany classified ads. Send check drawn in U.S. funds on a U.S. bank or Visa/MasterCard number and expiration date to *Gear Technology*, P.O. Box 1426, Elk Grove Village, IL 60009. **Agency Commission**: No agency commission on classified ads. **Materials Deadline:** Ads must be received by the 20th of the month, two months prior to publication. **Acceptance:** Publisher reserves the right to accept or reject advertisements at his discretion.

SERVICE

HOB SHARPENING
(763) 425-5247
★ *THIN FILM COATINGS* ★
HSS & Carbide up to 5" Dia.
Straight Gash,
Sharpened & Inspected
Per AGMA STANDARDS
Quick Turnaround



KORO SHARPENING SERVICE
9530 - 85TH AVENUE NO.
MAPLE GROVE, MN 55369
info@koroind.com

Induction Hardening
Specialists in Tooth by Tooth Contour Hardening of Internal *Spur, helical and bevel gears*

Our gear hardening equipment includes 5 NATCO submerged process machines and 5 AJAX CNC-controlled gear scanning machines. Tooth by tooth gear hardening from .5DP-10DP, up to 15 tons, 200" diameter.

American Metal Treating Company
Cleveland, Ohio
Phone: (216) 431-4492 • Fax: (216) 431-1508
Web: *www.americanmetaltreating.com*
E-mail: *bruce@americanmetaltreating.com*

Breakdown Service Available

GEAR GRINDING SERVICES

- Gear cutting from raw material to finished parts
- Ground tooth gears and pinions to 1 D.P. and up to A.G.M.A. quality class 12

From 1" Diameter, 64 D.P. to maximum sizes listed	Max. Face	Max. Size	Max. Pitch
Spur Gears	24"	92" P.D	1 D.P.
Helical Gears	24"	72" P.D.	1 D.P.
Spur & Helical Gears, Crown Hobbed	22"	72" P.D.	1 D.P.
Internal Gears & Splines	9"	100" P.D.	1-1/4 D.P.
Ground Gears, Crowned or Straight	16"	72" P.D.	1 D.P.
Herringbone Gears, Center Grove	14"	36" P.D.	2 D.P.

MIDWEST GEAR CORP.
Division of Penn Machine Company
2182 E. Aurora Rd., Dept MG, Twinsburg OH 44087
Phone: (330) 425-4419 • Fax: (330) 425-8600
***www.mwgear.com* • E-mail: sales@mwgear.com**

HIGH PRODUCTION GEAR BLANKING

- SOLID FORGED
- RING GEARS
- FORGED GEAR SHAFTS

MOSEY MANUFACTURING COMPANY, INC.

ISO 9002:94/QS
9000•98 Registered

262 Fort Wayne Ave • Richmond, IN 47374
Phone: 765-983-8800 • Fax: 765-983-8736
www.moseymanufacturing.com
Email: samosey@aol.com

Sharpening Service
for hobs, milling cutters shaper cutters, shaving cutters.

Star SU

★ GOLD STAR COATINGS

5200 Prairie Stone Parkway, Suite 100
Hoffman Estates, IL 60192
Tel.: (847) 649-1450 - Fax: (847) 649-0112

2083 W.M-55, West Branch, MI 48661
1-888-Resharp 1-888-737-4277
Tel.: (989) 345-2865 - Fax: (989) 345-5660

1580 Progress Dr., Richmond, IN 47374
Tel.: (765) 935-7424 - Fax: (765) 935-7631

sales@star-su.com www.star-su.com

INTERSTATE TOOL CORP.
CLEVELAND, OHIO

CUSTOM ENGINEERED & MANUFACTURED CUTTING TOOLS ESTABLISHED 1960

FORM RELIEVED & PROFILE GROUND MILLING CUTTERS
GEAR SHAPER & SHAVING CUTTERS
ALL CLASSES OF HOBS
HSS. SOLID CARBIDE & CARBIDE TIPPED

