GEAR TECHNOLOGY

June 2010

www.geartechnology.com

The Journal of Gear Manufacturing

Alternative Gear Manufacturing

Feature Articles

- Polymer Gears Meshing Nicely with Vehicles
- EDM Gives You an Edge When It Counts
- Single-Pass Honing of P/M Sprockets a Winner
- Hard Turning of Large-Diameter Parts

Technical Articles

- Ausform-Finished Gears Meet the Test
- Tooth Engagement and Load Sharing in Involute Splines
- Micropitting-Induced Tooth Fracture Failure—An Anatomy

Plus

- Addendum: Bacteria Turns Microgears

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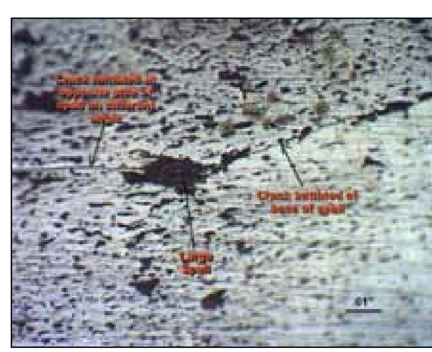
CONTENTS

FEATURES

TECHNICAL ARTICLES



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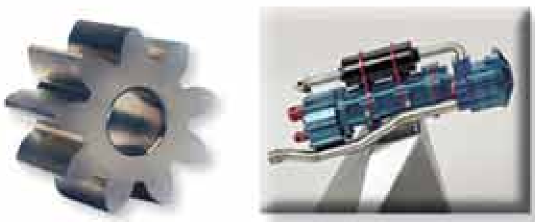
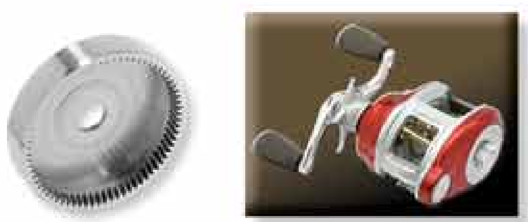


Star gear for racecar fuel pump…every car in the Indy 500 field has our product onboard



Internal spline gear for a levelwind fishing reel…casts twice as far

Gears for the drive wheels and actuators on Mars Rover…no room for failure or a service call

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Forest City Gear helps customers in an extremely diverse group of industrial, medical, aerospace, sporting goods, research lab and high-performance racing markets, plus many others. Some might foolishly suggest this makes us "a jack of all trades, master of none," as that old adage goes.

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CONTENTS

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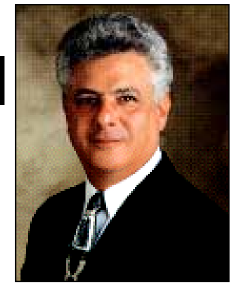

Summertime... and the Statistics are Easy

Summer is finally here. Well, not technically. According to the calendar, it's still a couple of weeks away. But school's out, baseball's in full swing, and the weather has turned sunny and warm. With this change of seasons seems to have come a change in mood as well. Manufacturers are optimistic.

News reports say their optimism is broad-based and well-founded. Here's a sampling of some of the statistics we've heard recently:

According to the National Association of Manufacturers and the NAM/Industry Week Manufacturing Index, manufacturers' confidence improved in the first quarter of 2010 to the highest level in more than two years. Seventy percent of survey respondents had a positive business outlook.

AMT—The Association for Manufacturing Technology recently reported that first quarter industrial workholding shipments were up 10.7 percent over first quarter 2009. Even more impressive, the association reports that overall manufacturing technology consumption has risen 33.7 percent over the same time period.

NEMA tells us that first quarter shipments of industrial controls grew 11.7 percent compared with first quarter 2009. In addition, NEMA's Electroindustry Business Confidence Index held at 71.7 in April, repeating its level from March. That level reflects the industry's highest confidence since May 2004.

The Institute for Supply Management tells us that economic activity in the manufacturing sector expanded in April for the ninth consecutive month. The institute's Purchasing Managers Index (PMI) hit 60.4 in April, its highest level since June 2004.

According to the U.S. Federal Reserve's May 14 statistical release, U.S. industrial production rose 0.8 percent in April, after having risen 0.2 percent in March.

There's a lot of good news out there. But every silver lining apparently comes with a cloud. We have to keep in mind that just because we're recovering, it doesn't mean we're out of the woods yet. The statistics look good now, but that's because we're comparing our situation today with what it was a year ago, when the manufacturing economy was horrible.

Last week I talked with a major U.S. gear manufacturer. He told me, "Business is great." He mentioned that his new orders had picked up. As a result, he rehired all of the employees he'd been forced to lay off last year, and even added some on top of those. This particular gear manufacturer was extremely optimistic about the future of his business. For the first time in a while, he'd had a very good month, and he said it looked like he had more good months coming up.

I was very enthusiastic and excited for him, right up until he told me his company wasn't quite making money yet. He still had to make up for the deficits from the beginning of the year.

To put things in proper perspective, take a look at our nation's capacity utilization. According to the Federal Reserve, we were at 73.7 percent in April, up 0.6 percent over March, and up 4.5 percent over 2009. Sounds pretty good, right? But when you compare today's capacity utilization with the 80.6 average we maintained over the period from 1972-2009, you'll see that we still have a ways to go.

Like most summers, we'll likely see some storms this year. How severe, or how damaging, no one can tell. Despite the recent manufacturing growth, many of us are keeping an eye on the horizon, watching for the thunderheads that may develop out of the jittery stock market or the European debt crisis.

I don't know whether those storms will pass, or if they hit, how deeply they'll affect manufacturing or the gear industry. But the recent data is encouraging enough that I'm hopeful we'll return to the type of manufacturing activity—and profits—we've seen in the past.

Michael Goldstein,
Publisher & Editor-in-Chief

Reader's Response to Past Issue

Hello Michael:

I thought your editorial that appeared in the March/April 2010 issue of *Gear Technology* magazine was the best I have seen on the topic of foreign trade deficits and manufacturing. It was right on the money.

If the United States does not wake up soon (within 10 years max), we will be well on our way to third world country status.

The current U.S. tax policies as they relate to manufacturing and capital formation are just plain stupid. And most legislators (national and state) have no comprehension of what goes into metal parts manufacturing. To them we are just "shop guys."

I also intend to purchase several copies of the book *A Nation on Borrowed Time* by Joe Arvin.

Would it be possible for you to email me a PDF of your page 9 editorial (...can you spare some time) from the March/April 2010 issue of *Gear Technology* magazine?

I would like to send copies to some of my friends, business associates and local politicians.

Thank You.

John Andrews,
Andrews Products

John—

Thanks for your kind words. Your extra copy of the PDF is on the way. The rest of our audience should be aware that Gear Technology *subscribers can get back issues and articles simply by visiting* www.geartechnology.com/issues. *You may have to register with the site (or re-subscribe if your subscription has lapsed).*

—MG

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Your success in focus

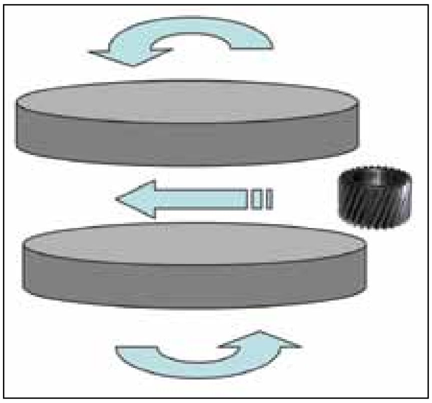
Faster Honing to Mirror Finishes

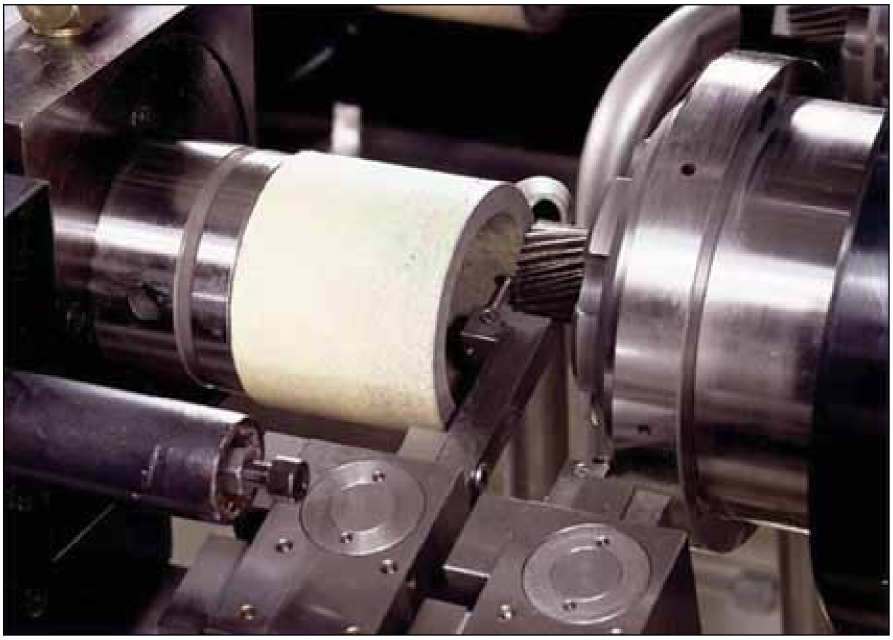
ON GEAR FACES AND BORES

Stringent NVH requirements, higher loads and the trend towards miniaturization to save weight and space are forcing transmission gear designers to increasingly tighten the surface finish, bore size and bore-to-face perpendicularity tolerances on the bores of transmission gears. Increasingly, most gears used in high-load applications are following this trend.

In the not-too-distant past, a surface finish of 0.15 μm Ra on bore faces was considered good. But today, increasingly, we see gear design engineers seeking finishes finer than 0.05 μm Ra and sub-micron bore-to-face perpendicularity tolerances.

Historically, achieving such a fine finish would require a 4-station honing machine— with two honing and two gauging stations—a double disk grinder to generate face geometry, a lapping/polishing machine to achieve mirror finishes on the face and, finally, expensive automation to tie all three machines.





If the volumes are fairly high, this process is fine as the equipment utilization is high. But this becomes undoable for low- and medium-volume applications as the utilizations remain very low. Also, this process has a quality drawback—in that a double-disk grinder does not impact the bore-to-face perpendicularity, and it basically carries it over from the prior operation.

In order to address this issue for low- and medium-volume manufacturers, Nagel Precision (Ann Arbor, MI) has developed a single machine that can take a heat treated gear and yield a mirror finish on both the gear face and bore—with excellent bore-to-face perpendicularity.

The heart of this innovation is seamless systems integration:

- A new Nagel ECO Series 40 flexible honing system that combines gauging and honing into a single spindle, eliminating multiple gauging stations.
- A Nagel SPV cup wheel face finisher.

In the ECO 40 Honing system, gauging is engineered into the honing spindle. Now the honing spindle also gauges the part while performing the honing operation, and this is integrated with a tool expansion system to automatically compensate tool wear.

The tool wear compensation system is designed to further minimize non-cutting time while enhancing bore quality. Once the tool is inserted in the bore, the tool expands at a rapid feed of 200 mm/sec and at high torque (45 percent of available) until it reaches a predetermined position close to the bore; it will then switch to a rapid stock removal mode of about 4 mm/sec at lower torques (15 percent of available) to avoid tool damage; and towards the end of the cycle, it will further reduce the expansion rate to about 2 mm/sec at 10 percent of the available torque. The system constantly monitors both the tool feed (mm/sec) and the applied torque (as percent of available). If the desired feed is not reached at the preset torque, the operator can either reduce the tool expansion rate if tighter tolerances are desired or increase the torque if quicker cycle times are needed. This is an added key process control parameter available to the operator.

The tool expansion is rapid when there is no cutting and is slowest for the final finishing cut, which results in a consistent bore in terms of finish, size and cylindricity.

In addition, the Nagel ECO 40 automatically senses the form error (for example taper, hourglass, barrel shape, ovality, bend, etc.) and makes automatic adjustments to correct it.

Most of the bore honing machines on the market today have a fixed stroke that is designed to hone a perfect bore, which, as we are aware, is not the case.

However, some machines do provide the operator the capability to dwell for a longer time at the bottom of the blind bore or to program a different stroke length to correct form errors. But this requires that the operator know the exact nature of inaccuracy coming in and generate a program to address that particular form error. The configuration will not be effective should the type of form error change. It therefore would require a skilled operator to inspect the incoming part and modify the stroking accordingly, which is not always feasible and could be time consuming. The Nagel ECO 40 can sense the form error coming in on each and every part and make automatic adjustments in stroke to more effectively correct it.

These enhancements in the honing technology have enabled Nagel to replace a multi-station system with a compact single-spindle machine without sacrificing part quality.

The SPV 150 Face Finisher differs from conventional grinding operations. The accuracy of ordinary grinding operations depends on rigid fixturing, as well as the accuracy of the grinding wheel's position relative to the part. Whereas the SPVE 150 utilizes free-cutting cup wheels and the tools self dress and conform to the contours of the part. This automatically compensates for inaccuracies in the machine.

continued

During this operation, the gear is clamped on the internal diameter of the bore and rotated in a direction opposite that of the cup wheel at a high surface speed. To prevent variations in flatness or axial runout when finishing flat surfaces, the cup wheel tool substantially overlaps the surface of the part during machining. The machine can remove as little as a few microns of stock to a few hundred microns very quickly. The automatic cup wheel changer enables wheel switching for each part, eliminating batch processing. In-process gauging (Fig. 8) accurately controls the part thickness.

Gear manufacturing is significantly improved by using this process. The conventional process to finish these gears—grinding them with a double disc after heat treatment—yields an axial runout of approximately 40 µm, and cup wheel finishing reduces the runout to less than 10 microns.

Heat treating to a mirror finish with excellent bore-to-face perpendicularity is now a possibility in just one machine. Multiple sensors incorporated in the machine constantly monitor the process and support "lights out" manufacturing for low- and medium-volume production.

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Sanjai.keshavan@nagelusa.com
www.nagelusa.com

Dry Cutting System

MANUFACTURES STRAIGHT BEVELS

Gleason Corporation recently introduced Coniflex Plus, a high-speed dry cutting tool system for manufactur-

ing straight bevel gears. According to Gleason, it is the first peripheral stick blade cutting tool system with positive blade seating, which results in cutting time reductions with improvements to gear quality and gear rolling characteristics.

Straight bevel gears are increasingly popular for use in certain applications, but prior to a Gleason's six-axis machining process, there was no other machinery for cutting or grinding them. The process, released in 2006, was wet cutting and used traditional high speed steel cutting tools.

The Coniflex Plus system allows use of coated carbide cutting tools in a dry cutting environment. Coniflex Plus is up to three times faster than its predecessor, avoids the use of cutting fluids and consumes 25 percent of the energy that traditional straight bevel gear cutting took.

The geometry of existing straight bevel gear designs will be duplicated using the Coniflex Plus cutter system. The free design of profile curvature, dish angle edge radius and blade point provide added freedoms for strength and noise optimizations. The Pentac stick blades are used in the Coniflex Plus cutter heads, and they can be sharpened on existing standard Gleason stick blade sharpening machines without additional software or fixtures.

For more information:

Gleason Corporation
1000 University Avenue
Rochester, NY 14692
www.gleason.com

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Stanyl Plastics Steer Handi-capped

DSM Engineering Plastics, through a partnership with the Swiss company Bozzio, has driven its precision gears made of Stanyl PA 46 resin to production in the joysteer X-by-wire system that provides people with a disability a safe, user-friendly solution to drive a car. It is available from car modification companies in Switzerland, Germany and the Benelux countries.

"We are proud to have brought to commercial production this important advance for people with a handicap, offering the greater mobility," says Matthias Hell, Bozzio CEO. "Our patented joysteer X-by-wire system is the end result of intensive cooperation by material supplier DSM Engineering Plastics, Bern University for Applied Science, Dynamic Test Center and many others."

In just three years, Bozzio achieved the strictest level of safety approvals for the European market (TÜV approval according to ECE-R 13H braking system and ECE-R 79 steering system). Bozzio sees a range of potential applications for the patented system in special purpose vehicles, such as municipal and agricultural vehicles, unmanned vehicles and areas requiring a high degree of reliability and safety.

The gear sets made from Stanyl polyamide 46 (PA46) resin in joysteer X-by-wire system translate a driver's steering movements into vehicle control. Two joysticks are mounted and coupled electronically to the vehicle's steering mech-

anism. The driver's movement of the joysticks is computed by joysteer, and the data sent to the control module that turns the steering column and thus steers the car. A video showcasing the system's capabilities is available at *www.joysteer.ch/uploads/media/joysteer_OnTheRoad.wmv*.

The Stanyl gears are part of the steering actuator module. Stanyl PA46 resin fulfills the essential requirements for dimensional stability, low wear and the ability to absorb vibration and noise. Stanyl PA46 resin has an extra strong crystalline structure, which makes it suitable for demanding automotive and electronic applications.

According to Hans Wennekes, DSM business development manager Stanyl, "This patented technology made available by Bozzio opens new opportunities for Stanyl polyamide 46 resin in [a] wide scope of special purpose vehicles."

For more information:
DSM Engineering Plastics
www.dsm.com

Dow Lubricant

MOVES MORE HEAT IN TURBINES

The Dow UCON GL-320 lubricant is a polyalkylene glycol (PAG) based lubricant that combines the PAG base with a proprietary Dow additive package, yielding a product with specific performance properties required for wind turbine and other gearbox operations.

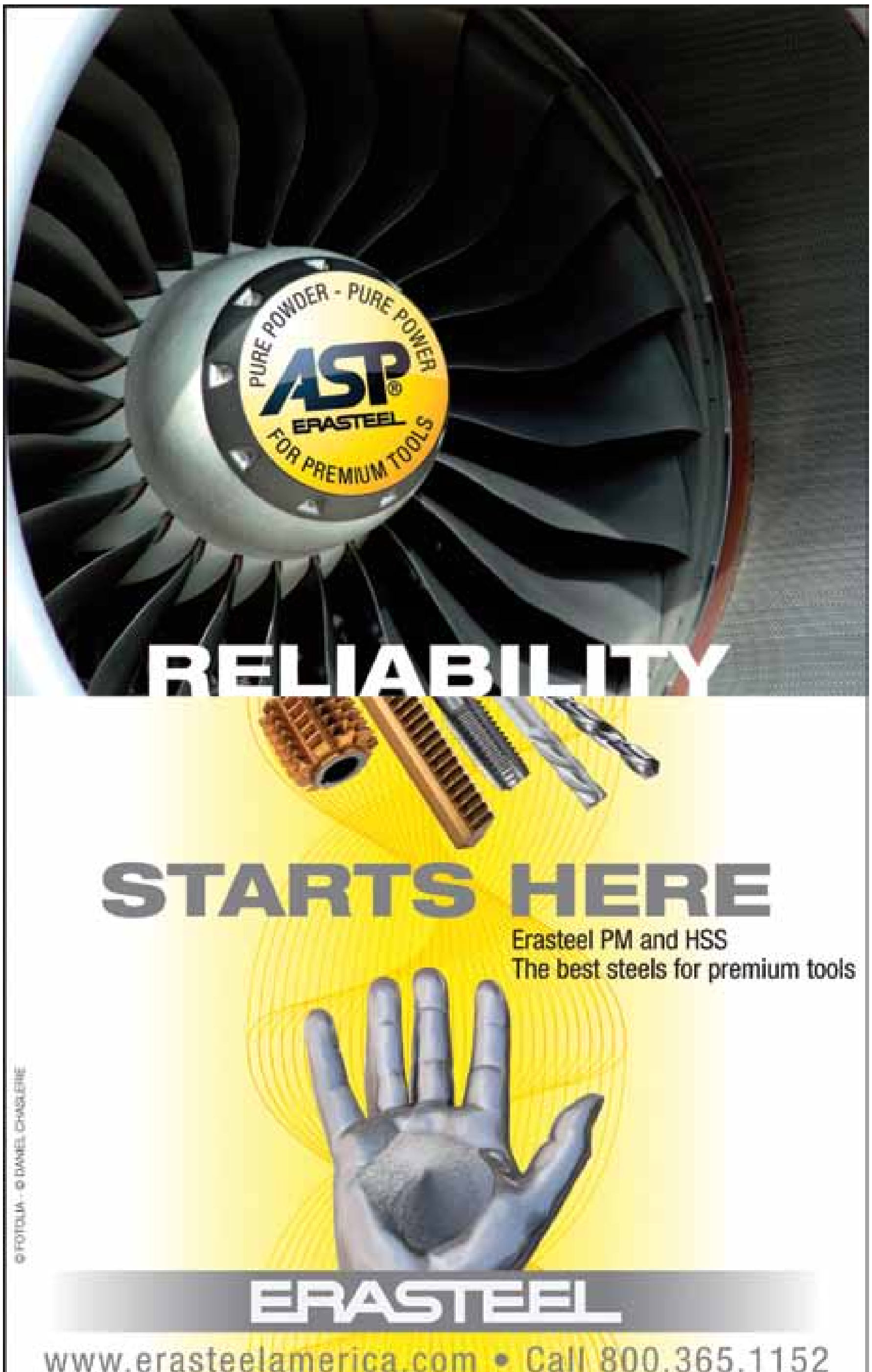
The high inherent viscosity index (VI) of UCON GL-320 addresses the issue of turbines shutting down in cold weather due to filter failures without needing extra VI improvers. The lubricant has a higher heat capacity than

continued

hydrocarbon oils, which allows it to move more heat, reducing shutdowns that can occur from high gear oil temperatures when turbine output is at its max. UCON GL-320 also has a better lubricity at ambient conditions, meaning that it has the potential to shift the power versus wind speed curve to the left, leading to more power output when the production is less then the maximum design output.

High viscosity lubricants, like the UCON GL-320, that provide a thicker lubricant film under operating conditions can help reduce damaging debris and worn particles that can build up. The product is available in bulk, drums or 20-liter containers.

For more information:
The Dow Chemical Company
Phone: (800)447-4369
wind@dow.com
www.ucon.com



Diaphragm Chuck

CONFORMS FOR PART SEATING

The model DPH-400W from Northfield Precision Instrument Corporation is a four inch diameter diaphragm chuck with special jaws and stops. The stops have three "air detect" holes for part seating conformation, which air is pumped through, and when the part rests on the stop, the air pressure rises, tripping a pressure switch telling the machine to start machining. Four clover adapters have grooves for a CAM follower to snap into for orienting the chuck when stopped. These are mounted to a four spindle Theilenhaus machine.

Northfield Precision also recently introduced the Model 450WHF chuck, which uses a four-port air tube and special piston to allow for open/close/autolube/air-detect functions. The top plate with pin is a radial banking surface (side of pin only), which picks up the side of the customer's part when it is loaded and twisted into position into the chuck. The three small pads with tiny holes in the center of the chuck are used to rest the part against tops of pads while the holes are used for the air-detect function. This is a positive indication that the part is indeed loaded into the chuck.

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440 Austin Blvd.
Island Park, NY 11558
Phone: (800) 810-2482
Fax: (516) 431-1928
sales@northfield.com
www.northfield.com

Unist Lubricator

ELIMINATES NEED FOR FLOOD COOLANT

The Unist lubricator is a through-the-tool MQL/near dry machining system that when used with the Coolube lubricant, eliminates the need for flood coolant and improves drill life.

The multi spindle drilling lubrication system independently controls the amount of the lubricant to each tool, so operators can apply exactly the required amount of lubricant. The Coolube is an all natural, biodegradable product. It is applied in small quantities, so the concerns associated with excess cutting fluid contaminating a shop or the environment are not issues. Unist offers this unit on a guaranteed free trial basis.

continued

Ono Sokki

RELEASES DIGITAL INDICATOR

The EG-225 digital indicator is Ono Sokki's latest multi-purpose inch/metric switchable gage used for a variety of applications. It can be used as a bench-top unit or for in-line measurement. The compact model conforms to AGD Group 2 mechanical specifications, which makes it directly interchangeable with existing mechanical gages, and the compact design ensures easy installation into most fixtures. The EG-225 performs highly accurate measurements to 0.00005 inches throughout its one-inch measuring range, according to the company's press release. This indicator allows you to obtain simultaneously maximum, minimum and range values with only one sweep or rotation of your part. The unit also has an adjustable measuring force, for taking accurate measurements on fragile and soft compressible materials that require low pressure.

A variety of measurement capabilities is provided to satisfy most applica-

For more information:
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4134 36th St. SE
Grand Rapids, MI 49512
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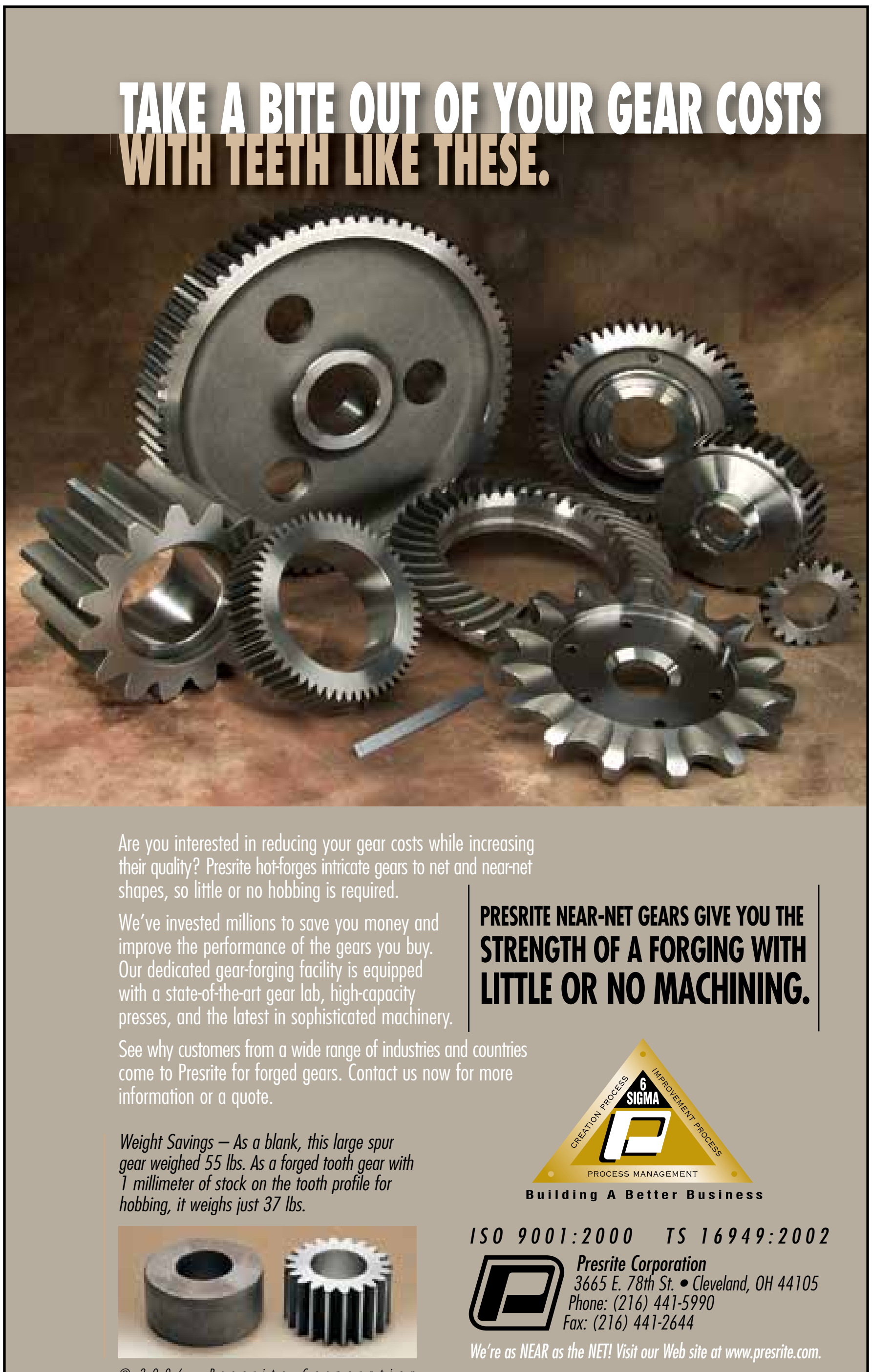
www.unist.com



tions, including preset, zero/absolute and a counting direction change switch. The EG-225 has a response speed that allows the spindle to travel 20 inches per second without an error reading. The indicator has a built-in rechargeable battery for portable applications or may be used with the supplied AC-adapter. The EG-225 features a data output speed of approximately 40 data per second. Other optional outputs include: RS-232C, USB Plug and Play, MTI, analog and to a wireless gauging system.

For more information:

Ono Sokki
Phone: (800) 922-7174
kujiiye@onosokki.net
www.onosokki.net

LMC

OFFERS C-FORM STEADY REST

LMC Workholding recently announced Richter's installation of a large C-Form Type 5-3 steady rest for a Heyligenstaedt HeynuTurn 2500 machine. This steady rest's capacities include a center height of 1,570 mm (61.8 inches), 1,800 mm (70.9 inches) maximum diameter, maximum workpiece weight of 30 tons and rollers that are 129 mm (5.1 inches) wide. Steady rests turn long shaft type workpieces where cutting can create unstable conditions or cause the parts to bend or deflect.

LMC engineers and manufactures chucks and standard and special workholding equipment, including international style power chucks and cylinders, wheel chucks, high volume machining power chucks, Neidlein face drivers and centers, Atling hydraulic steady rests, Richter manual steady

continued

rests, Stiefelmayer specialty clamping tools, Chandox brand chucks and cylinders and Talleres De Guernica large chucks.

For more information:
LMC Workholding
Phone: (574) 735-0225
Fax: (574) 722-6559
info@lmcworkholding.com
lmcworkholding.com

Mitutoyo

MEASURES ROUNDNESS, ROUGHNESS

Two metrology products from Mitutoyo America Corporation were released: the Roundtest RA-220 roundness measuring machine and the Surftest SJ-210 portable surface roughness tester.

The RA-220 provides versatile measurement with a compact footprint. Analysis options include roundness, cylindricity, coaxiality, concentricity, radial runout, squareness to axis and plane, wall thickness deviation, flatness and parallelism. The built-in operating panel provides control that is easy to use with an LCD screen supporting 10 languages. The unit has a built-in thermal printer and supports USB RS232C data output.

Featuring a rotational accuracy of 0.04 + 6H/10,000 mm, a precision air bearing, digital adjustment turntable rated up to 55 pounds (25 kg) and other features for optimizing rapid inspection, the Mitutoyo RA-220 brings lab-level accuracy to the factory floor.

The Surftest SJ-210 portable surface roughness tester has a 2.4-inch color LCD display that includes backlighting, oversize fonts and the ability to re-orient screen content to read vertically or horizontally, left and right. Color tolerance judgment, evaluation curves and all data can display in 16 languages. Self-timed measurement and optional foot switch enable smooth, consistent operation. Up to 10 measurement conditions can be registered, and the ten most recent trace results are stored automatically.

A micro-SD card stores up to 10,000 results and supports screen capture. The Surftest SJ-210 supports USB and RS-232C connectivity, and security is managed via a password lock. The portable surface roughness tester is appropriate for any manual inspection application with high accuracy (resolution of 0.0016 mm at a range of 25 mm), measurement speed up to 0.75 mm/s, nine optional exchangeable detector tips and features, including gear tooth surface detection.

For more information:

Mitutoyo America Corporation
958 Corporate Blvd.
Aurora, IL 60502
Phone: (630) 820-9666
Fax: (630) 978-5394
www.mitutoyo.com

Roller Hearth Furnace Delivered

J. L. Becker Co. recently installed a 20,000 pound/hour Roller Hearth Annealing Furnace Line for a major manufacturer in Ohio. The furnace processes 5/8 inches outside diameter to 6 5/8 inches tubing in lengths ranging from 10 to 40 feet long.

continued

The furnace line is around seven feet wide inside by 315 feet in overall length. This includes a 60-foot-long heating section, a 100-foot-long cooling section, as well as load and unload tables.

The furnace atmosphere is provided by a J. L. Becker 30,000 CFH Exothermic Gas Generator with auto start, variable output and automatic turn-down. The water cooling system consists of a cooling water tank, plate and frame heat exchanger, cooling tower and pumps to provide cooling and circulate the water through the cooling sections. A 300 kW natural gas-fired standby generator with an automatic transfer switch was provided to keep the system running in the case of a power failure.

The J. L. Becker Computer Management System (CMS) controls the entire line. The CMS touch screen monitors, control and displays the furnace operations, such as heating zone temperatures, roll speed and cooling section temperatures. The CMS also monitors and displays alarm conditions, calculates furnace downtime and measures gaps for production changeovers.

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The SECRET Is Out...
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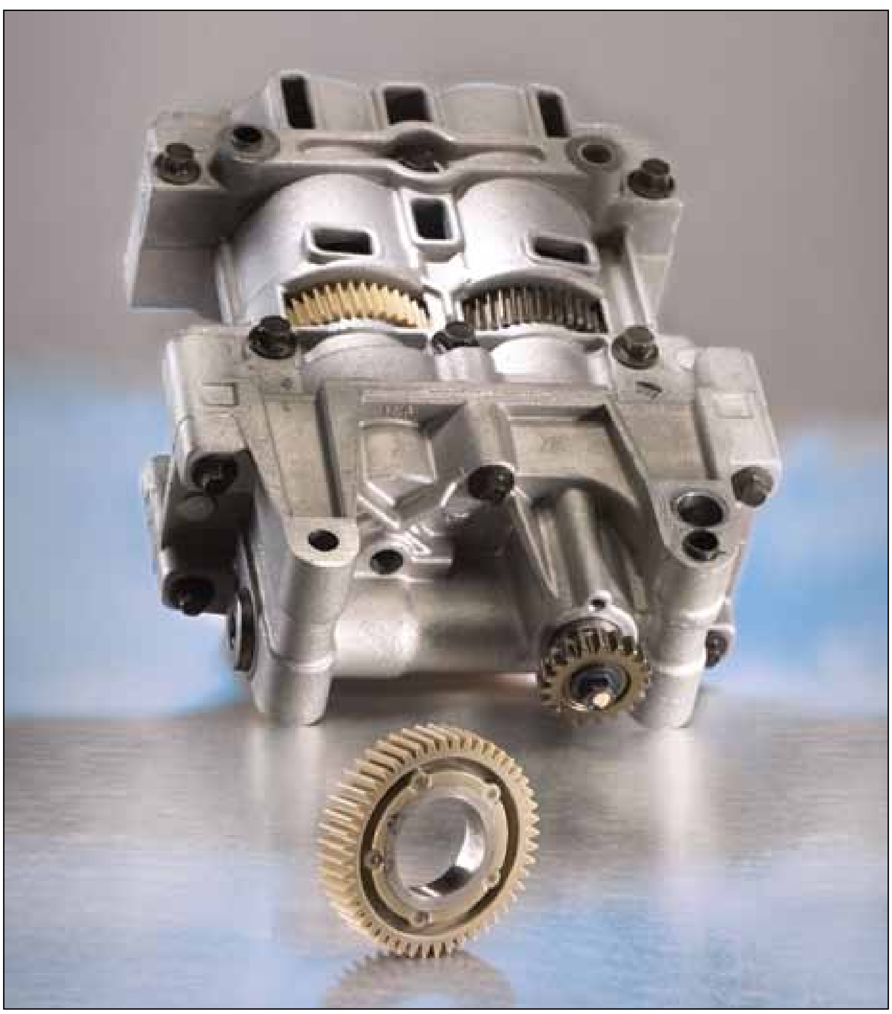
NEXT DIMENSION

At the "PEEK" of the Polymer Food Chain

Lindsey Snyder, Assistant Editor



Metaldyne balance shaft modules, featuring PEEK polymer gears, demonstrate reductions in inertia, weight and power consumption (All photos courtesy of Victrex).

In the hypercompetitive race to increase automobile efficiency, Metaldyne has been developing its balance shaft module line with Victrex PEEK polymer in place of metal gears. The collaborative product development resulted in significant reductions in inertia, weight and power consumption, as well as improvement in noise, vibration and harshness (NVH) performance.

"With our test data, we've shown that by switching from current iron gear to PEEK, we can save roughly 70 percent reduction in mass and almost 80 percent reduction in inertia. The combination results in a three to nine percent power consumption reduction," says Allen Hale, product development engineer for Metaldyne.

"With less power consumption, the engine is using less energy to turn the part and reduces fuel economy. Another important item that OEMs look for is to reduce NVH. We've recorded that we've been able to reduce the system noise level by three decibels."

Balance shaft modules help cancel the inherent shaking forces of an inline four-cylinder engine. Polymers are typically not used in a balance shaft module because of the high temperatures that the engine reaches—up around 155 degrees Celsius or 311 degrees Fahrenheit. PEEK is unique for its performance in extreme temperature environments, in which most plastics are not capable of surviving. PEEK features dynamic fatigue resistance at temperatures above 120 degrees Celsius (248 degrees Fahrenheit).

Other key properties include high strength and stiffness; low coefficient of thermal expansion; resistance to chemicals, solvents, lubricants and fuels; high PV values for use in demanding tribological environments; and low moisture absorption.

Frank Ferfecki, technical program leader at Victrex, explains some other benefits. "It has very good toughness and elongation properties. It can take the high contact stresses that can be seen in gear applications. Relative to polymers, it basically is at the top of the food chain. The other thing that is nice for gears about it is that relative to other polymers from a material performance standpoint, it doesn't need secondary operations like curing or annealing."

Another benefit of using PEEK is the cost reduction there is in the overall production. "We save a lot of money on capital equipment by injection molding the part and not having to do the extra machining," Hale says.

Metaldyne and Victrex began co-developing the gears using PEEK specifically for the balance shaft module line around 2002, according to Hale. "Basically, we contacted Victrex to see if they had some type of product that could withstand the operating environment. Metaldyne was looking for ways to reduce NVH and power consumption. We contacted Victrex, and they suggested PEEK. It has the chemical resistance, etc., that we need for the product because of the harsh operating environment."

Metaldyne supplies balance shaft modules worldwide to automotive manufacturers including Hyundai, Mitsubishi, Chrysler and Nissan for both gas and diesel applications. The modules with PEEK gears are not currently being tested for the more extreme diesel engine applications. There aren't yet any vehicles in production with this balance shaft module featuring PEEK polymer gears, as the focus thus far has been in developing and testing the product successfully. "Metaldyne did extensive testing of the modules. The next step is it needs to be validated by an OEM. Metaldyne is working with OEMs to date," says Janice Grzywa, market development manager at Victrex.

Hale describes the testing process used and the value there is in devoting the extensive time and resources to it. "We basically took traditional iron or steel gears and replaced them with PEEK gears. We did our testing in house, so we could go to customers with data that says, 'this works.' The customer doesn't have to do as much development work."

And although the product is not being rolled out on assembly lines despite being in development for a number of years, the time frame is pretty normal in the scope of these types of products for Metaldyne. "Typically, the products we are working on now are out another two or three years," Hale says.

Victrex does all materials testing for any kind of application at its applied technology center in the U.K., which features a recently acquired gear test rig. The gear test rig features up to 6,000 rpm and a 40 Nm torque; adjustable center distance from 50 to 150 mm OD; flexible configuration for spur, helical and worm gears; dry and lubricated testing (oil temperatures up to 150 degrees Celsius/300 degrees Fahrenheit); torque transducers and incremental encoders on both input and output shafts; dynamic loading of gear train; and measurement of composite error, efficiency, stiffness and backlash.

Victrex has been making a targeted effort at the gear industry with its PEEK polymer because it is a viable metal replacement material. "There's been a commitment on the part of Victrex, probably five or six years ago, to understand our material in gear applications," Grzywa says. "Not only

continued

The Victrex applied technology center in the U.K. features a gear test rig invested in as part of a targeted effort to appeal to the gear market in various applications.

in the gear test rig in the U.K., but in our commitment to various customer programs. We're putting our money where our mouth is.

"There were gear applications prior that, but in terms of financial and testing, there was a step up with the equipment set up in the U.K."

The Metaldyne collaboration is one of these customer programs in which Victrex recognized the opportunity in the gear industry and committed to a more active role. "Victrex changed our path and became almost a program manager and put quite a bit of money toward helping Metaldyne," Grzywa says.

Victrex is pursuing the gear market within various industry application areas, including medical, business machinery—such as printers and copy machines—and industrial machines, like textiles, weaving and knitting machines. "It's not so much the gear market as where do gears sit in some of these other markets we participate in because they lend themselves to metal replacement."

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By switching from iron gears to PEEK, Metaldyne achieves roughly a 70 percent reduction in mass and almost 80 percent reduction in inertia in its balance shaft modules.

Getting Wired Into EDM

TECHNOLOGY EMPHASIZES HIGH ACCURACIES AND IMPROVED SURFACE FINISHES

Matthew Jaster & Lindsey Snyder

Wire electrical discharge machining (wire EDM or spark machining) is an extremely accurate manufacturing process. The predictable and easy to automate technique was commercially developed in the 1970s, allowing manufacturers to work with harder materials while maintaining precision cutting. It's a process that involves a thin, single strand metal wire in conjunction with de-ionized water to cut metal using heat from electric sparks.

Online you'll find crowded manufacturing forums where engineers and machinists debate the technology's relevance in relation to gear manufacturing. As with any specialized machining technique, there's a fair share of supporters and detractors. The question is whether this could change in the future. For specialized gears or prototypes, it's a perfectly reasonable method of operation with definite advantages. But if you need to punch out thousands of gears in a short amount of time, there's probably a better way.

Mitsubishi/MC Machinery Systems, Agie Charmilles and Makino are three wire EDM companies that have experience working with gear manufacturers. With new machines and technologies debuting at IMTS in Chicago this September, there are more reasons for gear manufacturers to consider the benefits of having wire EDM equipment on their shop floors.

Wire EDM allows for increased accuracy, improved machining performance and a superior surface finish (courtesy of GF AgieCharmilles).

Mitsubishi/MC Machinery Systems

"Wire EDM benefits to gear manufacturing comes in many layers," according to Greg Langenhorst, technical marketing manager for MC Machinery Systems (Mitsubishi EDM/Laser).

Although *Gear Technology* has not discussed wire EDM cutting for gears very often, there are various benefits to the process for gear manufacturing, one of which is that it is not as complicated as using a slew of cutters specific to the gear parameters required. "With wire EDM, all we need is an NC program of the tooth form and the blank that needs the teeth cut on it," Langenhorst says.