WHETHER YOU NEED NEW TOOLS, MODIFICATIONS, RESHARPENING, REPAIRS OR M&M INSPECTIONS,
CONTACT US FOR A QUOTE TODAY!

www.interstatetoolcor.com
Tel: 216-671-1077 • Fax: 216-671-5431

Allen Adams Shaper Services, Inc
Servicing Fellows Gear Shapers

- **On-Site Service:** Emergency & Scheduled
- **Technical Support via:** Telephone, Fax, or E-mail
- **Parts:** New and/or used
- **Hydrostatic Guides:** New and Repair Service
- **Retrofits:** Counters, Servos, CNC axis(axes)
- **Training:** Operator, Set Up & Maintenance
- **Preventive Maintenance Plans:** Customized to Your Needs.

Allen Adams Shaper Services Inc. is comprised of all former Fellows employees. Between us, we have the knowledge and capability to support all models of Fellows shapers from the oldest, to the newest CNC and Hydrostroke machines. Please consider us for all of your Shaper needs.

Telephone: 802-259-2937
Fax: 802-259-3937
E-mail: adams@vermontel.net

Fellows Barber-Colman

O.E.M.
Gear Hobbers, Fellows Shapers, Grinders, HOB Checkers, Shaper Cutter Checkers, Inspection Systems and Lead & Involute Masters

REMANUFACTURING/RETROFITTING
Barber-Colman Hobbers, Fellows Shapers and Roto-Technology Inspection Systems

PARTS/SERVICE
- Bourn & Koch, Fellows, Barber-Colman, Roto-Technology, Ferguson, J & L
- Recalibration of Your Gear Inspection System, Lead & Involute Masters
- Gear Inspection & Hob Sharpening

BK BOURN &KOCH INC

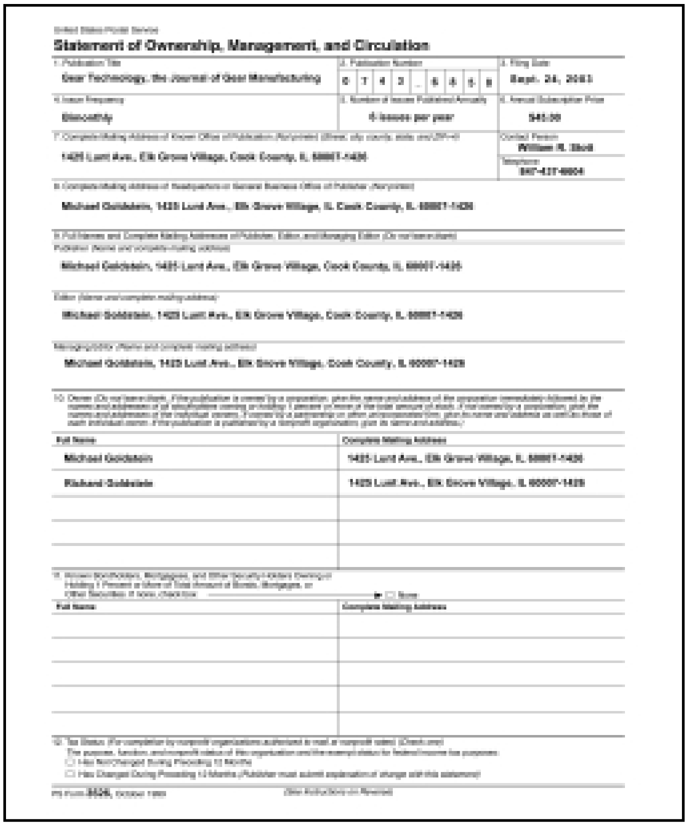
2500 Kishwaukee Street Rockford, IL 61104
phone 815/965-4013 fax 815/965-0019
www.bourn-koch.com bournkoch@worldnet.att.net
(800)922-8808 Springfield, VT Office

Be on the Cover of *Gear Technology*

Send us your high-quality gear-related images for our consideration.