Investing in software specific to gear cutting is a commitment MC Machinery systems made in the early '80s. Partnering with DP Technologies, they developed a software package, *ESPRIT*, to create involute gear profiles from the standard gear data describing tooth form.

"After inputting the gear data into the system, it generated a half tooth of geometry, and then we just copied it as many times as needed to create the complete gear. This takes a total of about 15 minutes from data input to NC program output," Langenhorst says. "The gear blank is then fixtured onto the machine table, the wire threaded, and with a press of the start button, the cut begins. So from getting the gear data on a sheet of paper to cutting the first part can happen inside of one hour. Try that with a hob or a broach if you don't have the cutters in house!"

Another big benefit of the EDM process for gears is that they can cut very hard material. As long as a material is not electrically conductive, a wire EDM can cut it. "With wire EDM, the blank can be heat treated first and then wire cut, which can reduce the possibility of material movement during heat treating," he says. "Wire EDM cuts hard steel, in most cases better than soft—and faster, too.

"Difficult-to-cut materials such as some of the high nickel steels used in aerospace, special materials used in the medical industry and even polycrystalline diamond used to create high production tooling inserts all end up in a wire EDM."

There isn't really a typical gear MC Machinery Systems cuts, although the EDM process cannot cut helical gears. Taper angles are possible by tipping the wire, so bevel gears, straight tooth helical gears and gear cutters like spline broaches are certainly within the EDM capabilities.

"Extremely small gears can be cut with wire sizes as small as .001 inches where the gear external diameter is as small as .050 inches and has six teeth," Langenhorst says, describing the range of gear applications possible. "On the other end of the spectrum, we have shops cutting gears for large mining shovels that are 20 feet in diameter with teeth bigger than your hand and 16 inches thick. We've cut screw machine tooling with involute forms, spline broach rings, powder metal and stamping punches and dies in all sizes with the tip and root radius determining the wire diameter."

One real disadvantage to using wire EDM for gear cutting is the lack of speed the process is known for. "It's a slow process compared to the way large production batches of gears are produced, but for prototyping, small quantity production, repair parts, quick turnaround pieces and gear tooling, you can't beat it," he says.

Another challenge with wire EDM is that it runs using de-ionized water as a dielectric, which can cause rust on some low grades of steel. In order to minimize this effect, MC Machinery developed an anti-electrolysis power supply, so it is only an issue on the much lower carbon type steels.

As far as new EDM technology coming from MC Machinery Systems goes, Langenhorst pleads the fifth. Generally speaking, increasing automation and cutting speed are always a goal, as well as boosting the large knowledge database the machines draw from as they monitor cutting processes. Despite tight lips on the subject of new developments, EDM is an area to keep watching in regards to unique future applications. "Small slots that require very small wire diameters, parts that can't have any machining burs and now with the ability to add a servo controlled B or rotary axis, some really crazy stuff is moving to using wire EDM."

Look for MC Machinery Systems at IMTS this year to find the company's latest wire, CNC sinker EDMs, small hole EDM drilling machines, the high-speed graphite and hard milling line, as well as the waterjet line of machines. You may just find wire EDM is a good match for a new project.

"I'm not sure if most gear people understand just how accurate the wire EDM process is," Langenhorst says. "We have feinblanking companies that make gear dies for starter ring gears that are 12 to 20 inches in diameter where the punch and die clearances are next to nothing. You can't grind parts like that and hold those tolerances in the same amount of time."

GF AgieCharmilles

The closed and controlled process involved in wire EDM is one of its lasting charms, according to Gisbert Ledvon, business development manager for GF AgieCharmilles. "This is a very predictable and easy to automate process if you want to make multiple gears; you're always using a fresh tool. The machine has an expert system built-in that allows you to get the same results time and time again."

For many years, GF AgieCharmilles has been working with F1 race car companies on their automotive gears. "These companies actually modify the gears based on each individual race track on the circuit," Ledvon says. "The wire EDM process gives improved machining performance, faster cutting speeds, increased accuracy and a superior surface finish. Our equipment is pivotal in shaping the gears in the high-end gearboxes of these race cars."

The high accuracy and exceptional surface finish found in these race car applications can be accomplished using one EDM machine in a single set-up.

Additionally, the company's new CUT 1000 Oiltech machine makes sur-

continued

MC Machinery has 35,000 square feet of EDM showrooms across the United States, housing more than $3.5 million in equipment, including this wire EDM at its East Coast showroom in Pine Brook, NJ.

These broach tools were cut by MC Machinery on a wire EDM.

Wire EDM can be used for micro-machining applications, including the gears found in watches (courtesy of GF AgieCharmilles).

face protection a priority while serving as an accurate wire EDM. It was designed for micro machining and other precision applications.

"Aerospace, defense, semiconductor and medical applications for example," Ledvon says. "You need to have a strong background in micro machining first, and it will allow you to consider nanotechnology down the road. We're able to go smaller and smaller with each new innovation."

While most wire EDM machines use de-ionized water as an inert dielectric, the oil found in the CUT 1000 eliminates the effects of corrosion due to long periods of immersion. "The oil allows for a smaller distance between the wire and workpiece, producing smaller internal radii compared to water-based machining," Ledvon says.

It's also equipped with a dual-wire system that allows the machine to switch back and forth between a large diameter wire and a small diameter wire. "These multiple configurations allow for better position accuracy and taper cutting capability for high precision parts," adds Ledvon.

Software packages are available for gear manufacturers through the company's website. Once considered a complex programming endeavor for gear manufacturers, it's now pretty painless to setup your software specifically for gears. "There's a lot of good stuff out on the market right now and a lot more coming out in the next couple of years," Ledvon says. "We'll have a few new machines and technologies on hand at IMTS this fall that show off some of these improvements."

As mentioned earlier, the wire EDM process is not ideal for large production runs. This technology is more appropriate for special gears or prototypes, items that require difficult materials without the need to build tools. But Ledvon believes wire EDM could be a great starting point even for mass production.

"If you're building a mass product of some type, there are still benefits to the wire EDM process. You can cut the first gear on an EDM machine as a prototype and build the tools with the EDM machine before you go into mass production. A single setup can save you time and money when working on prototype designs," Ledvon says.

Three years ago, Corey Hopwood, director of Hopwood Gear, purchased a Charmilles 440 cleancut machine. The machine has been cutting gears 24 hours a day since.

"Our main benefit is being able to cut very specific modules and DPs to drawings without the need for gear cutting tools to be manufactured," Hopwood says. "We can eliminate the need for some finish grinding of the teeth where possible, and very good accuracies can be achieved. We're also able to manufacture any splines with any sort of alterations the customer may require without the need to purchase expensive broaches."

Hopwood Gear, located in Manchester, England, uses wire EDM technology to manufacture straight spur gears, internal and external. Any type of modifications can be made to the gear teeth for tip corrections and root alterations. "Unfortunately, helical gears cannot be manufactured using this method," Hopwood says. "It's a time-consuming process, and there's a fine line between the cost of tooling versus cost of time for large quantity

MC Machinery can cut basically any type of gear using wire EDM, except helical gears.

production jobs."

Hopwood also notes that oddball gears are achievable with wire EDM without the need for expensive tooling. He believes the technology will start regularly appearing in job shops across the globe.

"It's a technology you should not delay on. Our wire EDM machine is now the kingpin of our business, and we would struggle without it. The machine is three years old and performs as good as the day it was first installed."

Makino

Machine tools and software are the foundation of Makino's wire EDM technology. The company has spent years on R&D to come up with innovative EDM systems. Brian Coward, EDM applications engineer, believes the automated capabilities will continue to be of interest to the gear community.

"The operator can be off doing something else once the parameters are taken care of and the machine can be left unattended. It frees you up to accomplish other tasks on the manufacturing floor."

Makino's 4-axis horizontal machines are used in aerospace, automotive, die/mold, parts production and general machining. "These machines let you do multiple parts very easily, and the gear module program simplifies the process," Coward says.

Wire EDM can accomplish certain cuts and angles that other processes cannot. "I can cut a circle on the bottom of a part and a square on the top of the same part with no problem at all," Coward says. "A tapered gear can be accomplished in one shot depending on your input and how you control it. The flexibility of wire EDM is probably its biggest selling point."

While speed is a factor in wire EDM, Makino has created a few technologies that can improve cycle time and overall part quality; e.g., its High Energy Applied Technology (HEAT) process enhances machining speeds.

"HEAT is designed for applications where flushing is difficult or impossible," Coward says. "With this technology, we can maintain a good cutting speed and actually increase the cutting speed by 50 percent. We can also hold tolerances of straightness to 0.0005 inch with one pass and 0.0002 inch with two passes."

Makino's wire EDM machines allow users to do multiple parts with a great deal of flexibility (courtesy of Makino).

Bellywizard software is another Makino technology that helps produce straighter parts with fewer passes. "Anyone that runs a wire EDM knows that inaccuracies to the belly or bow

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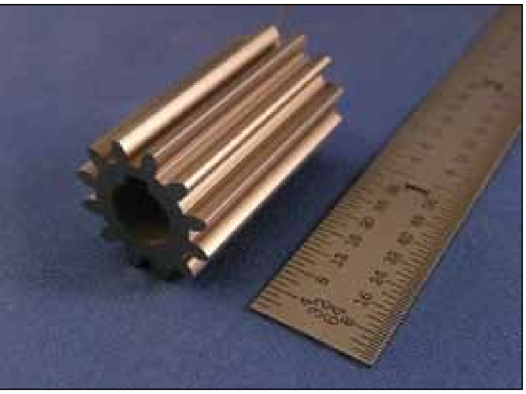

Coward at Makino notes that the wire EDM process can accomplish angles and cuts that might be difficult for other cutting techniques (courtesy of Makino).

of a workpiece occur during the initial rough cut operation," Coward says. "You tend to get a little bend at the center of the part. *Bellywizard* was created to improve the straightness. I was cutting an 11-inch gear for an automotive company, and it needed to be straight within .002 inches. In order to achieve this, I had to use this software."

Bellywizard compensates for changes in the wire caused by eroded wear and wire lag. Compensation is accomplished by automatically machining on a slight taper in the rough cut and through adaptive servo movements. These technologies, along with High Quality Surface Finish (HQSF) and *WireWizard* control technology, help bring more speed to more complex and involved geometries.

Makino also has an oil-based wire machine coming out at IMTS in September. "This will cut as fast as the water machines with a much better surface finish," Coward says. "We'll be featuring many of our technology packages along with our new machines in Chicago."

Coward is confident that the wire EDM process will continue to gain support in the gear industry as the technology advances.

"A lot of job shops use wire EDM, and a lot of shops don't," Coward says. "More shops are considering the technique; they just don't know enough about it. There are so many different uses for a wire EDM machine once you have one on the shop floor. People still aren't as comfortable with the process as they are with broaching or milling, but that's going to change in the very near future."

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Single-Pass Honing Holds the Line on P/M Sprockets

The VSS-2 Honing System from Sunnen helps Cloyes Gear maintain productivity and process capability in the manufacture of its variable valve timing stators.

BORE FINISHING SYSTEM FROM SUNNEN HELPS CLOYES GEAR AND PRODUCTS ACHIEVE HIGH ACCURACY, PRODUCTIVITY AND PROCESS CAPABILITY

William R. Stott,
Managing Editor

As a Tier One automotive supplier, Cloyes Gear and Products Inc. relies heavily on the productivity and accuracy of its manufacturing processes. At the company's facility in Subiaco, AR, one line churns out 4,000+ parts per day, seven days a week. Keeping the machines running—while hitting the required print tolerances—is how Cloyes maintains its competitive advantage.

One key process for Cloyes is the machining of bores on the company's

VVT (variable valve timing) stators for OEM automotive customers. These parts require 50-micron roundness and 80-micron total tolerance. In the past, the company used a roller burnishing process to finish these bores, but it struggled to hit the print tolerances.

"We originally processed the part with roller burnishing but found it difficult to hold the desired roundness and process capability, resulting in a high scrap rate," says Justin Carty, process engineering manager at the plant.

The Subiaco plant is home to the company's powder metal production facility. Cloyes controls the complete PM production process, employing presses ranging from 60–825 tons for both primary and secondary operations. Employing state-of-the-art technology, the company is able to achieve part densities up to 7.5 g/cc. Key capabilities include sintering to 2,250 degrees Fahrenheit, hardening (including induction, carburizing and carbonitriding) and a full range of secondary operations.

The Subiaco plant produces two VVT stators for a single customer. Both parts are made of sintered steel with a hardness of 45 HRA. The stator's minor ID is made up of five segments, constituting a bore that must be sized and finished after induction hardening in order to achieve the specified 50 microns roundness and 80 microns total tolerance.

The company considered turning the ID on a lathe, "but it would be very challenging on a production basis because of the highly interrupted bore," Carty says.

So in 2009, Cloyes installed a new four-spindle Sunnen VSS-2 Single-Stroke honing system on the VVT line. The new process allowed the company to simplify the process of bore sizing while at the same time, significantly reducing its scrap rate.

"We had a high level of confidence in single-pass honing based on three Sunnen machines in our plant already," Carty says, "so we purchased the company's new VSS-2 machine with four spindles and integrated it with an automated part load/unload system."

How Single-Pass Honing Works

When properly applied, single-pass honing is a quick, cost-effective method to get a precise bore size, geometry and surface finish. Parts made of cast iron, powdered metals, ceramic, glass, graphite and other free cutting materials—with length-to-diameter ratios up to 1:1—are ideal for the process. The length-to-diameter ratio for the Cloyes VVT stator is 23:84 mm. Single-pass bore sizing is also appropriate for splined bores or longer length-to-diameter ratios if cross holes or other interruptions are present to allow chip flushing.

The VSS-2 Single Stroke Honing system was introduced at IMTS 2008. According to Sunnen, it has the most accurate spindle alignment in the industry, along with flexible, easy-to-use controls. Spindles on VSS-2 machines are factory aligned, independently, for precision centering with the tooling plate. This produces better bore geometry than previous machines, which used an "average" alignment for the spindles. Alignment accuracy exceeds DIN 8635 requirements for vertical honing machines. VSS-2 series machines use up to six spindles to progressively size and finish part bores, using diamond tools of preset diameter and grit size. The control allows the column feed and spindle speed to be varied throughout the cycle. Standard stroke profiles, including pecking, short stroke and dwell are programmed into the controls, allowing operators to easily add them to a part setup.

The VVT stator starts as powdered steel, which is pressed, sintered and sized in a restrike press. A small hole is drilled near the periphery of the part. Then the teeth are brush-deburred and induction hardened before honing. The bores require removal of about 0.076 mm (0.003") material, so each of the

continued

The honing system at Cloyes' Subiaco plant employs four spindles and an automated part load/unload system. VSS-2 machines can be equipped with up to six spindles.

four spindles takes off a little less than 0.025 mm (0.001"). Tool life is around 80,000 parts, according to Carty. After honing, the parts are face ground, deburred, washed and packed. In operation, the VVT stator interfaces with a rotor that moves about 15 degrees to adjust valve timing for optimum engine performance, based on RPM and other parameters.

Like its other honing machines, Cloyes interfaced this machine with a part feeding systems that includes a FANUC M-6i robot, allowing the machine to run essentially untended 22 hours a day.

"This system is all about short cycle time, high production rates and high process capability, all without babysitting the machine," Carty added. "We might need to make an adjustment once a week to keep the parts within spec. That's the kind of productivity and process capability needed to be competitive in the OEM automotive market these days."

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Each spindle removes about 0.025 mm from the bore.

Hard Turning Large-Diameter Parts

FUJI'S VTP-1000 IS DESIGNED FOR HIGHLY ACCURATE FINE FINISHING OF CYLINDRICAL COMPONENTS UP TO ONE METER IN DIAMETER

William R. Stott, Managing Editor

Introduction

In recent years, the demand for large-part machining has increased due to growth markets such as wind energy. As a result, new production lathes in the one-meter class have been introduced by many manufacturers. Several, especially those coming from China and Korea, are heavy-duty cutting machines.

But the VTP-1000 from Fuji Machine Mfg. Ltd. is no ordinary vertical turret lathe, says Seiji Suzuki, sales engineer for Fuji Machine America Corp.

"If it's just large parts, there are tons of machine tool builders who can supply them," Suzuki says. "But if they want the same quality for 10, 15, 20 years, they need a machine specifically designed for hard turning."

The VTP-1000 was designed from the ground up as a hard turning machine for large components. It's built with the rigidity to achieve ± 1 μm accuracy on one-meter parts over the lifetime of the machine.

"To be able to hold a ± 1 μm tolerance on a one-meter machine is pretty phenomenal," says Bert Richey, sales manager. Even more important, Richey says, the VTP-1000 can hold that tolerance on two axes, allowing the machine to perform contouring operations that other machines simply can't handle.

"Regular turning lathes can't handle tapered cuts to the same tolerances," Suzuki says.

Wind power generation requires highly accurate bearings and gears, often requiring these parts to be hard finished after heat treatment. Normally, a rough machining lathe is used to turn the parts before heat treatment. After heat treatment, the parts require finishing with accurate contouring and profiling, as well as extremely accurate dimensional control. Previously, these hard finishing processes were accomplished with grinding. However, grinding usually requires some additional setup for part changeover, including grinding wheel dressing, workholding changes, etc.

But the Fuji VTP-1000 is designed to replace grinding in this process, and it does so with increased flexibility, reduced cost and shortened machining time, according to Fuji executives.

High-Accuracy Technology

Roller slides. One of the features of the VTP-1000 that contribute to its long-term accuracy and rigidity are its roller slides (RS). Typically the rigidity of hard turning requires a machine with box slideways. However, because of the long travel of these large ways, the stick-slip action from friction exerts a negative influence on fine position control. One way to overcome stick-slip is to use linear guideways. However, they lack the rigidity required for hard turning. So Fuji engineers incorporated a roller slide mechanism in its slideways.

The RS slideway incorporates both

continued

roller box and box ways to provide the best of both technologies. Stick-slip is avoided, but rigidity is maintained (Fig. 1). Pressure adjustment of the roller unit minimizes the contact space on the sliding surface and has improved the damping effect.

"You get the benefits of rollers without the penalty of stick-slip movement common with regular box-type slides," Suzuki says. "This is especially important with contoured movements."

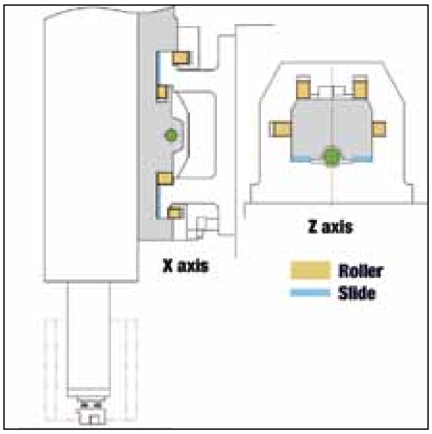

Figure 1—Roller slide mechanism.

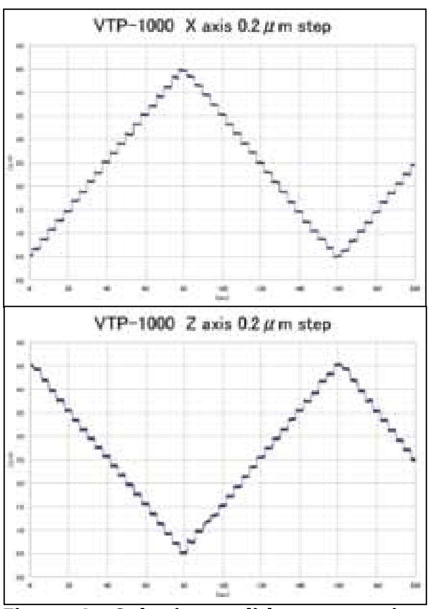

Figure 2—Submicron slide-step motion accuracy.

Figure 3—The VTP-1000's spindle structure uses a synchronous belt transmission instead of gears.

Figure 2 shows data from the measurement of the tool tip with a displacement sensor. The tool was sent a 0.2 mm move command at intervals of four seconds. Even with the z axis lowered in the direction of gravity—which is considered to be the most difficult condition—stick-slip control was maintained.

Vibration reduction. One of the important elements of vibration reduction is in the power transmission of the spindle. Transmission systems using gears are effective for heavy-duty cutting; however, microvibrations from these gears travel not only to the work, but also to the tools through the bed and column, which affects tool life and surface finish. The VTP-1000 is equipped with a synchronous belt drive system (Fig. 3), and spindle bearings are arranged to provide maximum rotational accuracy.

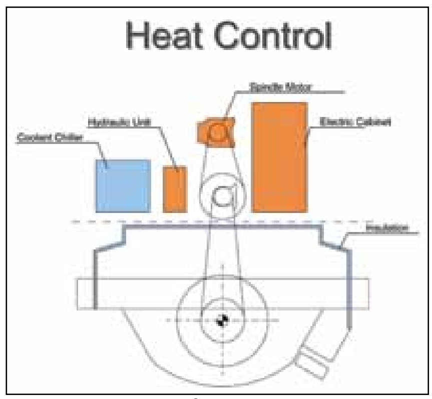

Figure 4—Most of the heat-generating components are placed outside the machining area to minimize machine and part distortion.

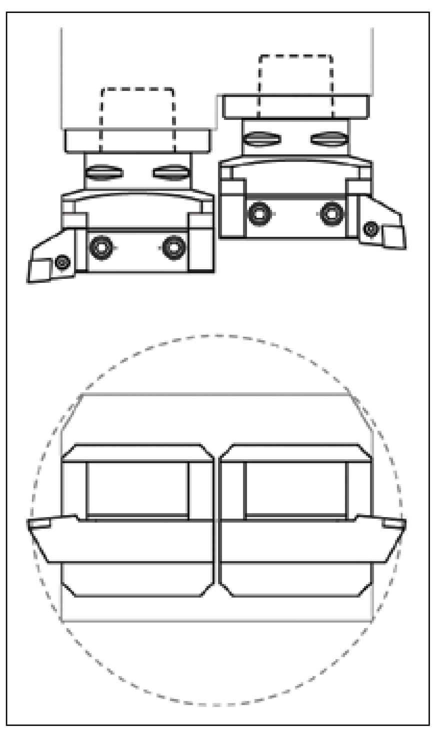

Figure 5—Tooling options with the VTP-1000.

Controlling the heat. By placing the heat generating sources (spindle, motor, control box, hydraulic unit and coolant pump) outside the machine, and also insulating the rear side of the column, thermal growth of the machine is minimized. Also, large parts of the machine structure, such as the bed, column and slide, were engineered symmetrically, to minimize heat displacement with respect to the center of the spindle (Fig. 4).

In addition, a pre-machining tank is provided to bring the workpiece up to the same temperature as the coolant in the machine. This minimizes growth or shrinkage of the part itself.

Multi-purpose and rigid tooling. The VTP-1000 is capable of mounting two six-tool automatic tool changers (ATC) on the tip of the ram. Figure 5 shows examples of various ram and ID processing. The machine is designed for the ram tip to hold two tools next to each other, one dedicated for ID and the other for OD. This design enhances the rigidity of the tool tip and reduces the overhang of the ram, as shown in Figure 6.

The standard ATC holds 12 tools, and any tool on either the left or right can be exchanged from one ATC. This ATC type provides flexibility and

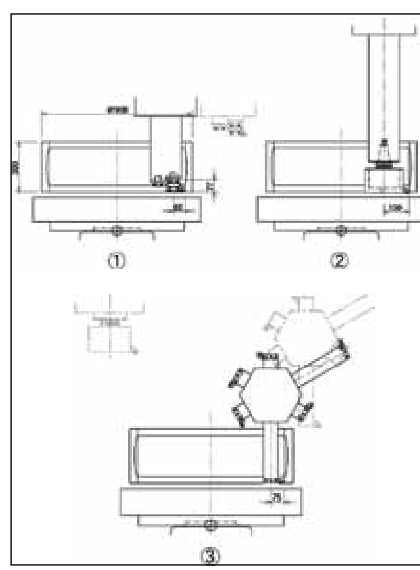

Figure 6—The VTP-1000's tool holder on the Z-axis tip accommodates two tools.

room for expansion.

High Accuracy Machining Example

Figure 7 shows an example of a hard turn finishing process. This test was performed without using coolant. The feed rate was 0.1 mm/rev to reduce the influence of tool tip heat abrasion. Even under this condition, machining surface roughness was 0.1–0.3 mm Ra.

In this example, the surface finish achieved with single-point hard turning compares favorably with grinding. The total cycle time is much lower than with grinding due to the elimination of dressing or changeover of the grinding wheel.

In addition, using a magnetic chuck allows processing of ID, OD and face all in a single clamping. Because there is no need to change from one work-holding device to another, the resulting accuracy is improved.

Options

On-board measurement. Measuring the dimensions of a large workpiece is not easy, especially measuring a one-meter-sized part. Normally, a large CMM is used, which is costly. The work handling time for this process consumes a large amount of the total processing time. In order to reduce this time, the VTP-1000 can be equipped with an on-board measurement system.

Twin slides. To make the production process even more efficient, the VTP-1000 is also available in a 4-axis version. This allows the reduction of machining cycle time by half.

Conclusion

The VTP-1000 is designed to replace grinding for fine finishing of large-diameter components. It's especially effective for manufacturers who require tight tolerances, contours, lower volumes and frequent changeovers. In those cases, the machine can be much more productive than grinding.

Because of that, several gear manufacturers specializing in wind turbine gears are already exploring investing in this new technology, Suzuki says.

And because the machine would typically cost two to three times less than a large-diameter grinding machine, the investment could pay for itself rather quickly for the right manufacturer.

For more information:

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171 Corporate Woods Parkway
Vernon Hills, IL 60061
Phone: (847) 821-7137
Fax: (847) 821-7815
www.fujimachine.com

Work material	SUJ 2
Work hardness	HRC 60
Feed rate	0.1 (mm/rev)
Stock removal	0.1 (mm)
Speed	200 (m/min)
Condition	Dry
Tool material	BNX10

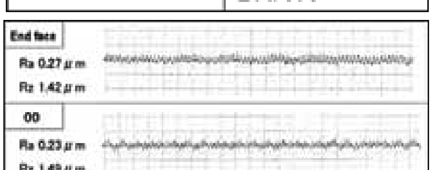

Figure 7—Example of a hard turning machining process.

Bending Fatigue, Impact and Pitting Resistance of Ausform-Finished P/M Gears

Nagesh Sonti, Suren B. Rao and Gary Anderson

Management Summary

The powder metal (P/M) process is making inroads in automotive transmission applications due to substantially lower costs of P/M-steel components for high-volume production, as compared to wrought or forged steel parts. Although P/M gears are increasingly used in powered hand tools, gear pumps and as accessory components in automotive transmissions, P/M-steel gears are currently in limited use in vehicle transmission applications. The primary objective of this project was to develop high- strength P/M-steel gears with bending fatigue, impact resistance and pitting fatigue performance equivalent to current wrought steel gears.

The ausform-finishing tooling and process were developed and applied to powder- forged (P/F)-steel gears in order to enhance the strength and durability characteristics of P/M gears, while maintaining the substantive cost advantage for vehicle transmission applications.

Bending fatigue and impact strength of ausform-finished P/F-steel gears were demonstrated to be comparable to conventional wrought steel gears. The pitting fatigue life of ausform-finished P/F gears was about 85% higher than wrought steel gears produced by current conventional processing techniques. Scoring and wear resistance of ausform-finished P/F-steel gears were also shown to be substantially superior to conventional wrought steel gears. This paper presents the processing techniques used to produce ausform-finished P/F-steel gears, and the comparative bending fatigue, impact and surface durability performance characteristics of ausform-finished P/F-steel gears as well as conventional wrought steel gears.

Introduction

The P/M process has the potential for substantial cost advantage for high volume vehicle transmission applications as compared to current wrought or forged steel parts (Refs. 1–2). Recent advances in P/M technology, such as double pressing/sintering, high- temperature sintering, surface densification and powder forging have substantially enhanced the tooth bending fatigue and rolling contact fatigue performance of P/M steel gears, comparable to current automotive wrought steel gears (Refs. 3–16). The use of P/M steel gears for power transmission applications, however, is currently limited to minimally loaded components, due to surface durability performance constraints.

The ausform gear finishing process developed at Penn State University has the potential to induce improved accuracy and surface finish in a cost-effective manner and thereby enhance the performance characteristics of P/M steel gears to be equivalent to current wrought or forged steel gears (Refs. 17–20).

Powder forged (P/F) and case hardened P/M steel gears were ausform finished in order to achieve bending fatigue strength, impact resistance and surface durability performance at least equivalent to current wrought steel gears. Test results from a comparative performance testing program are presented comparing ausform-finished P/F-steel gears, and baseline wrought steel gears.

Materials and Processing Details

A P/M standard gear design (24 teeth, 8 diametral pitch, 0.5" face width), which had been previously used in a CPMT-sponsored Gear Research Institute program to compare 16 different P/M formulations and/or processing techniques, was selected as the candidate test gear, with some alterations. Table 1 summarizes the test gear geometry details for baseline wrought steel gears and ausform-finished P/F-steel gears. Table 1 also describes the mate gears used for surface durability testing including pitting fatigue, scoring and wear resistance tests.

P/F-steel test gears were made from pre-alloyed P/M 4620 steel composition, a carburizing grade P/M formulation that is typically used to produce automotive P/M parts. Baseline gears were produced from wrought 4023 steel and mate gears (40 teeth, 8 diametral pitch, 1.0" face width) used for power circulating (PC) surface durability tests were produced from wrought 8620 steel. Table 2 shows the chemical composition of the respective steels.

Case hardening specifications for all test and mate gears required a surface hardness of 58–63 HRC, effective case depth to 50 HRC of 0.030–0.040" at mid tooth height and 0.15" minimum at root fillet, and core hardness of 28–34 HRC. The process sequence used for producing P/F-steel test gears involved pressing, sintering, powder forging, case hardening heat treatment, followed by ausform finishing. In comparison, the process sequence used for producing baseline and mate gears involved blank machining, forging, hobbing, shaving, case hardening heat treatment and shot peening. The tooth profile design of mate gears incorporated a pronounced tip and root relief in order to accommodate tooth bending effects in the test gear teeth during surface durability testing. Table 3 compares the processing steps used for the manufacture of ausform-finished P/F-steel test gears and wrought steel baseline and mate gears.

Table 1—Gear Dimensions

	Test Gears	Mate Gear
No. of Teeth	24	40
Diametral Pitch	8	8
Pressure Angle	18.65°	18.65°
Tooth Thickness	0.235-0.237	0.146-0.148
Base Diameter	2.842469	4.737449
Root Diameter	2.744-2754	4.543-4.555
SAP Diameter	2.8944	4.77
Pitch Diameter	3	5
EAP Diameter	3.357	5.147
Outside Diameter	3.36	5.152
Fillet Radius	0.0536	0.0507

Table 2—Chemical Compositions

	4620	4023	8620
C	0.17-0.22	0.2-0.25	0.18-0.23
Mn	0.45-0.65	0.7-0.9	0.7-0.9
Si	0.15-0.35	0.15-0.35	0.15-0.35
Ni	1.65-2.0		0.4-0.7
Cr			0.4-0.6
Mo	0.2-0.3	0.2-03	0.15-0.25
P (max)	0.035	0.035	0.035
S (max)	0.04	0.04	0.04

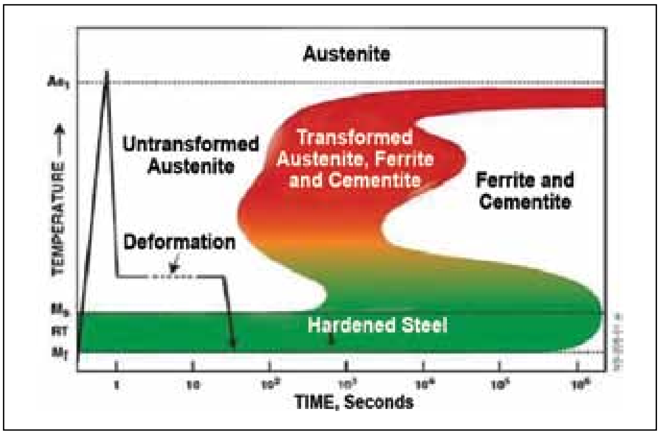

Figure 1—Ausform process schematic.

Ausform gear finishing. Ausforming is a modified heat treatment process applicable to medium-to-high carbon, low-alloyed steels wherein the steel is first austenitized followed by interrupted quenching to above the MS temperature to a metastable austenitic state. The part is then plastically deformed in the metastable austenitic condition and finally cooled to martensite. Figure 1 shows a schematic time-tem-

continued

perature-transformation diagram that describes the ausforming process. Research has shown that ausformed martensite resulting from deformed austenite possesses substantially higher strength as compared to conventional martensite transformed from un-deformed austenite. An increase of up to 50% in tensile and yield strength was reported in various steels, depending on the amount of deformation induced during ausforming (Refs. 21–25). A more than 600% increase in rolling contact fatigue of ausformed, cylindrical M50 steel specimens was demonstrated, with the degree of B_{10} fatigue life improvement increasing with the amount of deformation (Ref. 26). Bamberger reported a nine-fold increase in the B_{10} life of ausformed M50 steel bearings over conventionally heat treated bearings (Ref. 27).

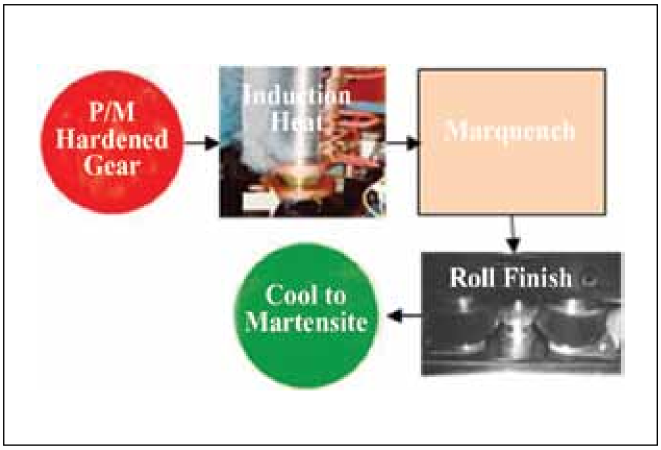

Figure 2—Ausforming process steps.

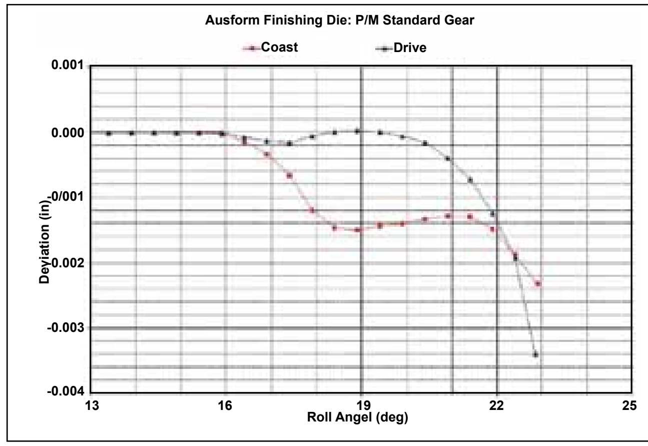

Figure 3—Ausform finishing: rolling die tooth profiles.

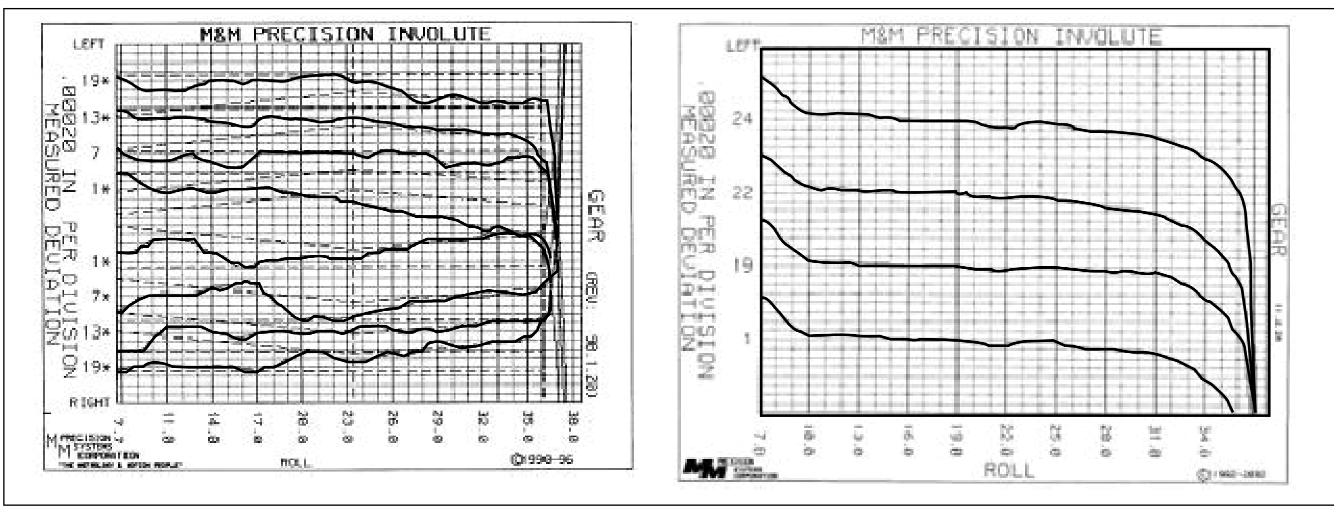

Figure 4—P/F gear tooth profile charts: pre-ausform (left) and ausform-finished (right).

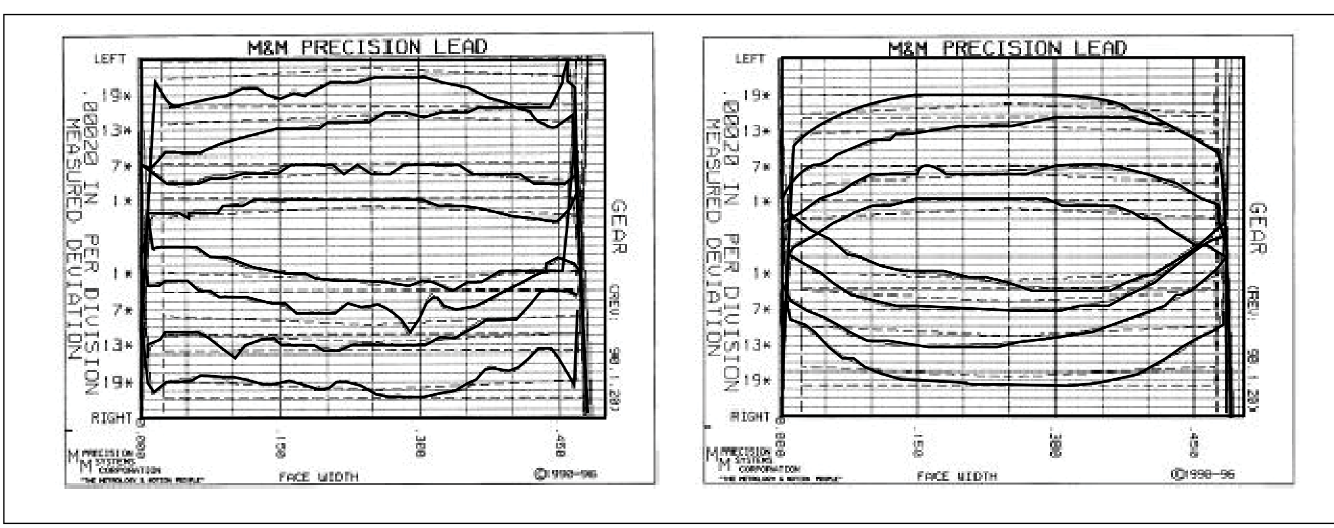

Figure 5—P/F gear lead charts: pre-ausform (left) and ausform-finished (right).

Penn State's technique applies ausforming to localized surface layers of contacting machine elements, such as gears (Refs. 28–36). Figure 2 shows a schematic description of the ausforming process as a gear tooth finishing operation for a typical case hardened, low-alloy steel gear, and involves induction austenization, marquenching, roll finishing and then cooling to martensite. Ausform finishing of spur and helical gears results in a very fine surface finish of 4 to 8 μin Ra in both the radial and tangential tooth profile directions. Furthermore, fully optimized ausforming tooling and process have been demonstrated to result in a finished gear tooth accuracy of less than 0.0002" in both the profile and lead inspections. Fine surface finish and gear teeth accuracy have been shown to contribute significantly to improved surface fatigue performance. Cycle times involved in ausform gear finishing are of the order of several seconds per gear as compared to several minutes for gear grinding, and therefore, the process is capable of integration in large production applications.

Ausform finishing of P/F steel gears. A double-die ausform gear finishing machine at Penn State was used to develop the tooling and process variables to process P/F-steel gears. The first step was to establish the dual-frequency induction heating process to be used to austenitize the case prior to roll finishing of gear teeth in metastable austenitic condition to final dimensions. The required induction heating process parameters were established for the P/F gears by experimental iterations. X-ray diffraction measurements showed a compressive residual stress at the tooth surface in the root fillet region of about 31 ksi for the ausformed P/F-steel gear as compared to about 22 ksi measured for pre-

continued

Table 3—Process Sequence Comparison

P/F Test Gears	Baseline/Mate Gears
Press	Barstock Cut
Sinter	Forge
Powder Forge	Normalize
Machine	Machine
Heat Treat	Hob
Hone Bore	Shave
Ausform Finish	Heat Treat
Temper	Hone Bore
Deburr	Finish Faces
Finish Faces	Shot Peen

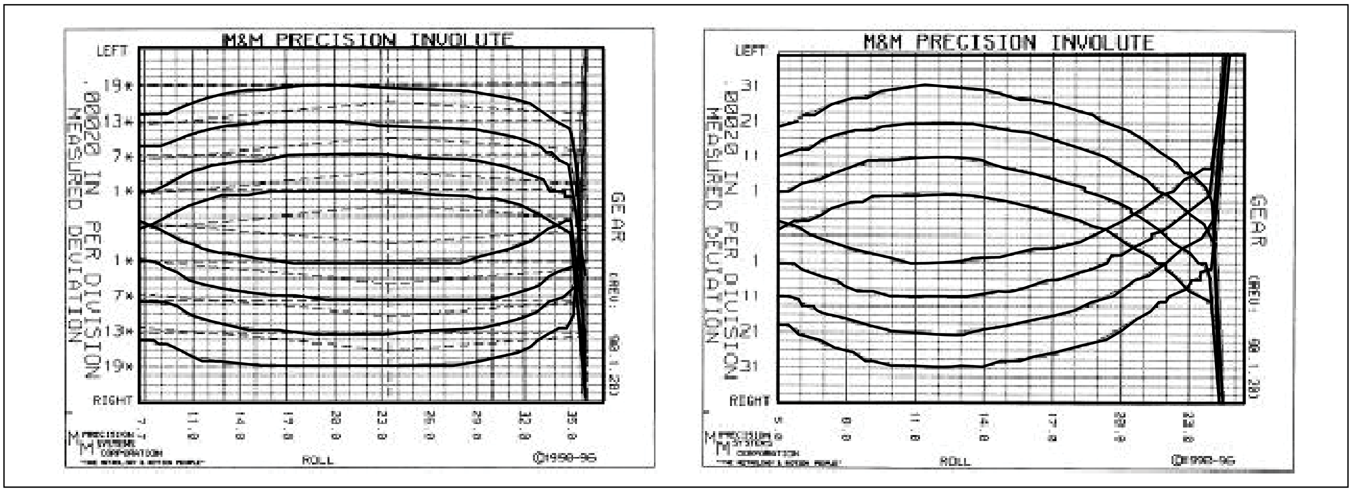

Figure 6—Profile charts: baseline gear (left) and mate gear (right).