It's a great chance for FREE publicity.

Contact:
Jean Bartz, Art Director
1425 Lunt Avenue
Elk Grove Village, IL 60007



United States Postal Service

Statement of Ownership, Management, and Circulation

1. Publication Title Gear Technology, the Journal of Gear Manufacturing	2. Publication Number 0 7 4 3 – 6 8 5 8	3. Filing Date Sept. 24, 2003
4. Issue Frequency Bimonthly	5. Number of Issues Published Annually 6 issues per year	6. Annual Subscription Price $40.00
7. Complete Mailing Address of Known Office of Publication 1425 Lunt Ave., Elk Grove Village, Cook County, IL 60007-1426		Contact Person William R. Stott Telephone 847-437-6604

8. Complete Mailing Address of Headquarters or General Business Office of Publisher
Michael Goldstein, 1425 Lunt Ave., Elk Grove Village, IL Cook County, IL 60007-1426

9. Full Names and Complete Mailing Addresses of Publisher, Editor, and Managing Editor
Publisher (Name and complete mailing address)
Michael Goldstein, 1425 Lunt Ave., Elk Grove Village, Cook County, IL 60007-1426
Editor (Name and complete mailing address)
Michael Goldstein, 1425 Lunt Ave., Elk Grove Village, Cook County, IL 60007-1426
Managing Editor (Name and complete mailing address)
Michael Goldstein, 1425 Lunt Ave., Elk Grove Village, Cook County, IL 60007-1426

10. Owner

Full Name	Complete Mailing Address
Michael Goldstein	1425 Lunt Ave., Elk Grove Village, IL 60007-1426
Richard Goldstein	1425 Lunt Ave., Elk Grove Village, IL 60007-1426

11. Known Bondholders, Mortgagees, and Other Security Holders ☐ None

Full Name	Complete Mailing Address

12. Tax Status
☐ Has Not Changed During Preceding 12 Months
☐ Has Changed During Preceding 12 Months

PS Form **3526**, October 1999 (See Instructions on Reverse)

13. Publication Title	14. Issue Date for Circulation Data Below	
GEAR TECHNOLOGY	SEPTEMBER/OCTOBER 2003	
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)	14,479	16,258
b. Paid and/or Requested Circulation (1) Paid/Requested Outside-County Mail Subscriptions Stated on Form 3541	8,939.33	8,883
(2) Paid In-County Subscriptions Stated on Form 3541		
(3) Sales Through Dealers and Carriers, Street Vendors, Counter Sales, and Other Non-USPS Paid Distribution	377.50	358
(4) Other Classes Mailed Through the USPS		
c. Total Paid and/or Requested Circulation ▶	9,316.83	9,241
d. Free Distribution by Mail (1) Outside-County as Stated on Form 3541	2,171	3,234
(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)	2,188.66	3,125
f. Total Free Distribution ▶	4,359.66	6,359
g. Total Distribution ▶	13,676.50	15,600
h. Copies not Distributed	802.50	658
i. Total ▶	14,479	16,258
j. Percent Paid and/or Requested Circulation	68.12%	59.24%

16. Publication of Statement of Ownership
☐ Publication required. Will be printed in the NOV/DEC 2003 issue of this publication. ☐ Publication not required.

17. Signature and Title of Editor, Publisher, Business Manager, or Owner
Michael Goldstein, Publisher Michael Goldstein
Date 9 / 30 / 03

Instructions to Publishers

1. Complete and file one copy of this form with your postmaster annually on or before October 1. Keep a copy of the completed for for your records.
2. In cases where the stockholder or security holder is a trustee, include in items 10 and 11 the name of the person or corporation fo whom the trustee is acting. Also include the names and addresses of individuals who are stockholders who own or hold 1 perce or more of the total amount of bonds, mortgages, or other securities of the publishing corporation. In item 11, if none, check the box. Use blank sheets if more space is required.
3. Be sure to furnish all circulation information called for in item 15. Free circulation must be shown in items 15d, e, and f.
4. Item 15h., Copies not Distributed, must include (1) newsstand copies originally stated on Form 3541, and returned to the publishe (2) estimated returns from news agents, and (3), copies for office use, leftovers, spoiled, and all other copies not distributed.
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 Octobe 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.

Failure to file or publish a statement of ownership may lead to suspension of Periodicals authorization.

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

Gears at Play

E-Bay shopping, newspaper reading and excessive e-mailing aren't a problem for most managers in the gear industry, but now there's a new employee distraction headed their way.

"Gears" is an interactive game located on *www.shockwave.com* and can suck the productivity out of even the most dedicated engineer. Designed like a puzzle, "Gears" is a series of rotating gears that players have to fit together. Players have to use a specific number of large and small gears in a predetermined design space. Part of the challenge is also getting output shafts turning in the right directions. The number of gears and their speeds increase with each level.

On the free version of the game, there are 23 levels. More serious players have the option of subscribing to *www.gameblast.com* where, for about $10, they can advance through 50 levels and receive hints.

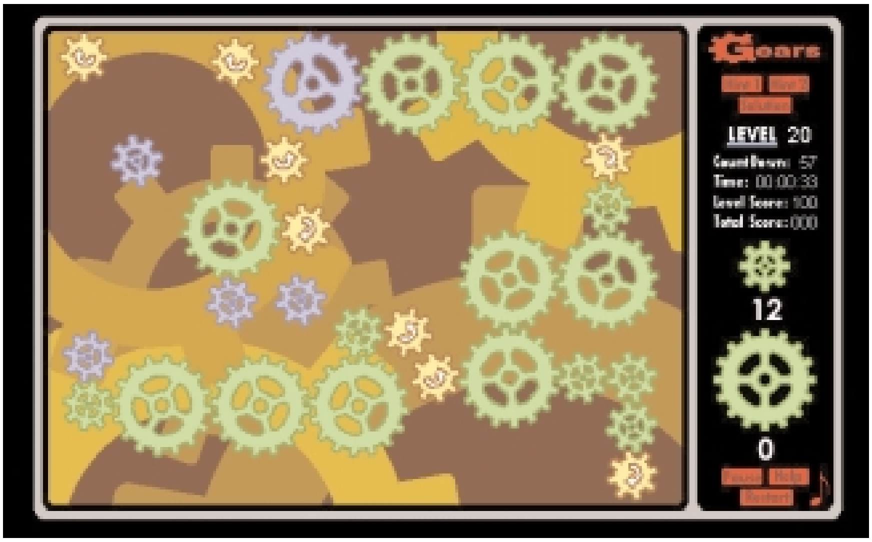
Andre Persidsky designed the game and obviously can pass through even the most advanced obstacles. But, he's not the only one. "I get e-mails from people all the time, saying they're on the 23rd level and begging for hints. But quite a few have completed it, despite all the players who say it's impossible."

It's not impossible, but it takes a very left-brained player to succeed at "Gears." The Addendum team attempted this puzzle and actually made it to Level 9, even without paying the fees for the hints, we might add.

Level 9 seems to be a bottleneck for most players, if the posted reviews are to be believed. One player accuses the company of rigging Level 9 to get more paid subscribers.

Other ratings for "Gears" have been mixed. An obvious gear enthusiast named "Circuit hottie" posted her opinion on Sept. 8 on *shockwave.com*, saying "Great puzzles! Very fun to play, especially at work!" On May 16, Razer Blade (who we believe must work in the cutting tools industry) said "Great game for working the mind. It's complex and it bugs you when you finally get the answer…omg, why didn't I think of THAT". 99bottles warns "If you don't want to think, don't play."

Persidsky spent six months creating "Gears," so he obviously wanted players to have to put some thought into their movements. He is a lifelong inventor and although he has never worked in the manufacturing industry, he now knows more than he ever wanted to about gears. Persidsky was looking for something unique, and rotating gears was a concept in online games he'd never seen before. He created the graphics using Adobe Photoshop and then coordinated the entire program through Director, a tool by Macromedia.