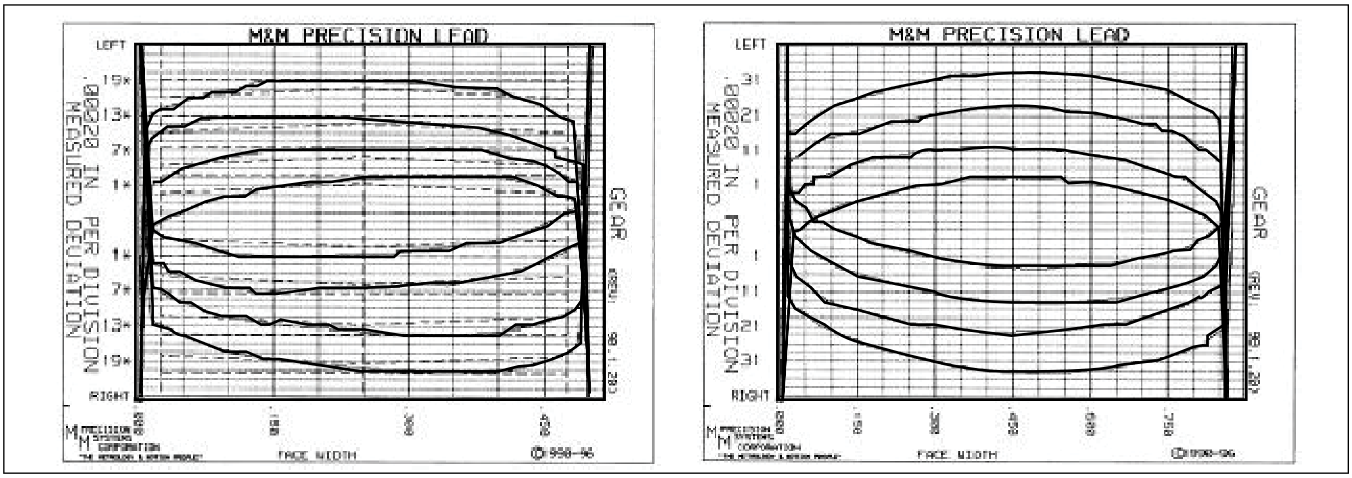

Figure 7—Lead charts: baseline gear (left) and mate gear (right).

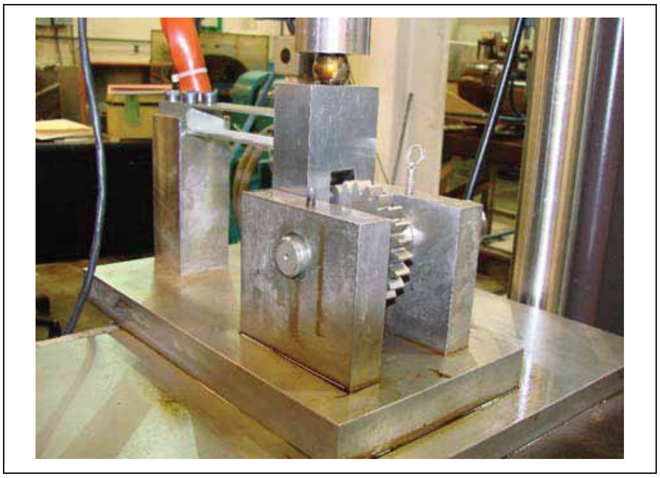

Figure 8—STF test fixture.

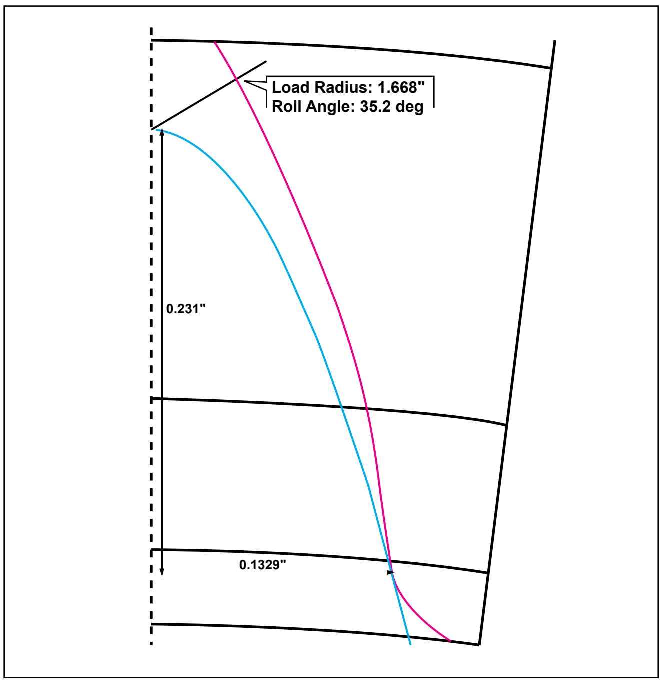

Figure 9—STF test loading details.

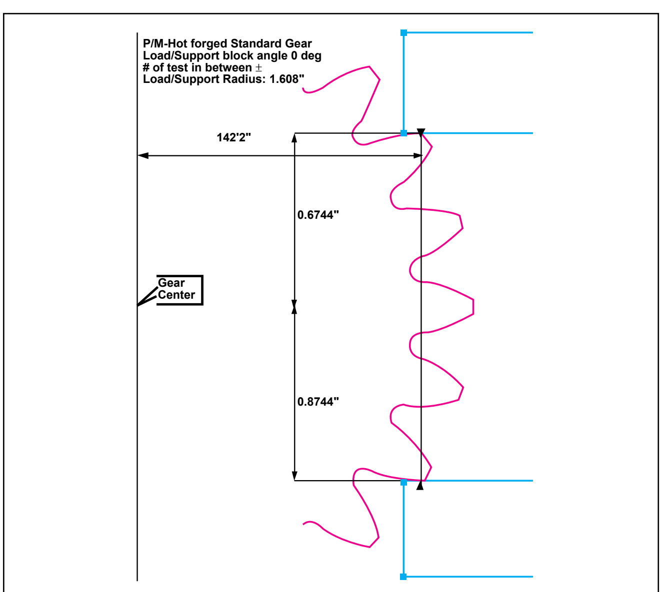

Figure 10—STF test layout.

ausformed P/M-steel gears.

The next step to ausform finish P/F-steel gears was to establish a gear roll finishing tooling and process. Ausform finishing resulted in reduction of chordal tooth thickness of about 0.003" to 0.004". Roll finishing operation of ausforming requires optimization of the rolling die tooth profile in order to achieve the desired finished gear tooth accuracy. The rolling die tooth profiles must be modified away from the nominally involute tooth shape, and die tooth profile optimization typically requires several experimental iterations. For the current program to ausform finish P/F-steel gears, the initial die tooth geometry was estimated based on numerical FEA-based process modeling, as well as prior results from similarly sized test gears. Figure 3 shows the rolling die tooth profile used on the drive and coast sides for ausform finishing of P/F-steel gears. Figures 4 and 5 compare the profile and lead charts of P/F-steel test gears before and after ausforming, and show the enhancements in both accuracy and surface finish of ausform-finished gear teeth. Profile charts in Figure 4 show the profile accuracy on the right flank of gear teeth to be less than ± 0.0001" achieved across the contact region of the teeth. Furthermore, ausform-finished tooth profiles in Figure 4 also show the desired tip relief of about 0.001" implemented by the rolling dies. The die tooth profile requires further development to optimize the profile accuracy on the left flanks, which show a localized hollow of 0.0003".

Lead charts shown in Figure 5 also demonstrate the ability of the ausforming process to produce uniform tooth surfaces with very fine surface finish. Ausform-finished P/F-steel gears show a characteristic lead crown—a straight region in the middle with edges rounding that falls off by over 0.001"—that is inherently produced as a result of the induction heating and roll finishing process characteristics. As a result, the effective contact of test gears was reduced to an effective face width of about 0.37", requiring the power circulating test conditions to be adjusted as described later to achieve equivalent contact stresses for ausform-finished P/F-steel gears, as compared to the baseline wrought steel gears.

Ausform finishing of P/F-steel gears resulted in additional densification in surface layers.

The densification effect due to ausforming of P/F-steel gears was determined by weight measurements in air and water of sections cut from pre-ausform and ausform P/F test gears. Pre-ausform P/F gears, which were already nearly fully dense, were measured to have an average density of 7.81 g/cc, and subsequent ausform finishing of P/F-steel gears resulted in an average density (of a sector of gear) of 7.83 g/cc. The densification due to ausform finishing is localized in the surface layers of the P/F-steel gear teeth.

After ausform finishing, post processing operations included final tempering operation, deburring and machining of bore and end faces to facilitate surface durability testing.

Baseline and mate gears. Mate wrought steel gears required for power circulating surface durability tests, as well as baseline wrought steel test gears required for comparative performance evaluation, were produced by New Process Gear, Syracuse NY, using a process sequence as described in Table 3 and to heat treatment specifications as described above. Figures 6 and 7 show profile and lead charts for baseline and mate gears.

Gear Performance Testing

Gears can fail due to bending fatigue, surface distress due to subsurface shear-induced pitting fatigue, wear, surface and/or subsurface pitting fatigue due to and initiating at intermetallic inclusions, scoring of tooth surfaces due to breakdown of lubrication film and fracture due to impact loading conditions (Ref. 37). Test results to establish the comparative performance of ausform-finished P/F-steel gears are presented in the following sections.

Tooth bending fatigue testing. Single-tooth fatigue (STF) testing of individual gear teeth has been used widely to generate accelerated bending fatigue data at comparatively high cycles without risk of losing tests to other modes of failure. STF testing of ausform- finished P/F-steel gears and baseline wrought steel gears was carried out on a 5 kip servohydraulic universal fatigue testing machine utilizing a specially designed test fixture to hold the test gear and to facilitate fatigue loading via a flexure arm. The STF test fixture is shown in Figure 8.

Figure 9 shows the loading geometry for the test gears, showing the location of cyclic test load at 1.668" radius (35.2° roll angle), as well as the width and height of the critical section in the root fillet region determined by the Lewis parabola. Two teeth were tested simultaneously by applying cyclic load at the above radius (Fig. 10) until runout (defined as no failure after seven million cycles) or when one of the teeth failed—known in statistical analysis as a "sudden death test." Sudden death fatigue tests are widely used in the bearing industry wherein several bearings are tested simultaneously until one bearing fails, then all bearings are replaced. Statistical analysis of sudden death fatigue tests takes advantage of improved statistical confidence due to the other parts not having failed yet. In this case of one of two teeth failing, ranking theory determined that the lowest value, in a set of two, clustered about a median location of $B_{29.29}$ point of the population. Also, as both test teeth were loaded in a similar manner, a test that ran out counted as two data points. The STF test machine was programmed to automatically shut down after a preselected increase in tooth deflection of 0.005" to ensure a consistent end of the test for valid comparison between various test gear lots.

STF tests are conducted at 3–4 load levels determined based on preliminary set-up tests. Several tests are conducted at each load level for replication and to establish the endurance limit. A modified staircase sequence technique was used to determine the fatigue endurance limit at seven million cycles. Load levels and number of tests were selected to achieve several failures at the highest loads, several runouts at the lowest loads and a combination of failures and runouts at the intermediate loads. STF test results for the three lots of test gears are shown in Figure 11, plotted as maximum bending stress as a function of cycles-to-failures. Numbers on the right side indicate data points of tests that ran out after seven million cycles. As seen in Figure 11, wrought steel gears performed the best showing in maximum bending fatigue strength, with ausform-finished P/F-steel gears showing performance close to wrought steel gears.

Statistical analysis of STF test data was carried out using normal probability techniques to determine the load corresponding to 50% failure at 7 million cycles, or mean runout load (MROL) for the three lots of gears, which represents the 50% endurance strength at the runout life of seven million cycles. Based on limited tests that were carried out, 50% was chosen for improved confidence. The MROL for baseline wrought steel gears was determined to be about 3,780 lbs., corresponding to a maximum bending stress of 179.8 ksi. Ausform-finished P/F-steel gears demonstrated an MROL of about 3,250 lbs., corresponding to a maximum bending stress of 154.6 ksi. Baseline wrought steel gears demonstrated about 14% higher MROL, as compared to ausform-finished P/F-steel gears.

It is to be noted that baseline wrought steel gears had been shot peened after heat treatment, which would explain the higher bending fatigue performance. Ausform- finished P/F gears were not subjected to shot peening, due to programmatic constraints. It is anticipated that the bending fatigue strength of ausform-finished P/F-steel gears would have improved further if subjected to shot peening after ausform finishing.

Impact resistance testing. Off-road vehicle gears may be subjected to substantial impact loads due to uneven and rough terrains. Characterization of gear tooth impact resistance was carried out to evaluate ausform-finished P/F-steel gears, and the effect of inherent porosity, although substantially surface-densified, as compared to baseline wrought

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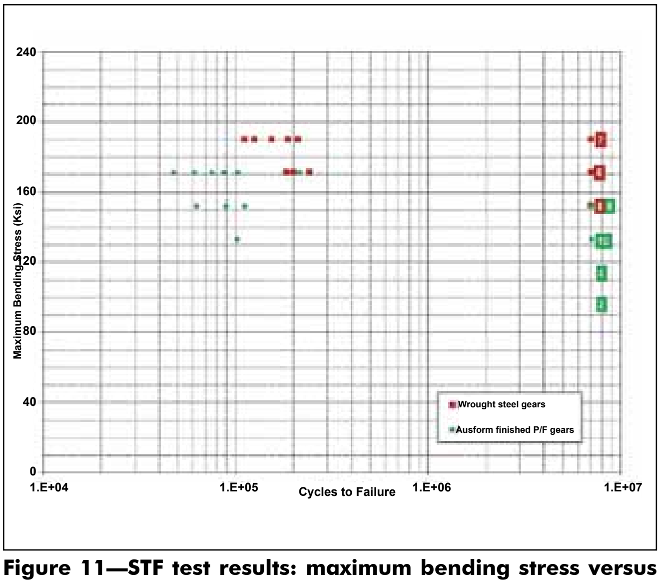

Figure 11—STF test results: maximum bending stress versus life.

Figure 12—Tooth impact test machine.

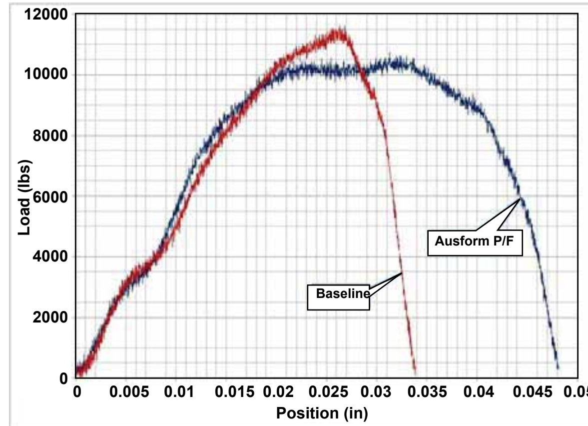

Figure 13—Impact load versus traverse (10" drop height).

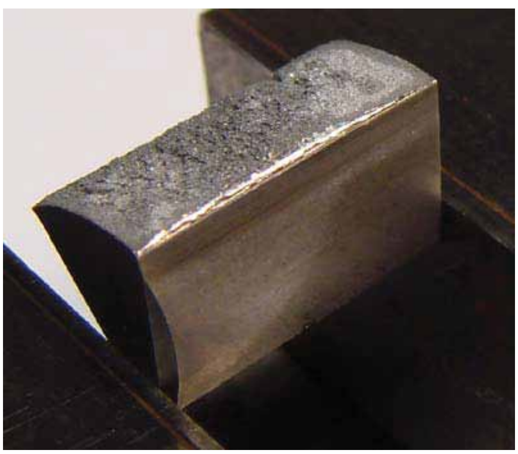

Figure 14 (a)—Wrought steel gear tooth impact fracture surface.

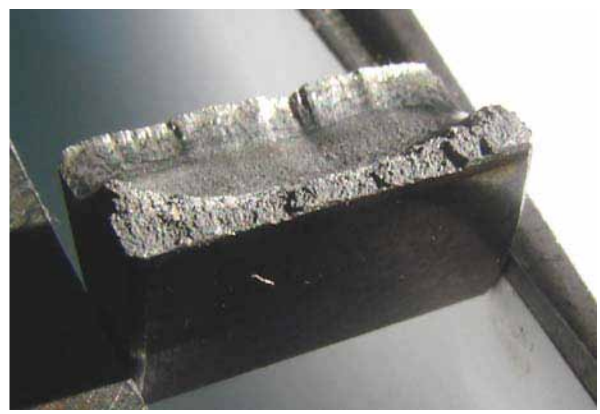

Figure 14 (b)—Ausform-finished P/F gear tooth impact fracture surface.

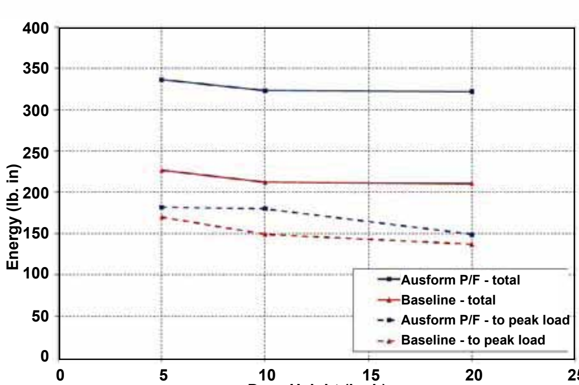

Figure 15—Impact energy versus drop height.

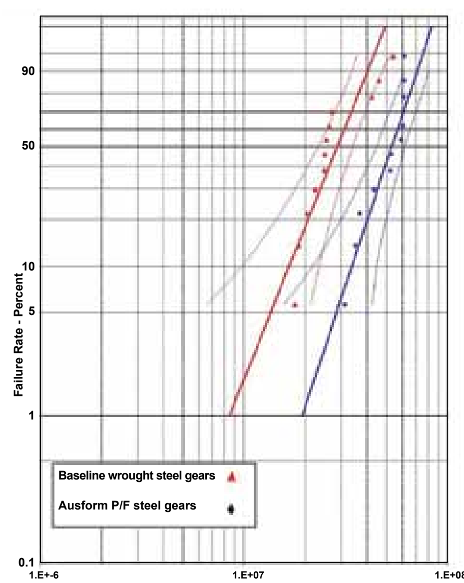

Figure 16—Pitting fatigue comparison.

steel gears. Gear tooth impact testing was carried out on a drop weight gear tooth impact testing machine (Fig. 12), wherein a target weight block is dropped from a preset height on a candidate gear tooth being tested. The machine is instrumented to record the instantaneous load generated and traverse during tooth impact fracture as a function of time.

The fixture designed to hold the test gears during impact test is similar to the STF test fixture shown in Figure 8, and impact loading of the upper tooth occurs at the same location as the STF loading shown in Figure 9. The main difference is that the in-line reaction support contacts close to the root fillet region, thus, causing only the upper test tooth to fail during the impact test. The test layout used for tooth impact testing is therefore similar to Figure 10, with the difference being that the reaction tooth is three teeth away from the upper-tested tooth. The tooth adjacent to the reaction support tooth was removed by EDM process to facilitate mounting of the gear on to the impact test fixture.

The gear tooth impact test procedure involved dropping the 138-lb. drop weight onto the test tooth from various drop heights representing increasing strain rates. The load cell output of reaction load generated as a function of time (in microseconds) was recorded during each tooth impact test. The recorded data was analyzed for each time step recorded, and the traverse of the drop weight was calculated based on initial velocity at impact and deceleration due to the tooth impact calculated from the measured instantaneous load. A plot of load versus traverse was thus generated based on the measured load data, and a representative chart for a 10" drop height is shown in Figure 13 for wrought steel gear tooth and ausform-finished P/F gear teeth. The area under the impact load versus traverse curve represents the energy absorbed during the gear tooth impact test (Ref. 38). As seen in Figure 13—although the peak impact load for the wrought steel gear tooth is slightly higher (on an average by about 5%)—the total impact energy absorbed by the ausform-finished P/F gear is substantially higher.