Only the elite of the gearing world ever see this screen in one of the three highest levels.

The computer generation portion of the project was easy for Persidsky, an expert on multimedia software who authored the books *Macromedia Dreamweaver MX for Windows and Macintosh*, *Director 8 for Windows and Macintosh* and *Ray Dream Studio 5 for Windows and Macintosh.*

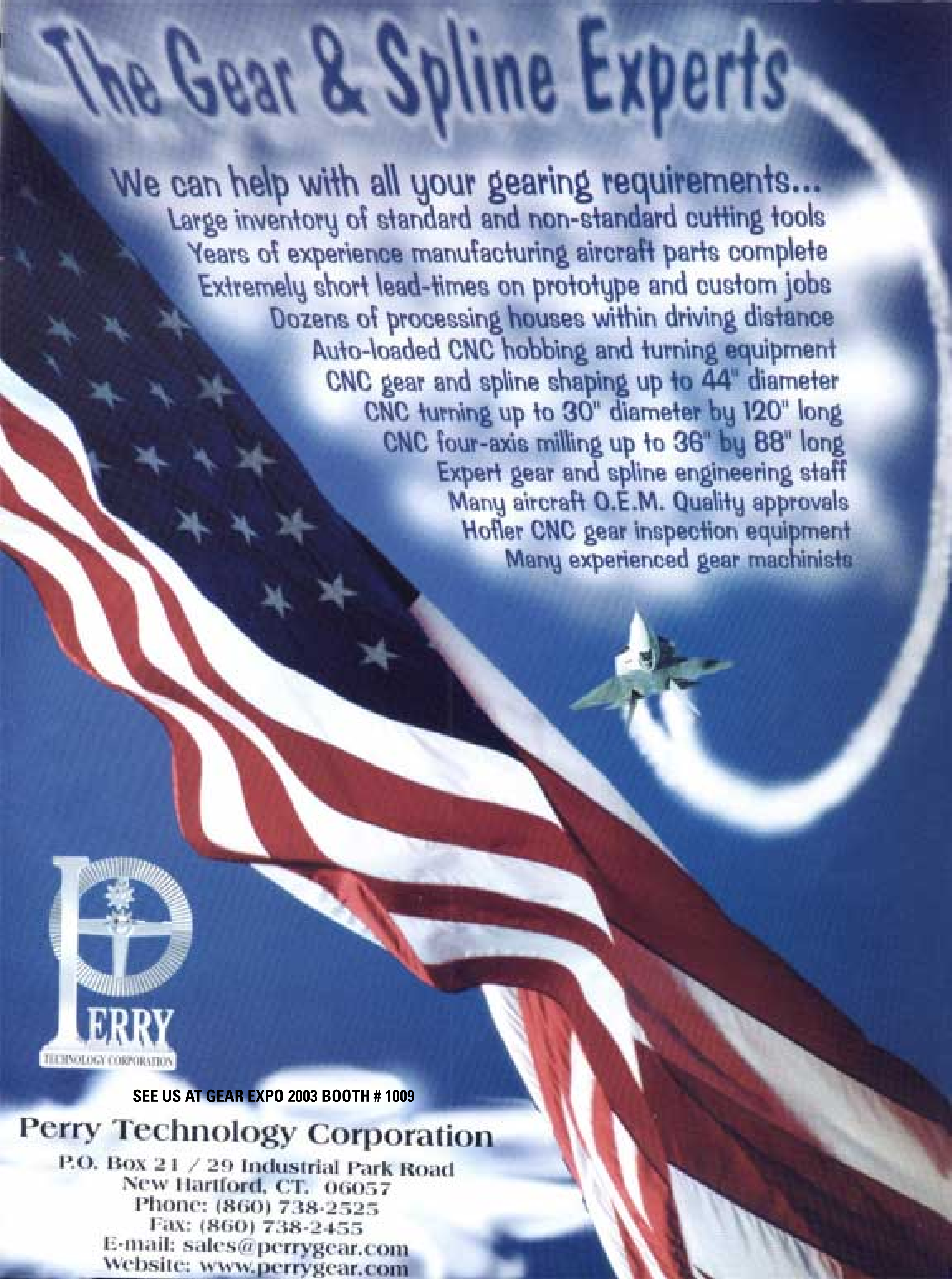
His writing career has awarded Persidsky the freedom to pursue his passion for Internet games, since the cyberworld still isn't very lucrative. "There's not much money out there in online games unless you have 50 out there. 'Gears' was a high performer and it's gotten my name out and I've found more work that way," he says.