Figure 14 shows a typical impact fracture surface for the two types of gears tested. The wrought steel gear tooth impact fracture surface (Fig. 14a) shows a typical brittle fracture morphology, whereas the ausform-finished P/F gear tooth impact surface (Fig. 14b) indicates a combination of brittle/ductile fracture morphology that has resulted in increased impact energy absorbed.

Figure 15 summarizes the tooth impact test data for the two groups of test gears tested using drop heights of 5", 10" and 20" respectively, to evaluate effects at three strain rates. At least three tests were conducted at each drop height, and Figure 15 shows the average absorbed impact energy for respective groups of test gear teeth at various drop heights. As seen in Figure 15, the impact resistance of ausform-finished P/F-steel gears is substantially higher than baseline wrought steel gears.

Pitting fatigue testing. In a recent paper, surface durability testing details and comparative performance results were presented for baseline wrought steel gears and ausform-finished P/F-steel gears (Ref. 39). A brief summary of testing methodology and results are presented here for easy reference. Power circulating (PC) gear testing machines with a 4" center distance were used to conduct accelerated gear surface durability tests to evaluate pitting and wear resistance. A standard break-in procedure was used by testing for 30 minutes at 50% load and lubricant at 80°F, prior to applying full- load test conditions.

Failure criteria used for the PC surface durability tests were either pitting of up to 5% tooth surface area on one tooth, smaller pits totaling slightly greater area, wear of tooth surface defined as loss of profile by over 0.001", progressive scoring or excessive vibration. Failure was determined by automatic shut-down due to various sensors and/or by visual examination. Runout for pitting fatigue testing was defined as 60 million cycles without failure (about 556 hours of 24/7 testing). Contact stress calculations for the pitting fatigue test program were based on the crowned gear procedure as delineated in cited Reference 37. In addition, the modulus of elasticity used for calculating the contact stress for baseline steel gears was $30e^6$ psi and that for the P/F-steel gears was assumed to be $29e^6$ psi.

Pitting fatigue tests were conducted to compare the pitting fatigue behavior of ausform- finished P/F-steel gears (12 tests) and baseline wrought steel gears (12 tests). Most of the tests were conducted at a maximum contact stress of 304 ksi. All tested gears were inspected for profile checks before and after testing, and in some cases, during testing. No measurable wear was observed in either the ausform-finished P/F-steel gears or the baseline wrought steel gears. Figure 16 shows the Weibull analysis plot comparing the performance of the two groups of gears, along with the respective 5% and 95% confidence bands. For the Weibull analysis, the two tests carried out at a contact stress of 320 ksi were transposed to estimated life if tested at 304 ksi using a power law relationship (power of 9.0 used for the transposition). As seen in Figure 16, the estimated G-50 life for the ausform-finished P/F-steel gears was 53.1 million cycles, as compared to 28.6 million for the baseline wrought steel gears. Ausform-finished P/F-steel gears demonstrated about an 85% increase in G-50 life compared to the baseline wrought steel gears, and they showed that ausform finishing of P/F-steel gears produced a combination of enhanced strength, gear accuracy and surface finish that resulted in pitting fatigue performance substantially superior to current wrought steel gears.

Scoring resistance test results. Scoring occurs due to breakdown of lubrication that protects the two mating surfaces of meshing gears and is caused by an adverse combination of test torque, rotational speed and tooth meshing characteristics with mating gears, surface finish, lubricant properties and operating temperature. A PC surface durability testing machine operating at 2,600 rpm, and with capabil-

continued

Table 4—Scoring Test Results

	#	Gear ID	Torque, lb in	Scored at, °F
Ausformed	1	2037	2000 2200 2400	>300 >300 >300
	2	2028	2000 2200 2400	>300 >300 >300
	3	2044	2000	300
	4	2038	2000 2200 2400	>300 >300 >300
Baseline	1	B-6	2000	260
	2	B-7	2000	260
	3	B-8	2000	270
	4	B-9	2000	270

ity of oil jet lubrication, was used for the scoring resistance test. After the initial break-in procedure similar to that described for pitting fatigue tests, scoring tests were initiated at a locked-in torque of 2,000 lb. in and at a rotational speed of 2,600 rpm. Oil inlet temperature at the beginning of the test was about 100°F.

With the torque and speed maintained at the same level, oil inlet temperature was increased progressively in steps of 10°F, with the test running for 10 minutes. If no scoring was detected during that time—as monitored by oil outlet temperature and/or vibration sensors—then the oil inlet temperature was increased to the next level. The test procedure was repeated up to oil inlet temperature of 300°F, unless scoring was detected. The highest oil inlet temperature permitted without onset of scoring was used as a measure of scoring resistance of the test gear, with a higher scoring temperature representing better performance. If no scoring resulted at up to 300°F, then the torque was increased to 2,200 lb. in, and the scoring test repeated as described above. If no scoring occurred even at 2,200 lb. in torque, then the test was repeated at a torque of 2,400 lb. in—the highest torque permissible without fear of causing other modes of failure.

Table 4 summarizes scoring resistance test results for the three groups of test gears (Ref. 39). The scoring temperature for ausform-finished P/F-steel gears was 300°F—i.e., higher than 260-270°F for baseline wrought steel gears. Scoring tests demonstrated that the scoring resistance of ausform-finished P/F-steel gears was superior to the baseline wrought steel gears.

Summary and Conclusions

Performance of ausform-finished P/F-steel gears has been demonstrated to be comparable to or better than wrought steel gears in comparative bending fatigue and surface durability tests. In particular:

- Tooth bending fatigue strength of ausform-finished P/F-steel gears was comparable to shot peened baseline wrought steel gears.
- Impact resistance of ausform-finished P/F-steel gears was equivalent to or slightly better than baseline wrought steel gears.
- Pitting fatigue behavior of ausform-finished P/F-steel gears was substantially superior to baseline wrought steel gears produced by conventional processing techniques, with about 85% higher G-50 life at 304 ksi, as compared to wrought steel gears.
- Scoring resistance of ausform-finished P/F-steel gears was demonstrated to be superior to baseline wrought steel gears produced by current conventional processing techniques.

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Variation Analysis of Tooth Engagement and Load Sharing in Involute Splines

Kenneth W. Chase, Carl D. Sorensen and Brian DeCaires

Management Summary

Involute spline couplings are used to transmit torque from a shaft to a gear hub or other rotating component. External gear teeth on the shaft engage an equal number of internal teeth in the hub. Because multiple teeth engage simultaneously, they can transmit much larger torques than a simple key and keyway assembly. However, manufacturing variations affect the clearance between each pair of mating teeth, resulting in only partial engagement.

A new model for tooth engagement—based on statistics—predicts that the teeth engage in a sequence, determined by the individual clearances. As the shaft load is applied, the tooth pair with the smallest clearance engages first and then deflects as the load increases, until the second pair engages. The two engaged pairs deflect together until a third pair engages, and so on, until the full load is reached. Thus, only a subset of teeth carries the load. In addition, the load is non-uniformly distributed, with the first tooth carrying the greatest share. As a consequence, the load capacity of spline couplings is greatly reduced, and yet still greater than a single keyway.

The statistical model predicts the average number of teeth that will engage for a specified load—plus or minus the expected variation. It also quantitatively predicts the load and stress in each engaged pair. Critical factors in the model are the stiffness and deflection of a single tooth pair and the characterization of the clearance. Detailed finite element analyses (FEAs) were conducted to verify the tooth deflections and engagement sequence. The closed-form statistical results were verified with intensive Monte Carlo simulations (MCSs).

The more accurate model has led to increased understanding of the mechanics of involute spline couplings, while providing better prediction tools for designers and improved performance of their designs.

Introduction

An involute spline coupling consists of a shaft with machined gear teeth on its exterior, mated to a hub with a matching set of interior teeth, as shown in Figure 1. They are found in gear trains, transmissions, pumps and many other rotating machines. The involute profile makes them self-centering. The transmitted torque is distributed over the teeth, decreasing the load on any one tooth. It is therefore superior to a single key and keyway assembly in that it results in lighter, more efficient shaft designs.

In theory, the full ring of gear teeth on the shaft engage with an equal number of teeth in the hub, resulting in the load being equally distributed over all the teeth. But in practice, only a fraction actually transmits the load. Due to manufacturing variations—even with precision gear hobbing processes—only a fraction of spline teeth engage. Splines, therefore, perform far below their theoretical capacity. Designers commonly assume only 1/4 to 1/2 of the teeth carry the full load. They also approximate the load as uniformly distributed among the load-bearing pairs of teeth. These assumptions are often satisfactory, but can lead to early failures when applied to high load applications.

Consider an extreme application: the multi-disk brakes on an industrial mining dump truck, shown in Figure 2. The tires on this behemoth are 13 feet in diameter. The driver climbs two stories to the cab. It hauls loads up to 380 tons over challenging terrain. Stopping at any speed punishes the brakes.

The multi-disk brake assembly consists of a set of friction plates—separated by pressure plates—as shown in Figure 3a. Friction plates are splined on the inside circumference and engage the shaft spline. Pressure plates are splined on the outside circumference and engage the non-rotating hub. The brake is actuated by a ring of hydraulic pistons that clamp the pressure plates to provide braking force. The piston cylinders can be seen on the brake assembly in Figure 3b.

The spline couplings must transmit the high braking forces to the hub. Examination of failed plates revealed cracks at the base of the teeth—an indication of bending fatigue failure. Failed tooth fragments can jam between the plates or block cooling passages, possibly leading to complete failure. Also, uneven wear was observed, suggesting unequal tooth loads.

A desire for a better understanding of the mechanics of tooth engagement led to the current study. Concerns focus on the effect of variation on the load distribution within an involute spline joint. Insights leading to more reliable designs were sought.

The objectives of the research reported here include:

- Develop a statistical model to predict tooth engagement and loads
- Investigate the effects of tooth clearance variations on spline performance
- Estimate tooth load sharing and stresses
- Verify the tooth engagement model with MCSs
- Verify the loads with finite element simulations
- Determine the effects of spline design parameter combinations
- Develop software for analysis and design of spline couplings

Previous studies of splines have investigated:

- Spline standards and design (Refs. 1–4; 6 and 8–10)
- Process error sources and resultant tooth errors (Refs. 2, 8 and 11–12)
- Tooth stresses and deflections (Refs. 3,7, 11, 13 and 17)
- Spline tooth engagement (Refs. 2, 8 and 11)
- Tooth load distributions (Refs. 2 and 16)

Many studies of deflection and stress in gear teeth have been published, with valuable results. But spline couplings, although they share involute geometry with gears, are a very dif-

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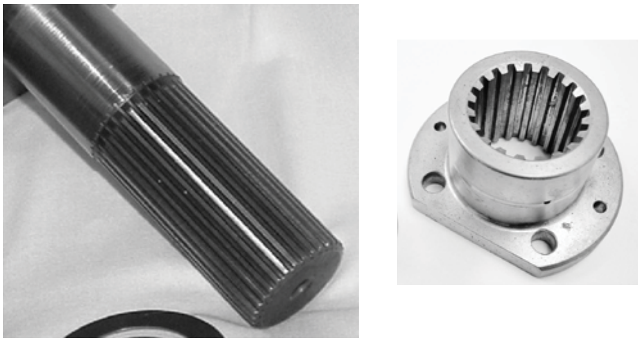

Figure 1—Involute splines.

Figure 2—Industrial mining truck (courtesy Caterpillar, Inc.).

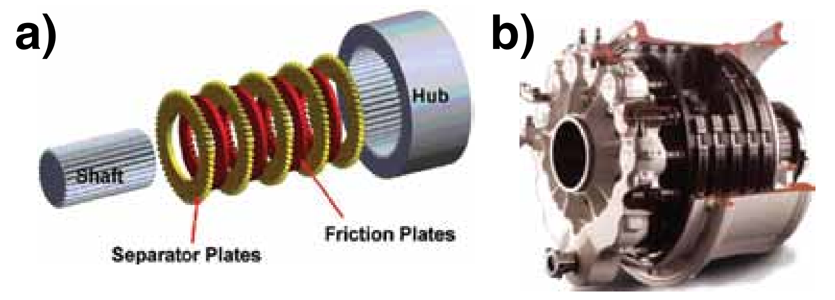

Figure 3—Multi-disk brake assembly (courtesy Caterpillar, Inc.).

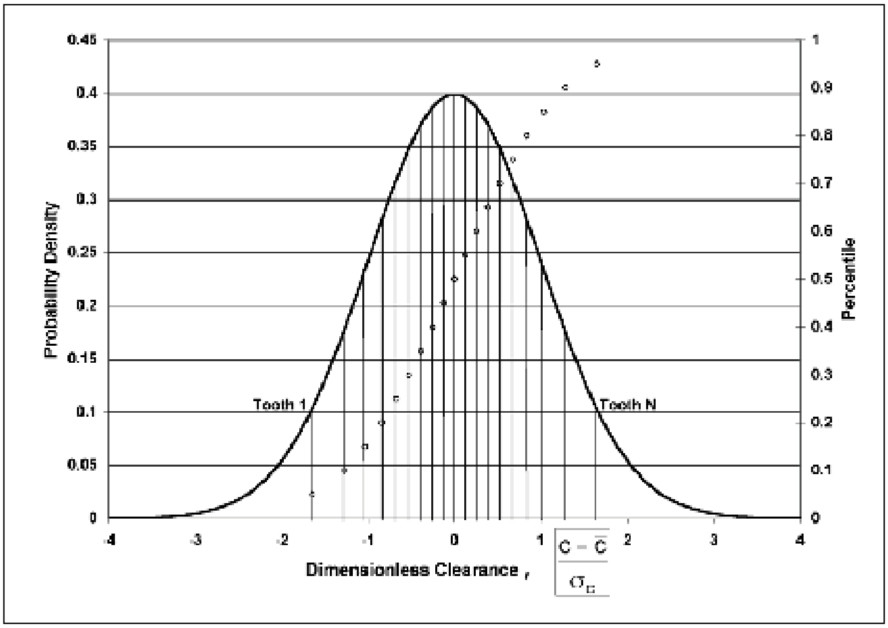

Figure 4—Normal distribution of tooth clearance.

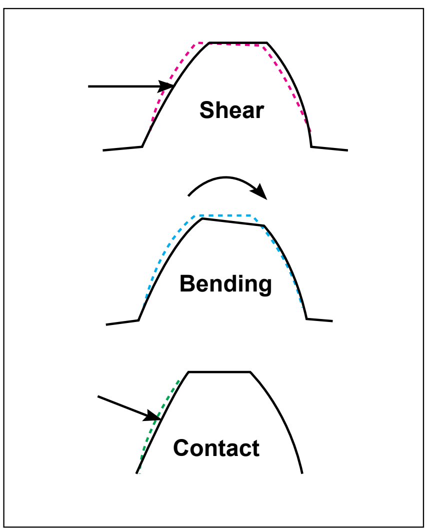

Figure 5—Three modes of tooth deflection.

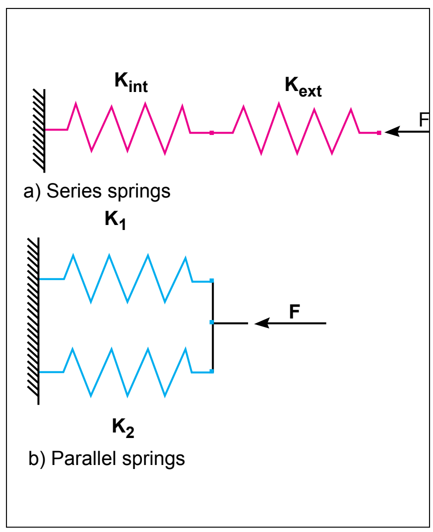

Figure 6—Tooth stiffness models.

ferent application in that gear designers do not seek simultaneous contact between all the pairs of teeth. For spline design, this is the goal—but it is not possible, due to tooth variations. There is, as yet, no quantitative algorithm for predicting tooth engagement in splines resulting from manufacturing process errors. With a realistic analytical tool, which includes all critical spline parameters, as well as realistic estimates of tooth errors, designers may be able to find an optimum combination that significantly improves spline performance.

The results of this study include:

- The effects of tooth errors on mating tooth clearances
- Statistical characterization of clearance variations
- Prediction of tooth engagement
- Sequence of tooth engagement versus load
- Stress in each tooth resulting from non-uniform tooth loads

Analytical Model

Tooth errors/tooth clearance. The natural variation in the spline manufacturing process leads to non-uniform clearance between pairs of mating teeth. Three common sources of variation for this study were suggested by a gear manufacturing expert: index error, profile error and tooth thickness error (Refs. 12 and 15). Both the internal and external teeth are subject to all three. With six sources of error, it may be assumed that the clearance variation would approximate a normal or Gaussian distribution, as shown in Figure 4 (Ref. 14). Note that the majority of teeth are clustered close to the mean clearance and spread out in the tails.

A requirement for smooth braking action of the truck brakes is that the clearance be sufficient to allow the pressure plates to slide axially. Extra clearance and a decreased pressure angle are provided for this application.

Lead error is another source for long spline teeth, but it did not contribute in this application because the brake plates are thin and adjust independently. The shaft and hub centerlines were also assumed to remain in alignment due to their stiffness and self-centering geometry.

Tooth engagement. The realization that tooth clearance varies from tooth to tooth led to a new statistical model for tooth engagement (Ref. 5). Consider a shaft and hub assembly: as the shaft rotates to engage the mating internal teeth, the clearance is reduced to zero. However, clearance between all tooth pairs does not go to zero simultaneously. The pair of teeth with the smallest clearance engages first and begins to transmit the torque load. As the load increases, the tooth pair deflects until the second pair engages. The load continues to increase, causing both to deflect until a third pair engages, and so on, until the full applied load is reached.

Thus, tooth engagement is a sequential process, sorted in order of increasing clearance. However, due to the random nature of the process errors, the teeth do not engage in numerical order. And so the engagement sequence will be as random as the clearances.

Tooth stiffness. The resultant tooth loads depend on the stiffness of a tooth under load. Three modes of deflection contribute: shear, bending and contact (Fig. 5).

For small deflections, spline teeth

may be modeled as linear springs (Fig. 6). When a tooth on the shaft engages a tooth on the hub, they combine as springs in series. Their stiffnesses add as reciprocals. When two pairs of engaged teeth share the load, their stiffnesses add linearly. Thus, as teeth engage sequentially, the combined stiffness increases incrementally.

A plot of the resulting force deflection curve for the spline assembly (Fig.7) shows a steepening curve composed of straight, linear segments. Each change in slope is the result of another pair coming into engagement to share the load. At some point, the full, applied load is reached and the number of engaged pairs is determined. Thus, the number of pairs that engage, and their engagement sequence, is a complex interaction between applied load, tooth stiffness and the clearance magnitude and variation.

Note that the deflection from Tooth 1-to-2, 2-to-3, 3-to-4, etc., gets smaller as each new tooth engages. This is due to the normal distribution of the clearance (Fig. 4). Tooth clearances are clustered more closely near the mean of the clearance distribution and spread out in the tails.

Of course, the tangential force on the tooth produces a torque, and the tangential deflection produces a rotation. Both force and deflection act at the same radius, hence, the force versus deflection curve is equivalent to a torque versus angular deflection curve.

Load-sharing. A significant result of sequential engagement is that load sharing between the teeth is not uniform. In Figure 8, the force deflection curves for several pairs of teeth are shown as they engage sequentially. The first pair to engage starts at zero and the load increases with slope K_1. As the load increases, the first pair deflects until the second engages. Both pairs share the load and deflect together with a combined stiffness $K_1 + K_2$ (Fig. 7). The next pair to engage increases the stiffness to $K_1 + K_2 + K_3$.

A vertical line in Figure 8 intersects all three force-deflection curves. The total load is $F_1 + F_2 + F_3$. The loads are unequal because the first pair deflected δ1, the second δ2, and third δ3. The first pair carries a bigger share, because it has deflected further.

The load-sharing plot (Fig. 9) shows that the load is not uniformly distributed. The first tooth pair carries 18% of the load, with each successive pair carrying a smaller percentage. The curve is not smooth because of the random variation in clearance.

Strength of materials model (SMM).

Tooth stiffness is the key factor in an analytical model of tooth engagement. The strength of materials model represents each tooth as a stubby, cantilever beam, with a tapered cross section, subject to a load acting normal to the surface. The involute profile is

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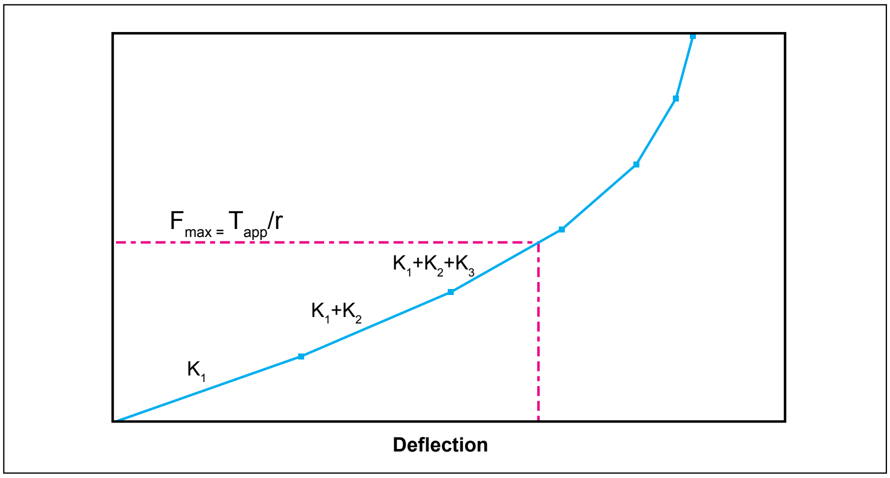

Figure 7—Force-deflection plot due to sequential tooth engagement.