These online games all are created through Onward Designs, Persidsky's company. Among his current projects are a top-secret game using word puzzles, which also will be listed on *www.shockwave.com.*

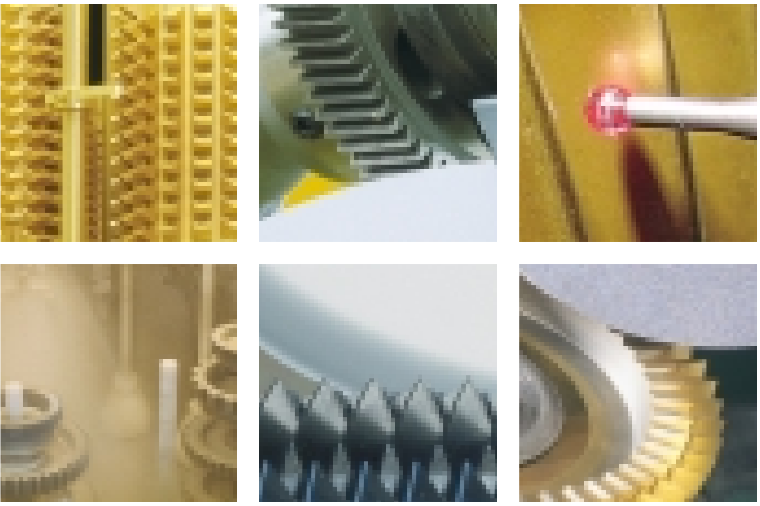
That one probably won't be so popular with gear guys, which is a positive because it's one less distraction at work. The good news with "Gears"?—you can always tell the boss you're just honing those design skills. ✪

Tell Us What You Think . . .
Visit *www.geartechnology.com* to
- **Rate this column**
- **Request more information**
- **Contact the organizations mentioned**
- **Make a suggestion**

Or call (847) 437-6604 to talk to one of our editors!



We're all about tools



Choose from a comprehensive line of gear cutting tools – including patented solutions you will find only at Star SU.

- HSS and carbide hobs, **Fellows** shaper cutters
- Milling cutters, rack and saw cutters
- Shaving cutters
- Profile grinding wheels
- Master gears
- Chamfering and deburring tools (incl. sprocket wheels)
- Gun drills and reamers

Creative and proven designs, excellent base materials, custom-made production machines and certified processes are bound together to form a final product of superior quality.
To maintain the level of quality and to meet your requirements, we offer tool regrinding services for hobs, shaper cutters, milling cutters, shaving cutters and master gears in our Service Centers in the US and all over the world.

Not only are we experts in gear cutting tool applications but we also offer a complete range of gear roughing and finishing machines for various applications including a variety of brands like Bourn & Koch/Fellows shaping technology as well as Samputensili and Star machine technology.

Visit our website to download our complete program of products and find out the match for your particular need.

Contact us today. We're closer than you may think.

Star SU LLC
5200 Prairie Stone Parkway
Suite 100
Hoffman Estates, IL 60192
Tel.: (847) 649-1450
Fax: (847) 649-0112
sales@star-su.com
www.star-su.com

GT 0803