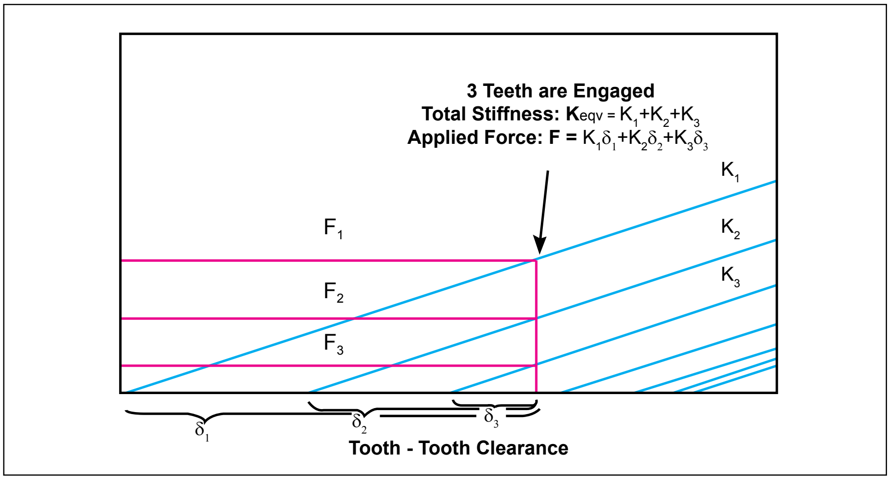

Figure 8—Force-deflection plot for individual teeth.

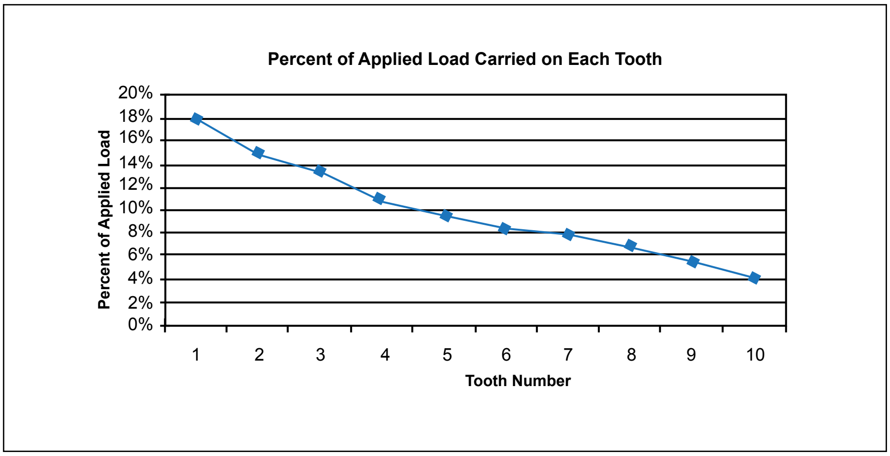

Figure 9—Load sharing plot for 10 engaged teeth.

approximated by a trapezoid, as shown in Figure 10. Fillets are neglected in the stiffness calculations, but are included in the stress calculations. Deflections due to contact stress are also neglected in the stiffness calculations.

The load does not move from root to tip, as occurs in involute gearing, but remains stationary, near the pitch diameter. The normal force, F_n, is resolved into tangential and radial components (Fig. 11). The tangential force, F_t, produces both bending and shear deflections and stresses. The radial force, F_r, produces a radial force and a reverse bending moment (Fig. 11).

The stress distribution at the base of the tooth is shown for each component of load, and the resultant combined stress distribution, in Figure 12. The stress and deflections are all calculated in closed form, for instant results, as opposed to conducting a full finite element analysis.

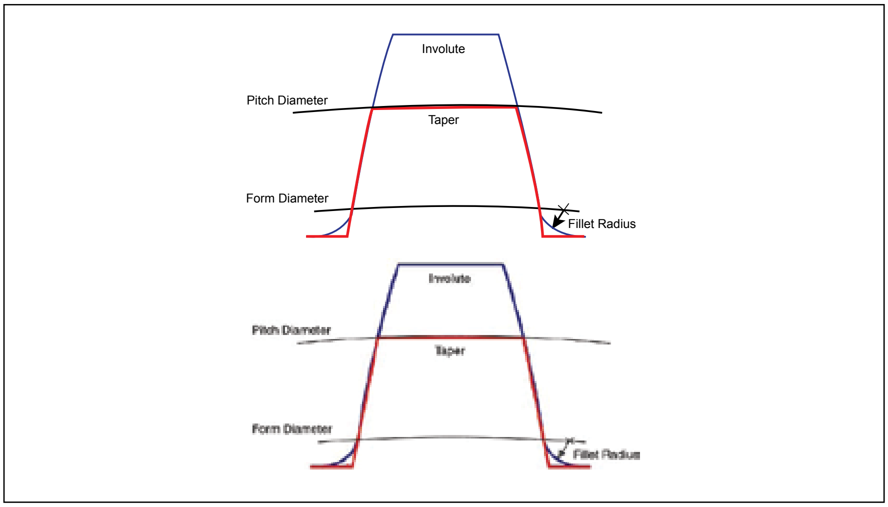

Figure 10—Simplified tooth geometry.

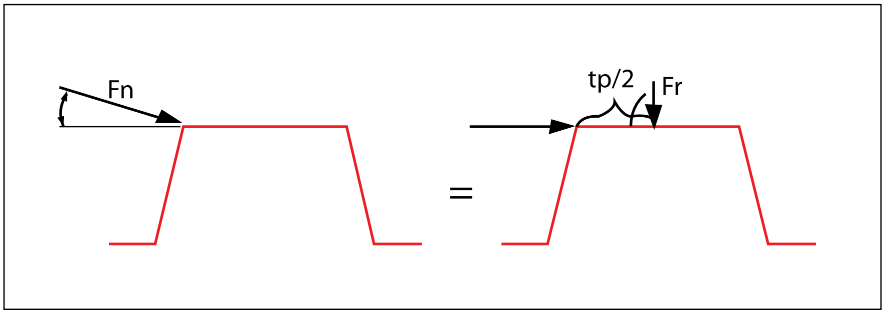

Figure 11—Equivalent loads acting on a tooth.

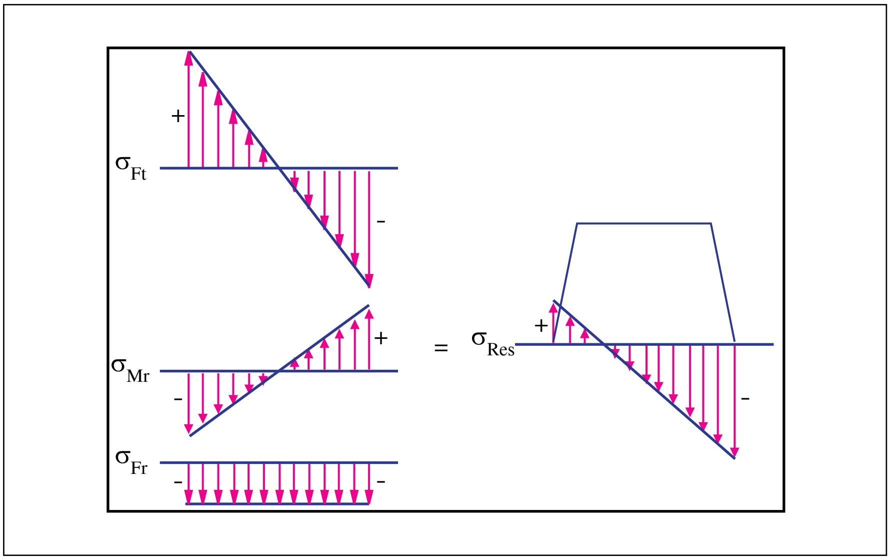

Figure 12—Total stress at the base of the tooth.

Map uniform tooth spacing to a normal distribution. As stated previously, the combination of several sources of process variation, for both the external and internal splines, is modeled as a normal distribution. The resultant variation in clearance is clustered about the mean, becoming sparse approaching the tails.

Figure 13 illustrates a procedure for mapping a uniformly distributed clearance onto a normal distribution for a seven-tooth spline. The vertical axis is divided into seven equal intervals, with the center of each interval located and projected horizontally until it intersects the Cumulative Distribution Function (CDF) for the standard normal distribution. At the intersection point, project down to the horizontal axis to determine the clearance for each tooth. The Probability Density Function (PDF) is plotted below the (CDF) to illustrate the resulting normal distribution.

Note that the CDF goes to infinity at $y = 0$ and $y = 7$, but since Tooth 1 and Tooth 7 are one half interval inboard, the extreme values of clearance are always finite. Also, note that the clearance always increases going from Tooth 1 to 7, but the change gets smaller as you approach the mean, then increases again after the mean is passed.

These values of clearance represent the average, or mean values for Tooth 1, Tooth 2 and so on, up to 7. But, if clearances were measured for 1,000 spline assemblies, there would be a variation about the mean value for Tooth 1 through 7, resulting in a set of distributions, clustered about the mean clearance. (*A follow-up paper on this topic is included in Appendix A.*)

The mapped method gives an adequate estimate of the number of teeth engaged for any specified load, as well as the load sharing.

Verification

The SMM model for tooth deflections and stress has been verified by FEA. Finely meshed models were analyzed for several cases of differing tooth sizes and parameters. Single pairs of engaged teeth were analyzed by FEA and compared to the SMM results for stiffness, deflection and stress. Spline sections with several teeth engaged, and having prescribed random clearances, were analyzed to verify the load sharing predictions of SMM.

A careful study of contact stress between mating cylinders was done to develop confidence in the use of FEA contact stress elements. These results were compared to classical Hertz contact solutions. A more critical issue was the common assumption used in gear stress analysis that Hertz theory for mating cylinders may be applied to mating involutes. Each cylinder in the Hertz model has constant radius of curvature while involute curvature changes continuously. The assumption is based on the fact that contact phenomena are so localized that curvature variation does not significantly affect the contact stress results. Figure 14 shows the geometry for the two cases.

FEA analysis results. An example FEA mesh of mating spline teeth is shown in Figure 15, but the clearance is too small to see.

Sample results of the FEA verification of the contact stress case studies are presented in Table 1. Width *b* is half the width of the rectangular contact zone. The contact pressure generated in the contact zone is assumed to be parabolic, with the peak value P_{max}. The comparison is the percent difference between the two values.

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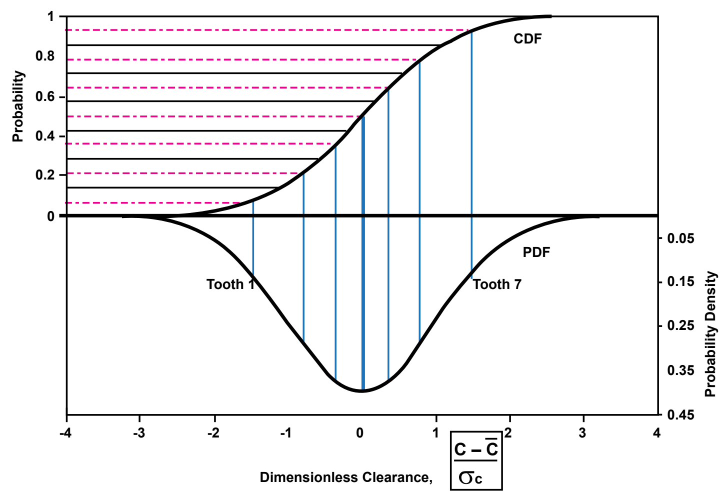

Figure 13—Mapping the spline tooth clearances onto a normal distribution.

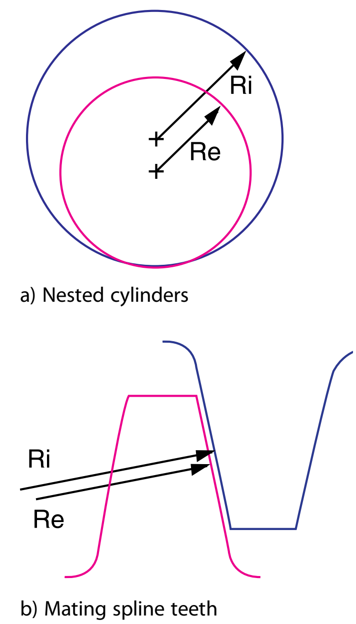

Figure 14—Contact stress case studies.

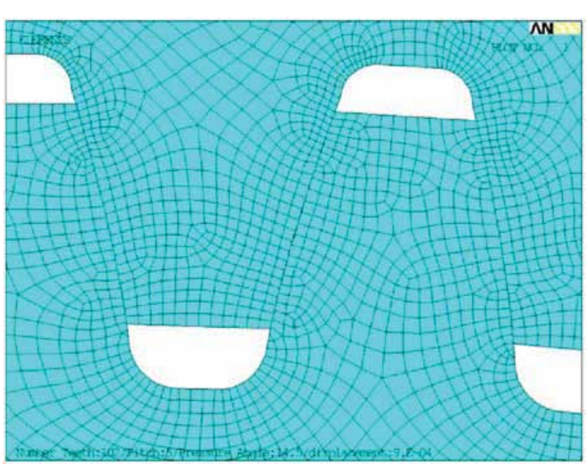

Figure 15—Finely meshed teeth for FEA contact stress analysis.

Table 1— Contact Stress Analysis Results.

Percent Difference in *ANSYS* and Hertz Results

Parameter	Parallel Cylinders	Nested Cylinders	Contacting Splines
Contact width, *b*	7.2%	3.7%	0.54%
Contact pressure, Pmax	3.8%	3.9%	1.3%

This much error is acceptable for most applications.

The results in Table 2 are a sample of the FEA verification for mating spline teeth. They include: maximum contact pressure, maximum bending stress on the external and internal teeth, deflection at the contact point and the equivalent stiffness of the two engaged teeth.

The SMM maximum stress values in Table 2 require a stress concentration factor similar to those used in strength of materials courses. Charts are available for common loads and geometries, obtained from classical solutions, repeated for a range of geometric ratios.

However, such data are not available for involute spline geometries. The closest that could be found was obtained experimentally for gear geometries by means of photoelastic models (Ref. 7).

Although involute splines and gears share the same mathematics, standard spline teeth are shorter and wider than standard gears. A study devoted to splines will be necessary before improved stress predictions can be obtained.

Tooth engagement results. To verify the SMM, a multi-tooth FEA model was created. The model in Figure 16 represents a 10-tooth segment of a 102-tooth spline. Boundary conditions were constructed to allow the outer ring to rotate clockwise relative to the inner with a tangential load applied. An extra tooth at each end provides support. The same random clearances were applied to the FEA model and the SMM model for comparison.

The 10 teeth with the smaller clearances were selected for the model. In reality, they would be randomly placed among the 102 teeth, but the teeth essentially sort themselves. The tooth with the smallest clearance makes contact first, then the next smaller and so on. For convenience, the teeth were sorted by increasing clearance, so the clearance sequence and tooth number sequence coincide. The remaining teeth are not loaded and were omitted from the model.

The same load was applied to both the SMM and FEA models, and all 10 teeth made contact. The resulting FEA stress plot is shown in Figure 16. The contact force on each tooth is proportional to the peak contact stress. A plot of tooth load versus tooth number is shown in Figure 17 as a percent of total load. The non-uniform load predicted by the SMM model is clearly confirmed by the FEA results.

Table 2— Mating Spline Contact Pressure, Bending Stress, Deflections and Stiffness.

Comparison of *ANSYS* and SMM Results					
Model	P_{max}, MPa (ksi)	σ_{max} Internal, MPA (ksi)	σ_{max} External, MPA (ksi)	δ_{tot}, mm (in)	K_{tot}, kN/mm (kip/in)
ANSYS	51.4 (7.45)	259 (37.7)	273 (39.6)	23.8×10^{-3} (9.35×10^{-4})	16.00 (280)
SMM	51.7 (7.50)	252 (36.5)	289 (41.9)	23.1×10^{-3} (9.11×10^{-4})	16.45 (288)
Error	0.6%	3.1%	5.9%	3.6%	2.8%

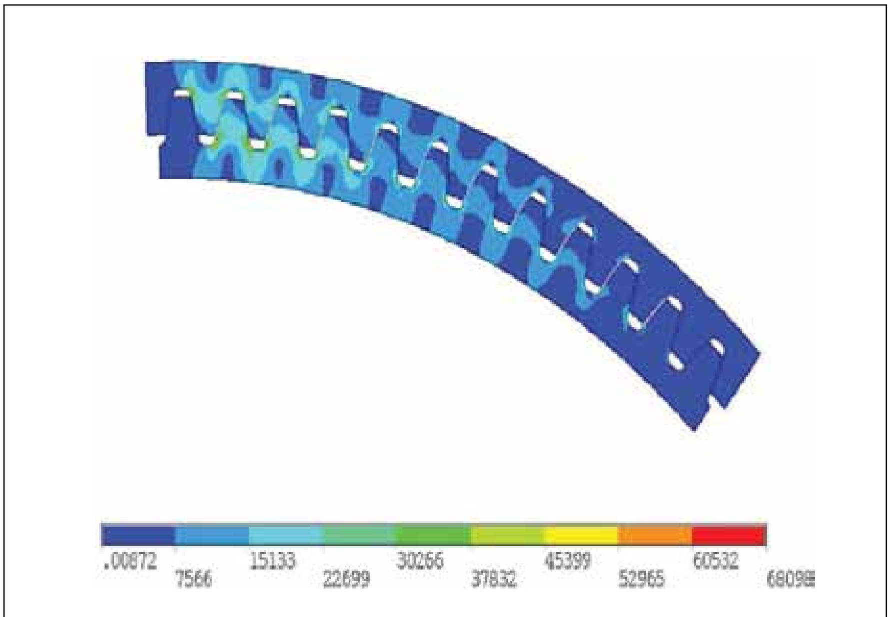

Figure 16—Multiple-tooth FEA model—with teeth ordered by increasing clearance—showing von Mises stress in psi.

Creation of the* STEM *spreadsheet. A research objective was the development of a spreadsheet for the prediction of tooth engagement and load sharing based on the SMM. Called *STEM—Statistical Tooth Engagement Model*—it includes all of the important parameters that affect tooth engagement, including the total number of teeth, tooth size, pitch, pressure angle, Young's Modulus, yield strength, etc., as well as the total applied load. It is closed-form, based on the strength-of-materials-model for tooth stiffness and a normally distributed tooth clearance.

The spreadsheet results have been verified by FEA and MCS. It provides a realistic prediction of tooth engagement and tooth loads for a given applied load. Because it is computationally efficient, it is suited for design iteration in the selection of spline parameters and materials, and in pursuit of optimum performance.

Parametric studies. To demonstrate the power of the *STEM* spreadsheet for spline design, several parametric studies were performed to see the effect of key spline parameters—they are not all independent. For example, if you increase tooth size, you must either increase the pitch diameter a corresponding amount or decrease the number of teeth. Similarly, changing the size affects tooth stiffness and stress, which affect performance.

The case studies performed included:

- 3 pressure angles
- 3 tooth sizes
- 5 standard deviations of clearance
- Normal versus uniform distribution
- Number of teeth

The results of the parametric studies are presented in Reference 5.

Many studies are worth pursuing in the future using these tools. Questions to consider include:

- Which is better?
  - – A stiffer tooth or a more flexible tooth?
  - – A larger or smaller pressure angle?
  - – Full tooth engagement, or less?
  - – Tight clearance tolerances, or liberal?
- Which is better for extreme loads or longer life?
  - –A large number of teeth, most of which will never share the load?
  - –Or fewer, stronger teeth?

These, and other interesting questions may be investigated analytically, with minimal investment in time and resources.

Results. Good agreement between the strength of materials model and FEA, including:

- Tooth stiffness, tooth engagement, load distribution
- Deflection, bending stress and contact stress
- Good agreement between the closed form statistical model for the clearance and the Monte Carlo Simulation

Discoveries

- Contact deformation is a negligible contributor to stiffness
- Contact surfaces change curvature as a result of deflection (nonlinear solution)
- Both Hertzian theory and FEA have singularities when both radii of curvature are equal
- From FEA, it appears that the contact point is further out than expected, which changes the stiffness
- It also appears that the contact zone is larger than expected, which changes the deflections

Conclusions/Contributions

- A new, sequential model for spline tooth contact has been developed and confirmed by conventional stress analysis and FEA
- The statistical-based model uses the tooth clearance distribution combined with a tooth deformation model to predict the probable engagement sequence
- It also predicts tooth load sharing and stress distribution as the load is applied, as well as the maximum number of teeth required for a given load
- Provides new understanding of spline mechanics
- Closed form statistical model is confirmed by MCS
- A new spreadsheet design tool (*STEM*) was created, which is closed-form; i.e.—no FEA or MCS is required
- The *STEM* spreadsheet is reasonably accurate in predicting tooth engagement, tooth loads and stresses
- *STEM* is much more efficient than performing design iterations with a full FEA model and MCS

Future Directions

- Stiffness and clearance are key factors in predicting spline performance. Further study is warranted, with in-depth testing to confirm the sequential model experimentally.
- An extension of this research to include the effects of axial errors, such as lead error, could be conducted. The effects of torsional deflection of the shaft could also be modeled.
- An empirical function for fillet stress concentrations is needed for splines, similar to gear fillets.
- No database of error sources is available to estimate clearance. Thus tooth clearances and tooth deflections are difficult to measure, making gathering a database challenging.
- An in-depth study using *STEM* could be made to chart the effects of spline parameters.
- *STEM* could be combined with an optimization tool and applied to search for superior designs, based on desired performance measures.

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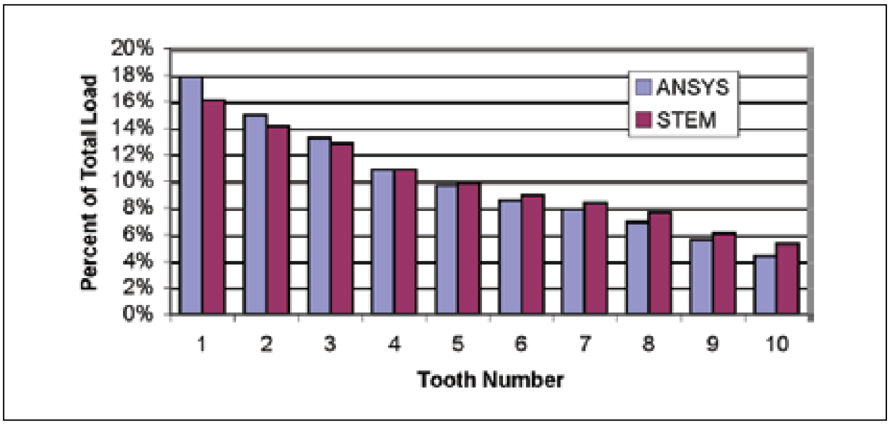

Figure 17—Percent of applied load carried by each tooth from FEA and *STEM*.

Appendix

The statistical model described in the body of this report only predicts the *average* tooth engagement sequence. From one spline assembly to the next, the first tooth to engage would always be the pair with the smallest clearance. However, due to statistical variations, the clearance of the first pair would be different from assembly to assembly.

If you measured tooth clearances in 1,000 assemblies, the smallest clearance would approach a distribution, similar to the left-most distribution in Figure A1 (Tooth 1).

Similarly, the next tooth to engage would have a distribution like the next distribution in Figure A1 (Tooth 2), and so on.

A full statistical model was also developed as a part of this study. It is the subject of a follow-up report, which is in preparation.

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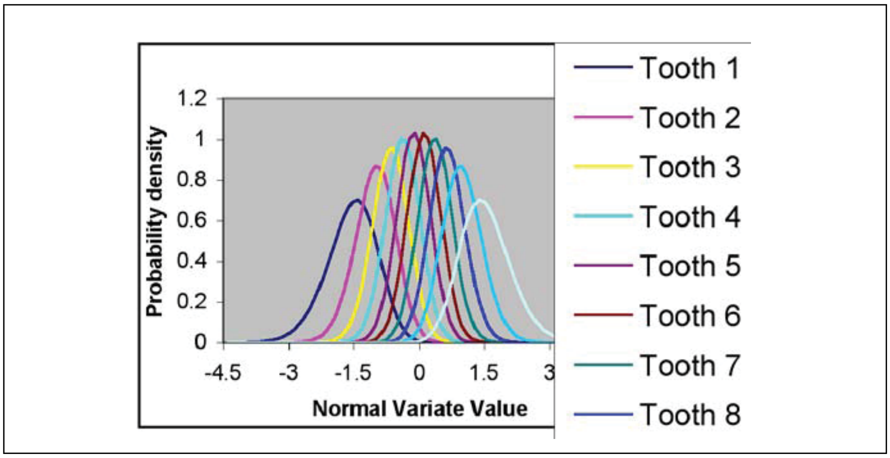

Figure A1—Full statistical model of tooth clearance, showing tooth-by-tooth variation.

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The Anatomy of a Micropitting-Induced Tooth Fracture Failure—Its Causation, Initiation, Progression and Prevention

Raymond J. Drago, Roy J. Cunningham and Steve Cymbala

Management Summary

Micropitting has become a major concern in certain classes of industrial gear applications, especially wind power and other relatively highly loaded, somewhat slow-speed applications, where carburized gears are used to facilitate maximum load capacity in a compact package. While by itself the appearance of micropitting (Fig. 1) does not generally cause much perturbation in the overall operation of a gear system, the ultimate consequences of a micropitting failure can, and frequently are, much more catastrophic.

Micropitting is most often associated with parallel axis gears (spur and helical), but the authors have also found this type of distress when evaluating damage to carburized, hardened and hard-finished spiral bevel gears.

This paper presents a discussion of the initiation, propagation and ultimate tooth fracture failure mechanism associated with a micropitting failure. The subject is presented by way of a discussion of detailed, destructive metallurgical evaluations of several micropitting failures that the authors have analyzed on both parallel axis and bevel gears.

Introduction

Although most frequently associated with lower speed gear systems, micropitting can also be observed in high and very high-speed gear systems as well, though the failure sequence can be somewhat different at the high-speed end of the spectrum.

Unfortunately, the micropitting phenomenon—including the underlying causes and analysis methods directed at prevention in the design stage—is not fully understood. Indeed, even the condition to which the term should be applied is subject to some discussion and disagreement. We do not propose, herein, to address the greater subjects of classification, analytical evaluation and terminology in a "Standard" sense. Rather, this paper presents a discussion of the initiation, propagation and ultimate tooth fracture failure mechanism associated with a micropitting failure.

While micropitting is most often associated with parallel axis gears (spur and helical), the authors have also found this type of distress when evaluating damage to carburized, hardened and hard-finished spiral bevel gears. Micropitting observed on both parallel axis and bevel gears

continued

Figure 1—Typical micropitted region.

will be addressed in this presentation. Although no specific failure "case" is presented, information has been extracted and condensed from several individual actual tooth fracture failure investigations conducted by the authors so that a better understanding of the specific conditions that lead to micropitting—and the actual progression from micropitting to fracture—can be better understood.

Before we can discuss the occurrence and propagation of micropitting (also known as "grey staining"), we will have to understand what it is and how it differs from classic fatigue pitting. Micropitting has become a serious problem in high-quality, usually ground or otherwise hard-finished, carburized industrial gearing—especially in critical applications such as wind turbine, conveyor and some lower-speed aerospace gearboxes. While the problem is more often observed in parallel axis gears, it is also observed in bevel gears where the contact conditions are "right."

Macropitting

Until fairly recently, surface durability of gears has been defined by macroscopic pitting, or macropitting, in which a crack initiates at a subsurface location where the shear stress exceeds the shear allowable (Fig. 2A). When such a crack propagates to the tooth surface, a small piece or, more often, several small pieces of material (Fig. 2C) are liberated, leaving an inverted, cove-shaped defect (Fig. 2B).

As this process is repeated, more and more pits appear and eventually the tooth surface is heavily damaged (Fig. 3). Eventually, and if the loads are high enough, the pitting- damaged region of the tooth acts as a significant stress concentration, and bending fatigue failure of the tooth may occur through the pitted region (Fig. 3B).

Micropitting

More recently (the last 10–15 years) a microscopic pitting phenomenon—generally referred to as micropitting—has become a very problematic failure mode in certain applications. Typically, where high loading is present at lower speeds under low or marginal film thickness conditions, micropitting becomes a significant risk. It is important to note, however, that although it usually appears in a somewhat different presentation, micropitting is also a factor in the operation of higher-speed gears as well. In the latter instance, micropitting is frequently present as a "hard line' that leads fairly quickly to the formation of large spalls that may lead rather rapidly to tooth fracture failures; as such, the original micropitting "evidence" is often lost in the failure. Extremely careful metallurgical evaluation of the fractures can, however, often pinpoint the micropitting "connection" (Figs. 14C and 15).

The cause of micropitting remains elusive. Initially, it was thought that the cleanliness of the steel might be playing a significant role, but micropitting exists even where very clean steels are used. It appears at local surface irregularities, including tooling witness lines (Fig. 4) and general-surface roughness peaks. It has been demonstrated that micropitting capacity can be improved through the use of improved finishing techniques, especially "super finishing" processes that reduce the surface finish down well below 10 RMS. The use of

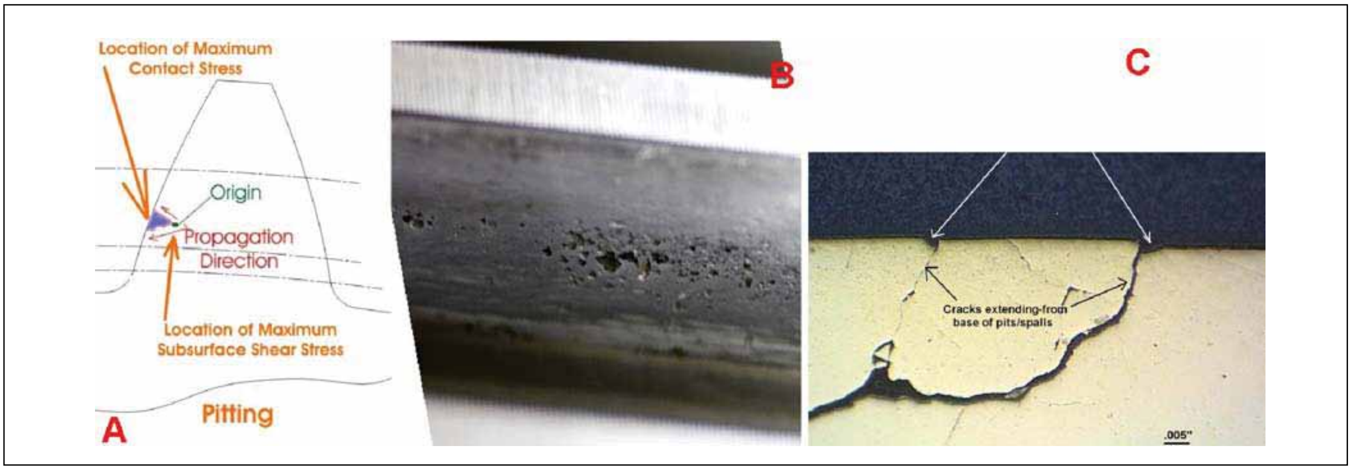

Figure 2—Classic macropitting fatigue.

Figure 3—Heavy pitting often leads to local tooth fracture.

some extreme pressure (EP) additive oils to avoid scoring type failures has also been shown, at least anecdotally, to increase the incidence of micropitting, at least with some formulations.

The Lubricant Connection

While some testing has been accomplished to investigate the relation between micropitting and specific lubricant additive package combinations, it is still not well understood. Figure 5 shows, for example, the results of one set of FZG tests that compared the efficacy of a biodegradable, straight mineral with an ester-based fluid in the occurrence of micropitting.

The amount of micropitting damage that occurred during these controlled tests shows that the lubricant in use—under identical, controlled test conditions—can significantly affect the rate of micropitting formation. Just as interesting, however, is the finding that micropitting occurred with both lubricants, though at differing rates. New oils have been developed specifically aimed at providing improvements in the lubricated contact that will forestall the occurrence and reduce the progression of micropitting on gear teeth. These new lubricants have been successfully applied and have proven to be good solutions in specific applications. Our purpose here, however, is to understand the specific nature of the micropitting failure mode so that we can postulate ways in which the basic design of the gears can be modified to reduce the probability of micropitting occurring.

Designing Against Micropitting

The hill-and-valley effect of the surface topography produced by the specific finishing method used is a bit easier to understand, at least qualitatively. And since no specific, analytical technique has yet been developed to predict micropitting in general, designing against it remains challenging. The best course of action appears to lie in recognizing the general circumstances that lead to micropitting, and then applying known enhancements to reduce the probability of its occurrence. These enhancements include treatments of the gear itself (finer surface finishes and some coatings), reducing sliding velocity along the tooth profile, reducing the friction coefficient and using specially developed anti-micropitting oils.

Effect of Micropitting on Operation

The simple existence of micropitting of and by itself is, however, not generally an operational problem for most gear systems. The progression of micropitting to a more catastrophic form, however, can and often does cause a cessation of function of the entire gear system. It is this progression that is the real cause for concern and the phenomena that we will deal with here.

Figure 6 shows a helical gear tooth that exhibits a fine micropitting pattern in the flank region. This very fine damage—which is very difficult to see without special lighting effects—would appear to be of little consequence. After its progression, however, the ultimate result of this micropitting is the

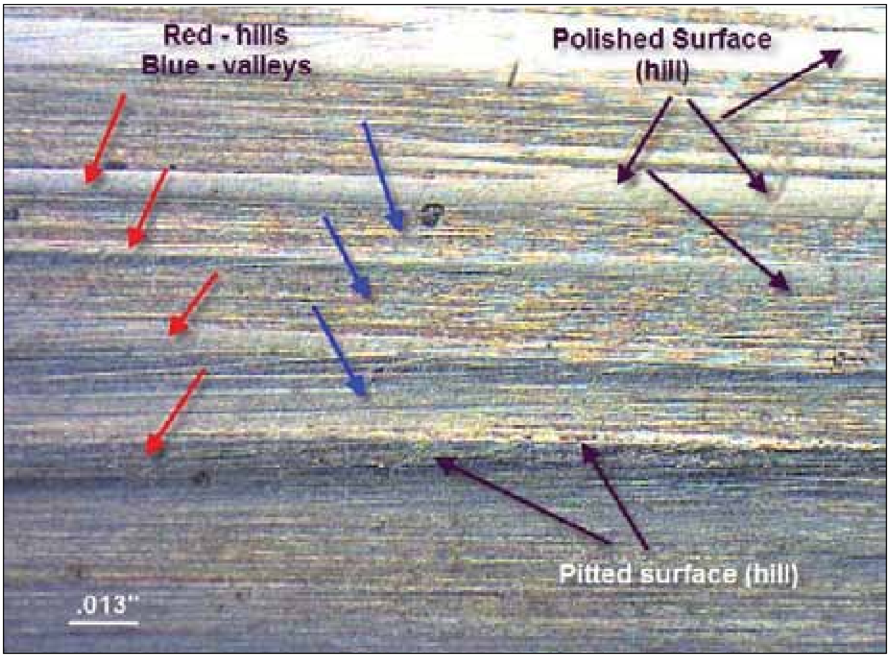

Figure 4—Micropitting aligned with finishing tool witness lines.

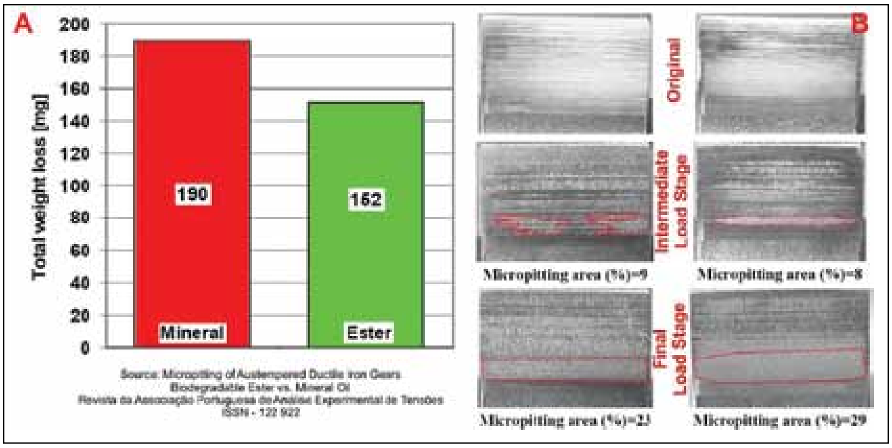

Figure 5—Effect of lubricant selection on micropitting performance.

Figure 6—Helical gear tooth exhibiting fine micropitting patterns (red arrows) in flank.

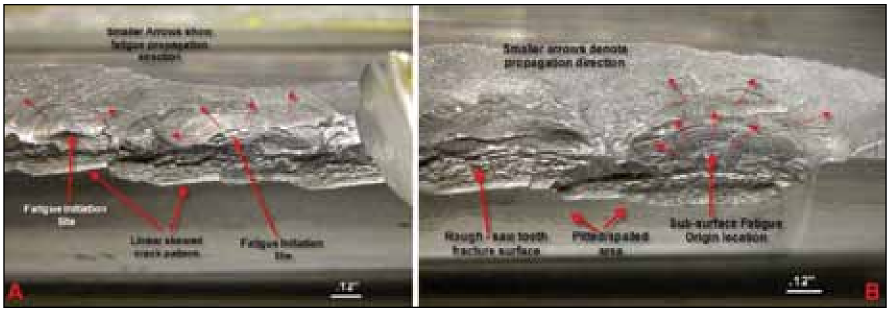

Figure 7—Helical gear tooth after partial tooth fractures.

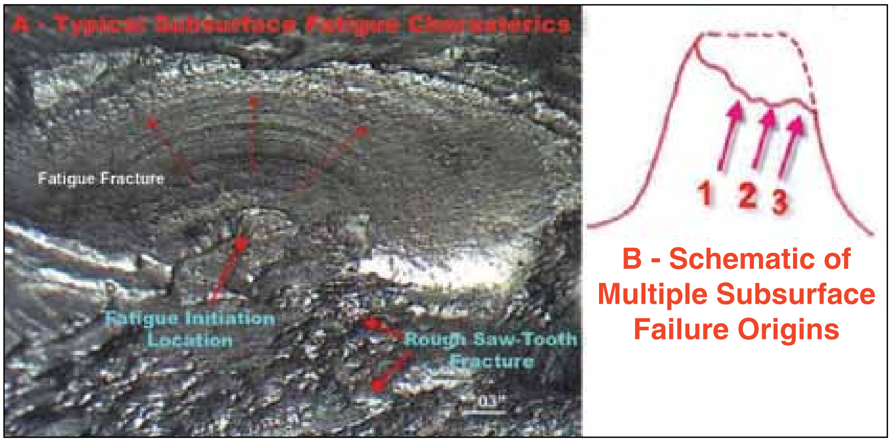

Figure 8—Magnified view of subsurface fatigue characteristics.

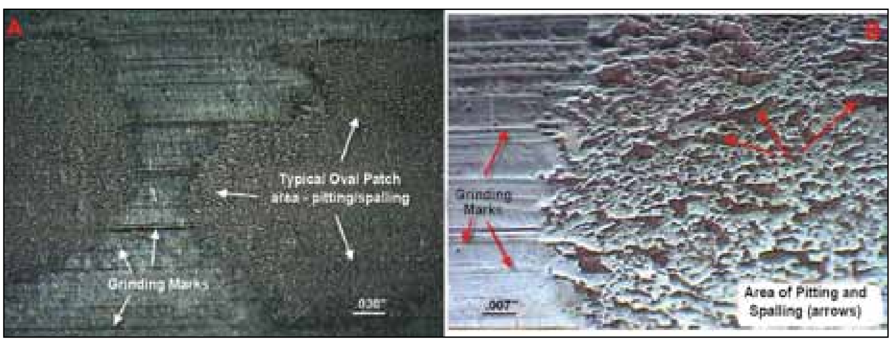

Figure 9—Typical micropitted tooth surface appearance.

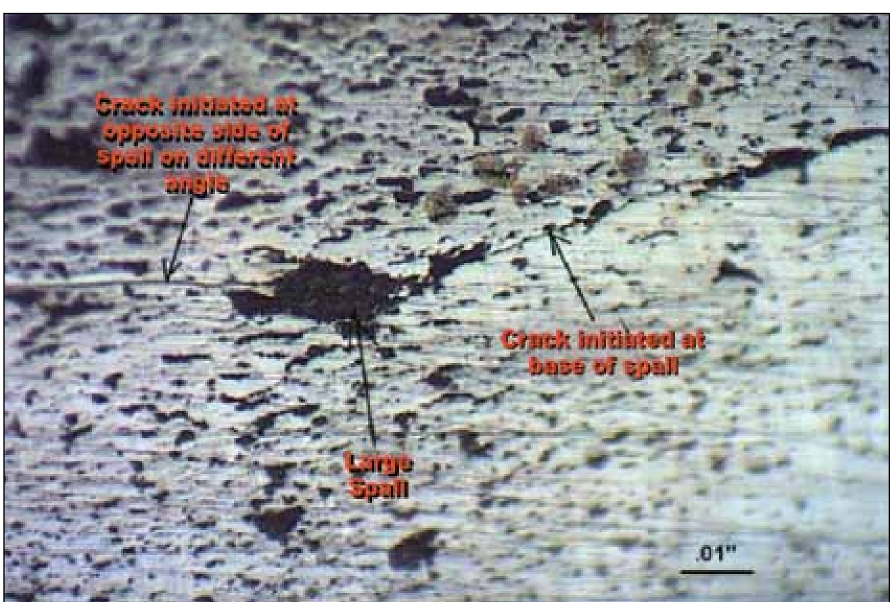

Figure 10—Cracks emanating from small spalls in micropitted region.

tooth fractures shown in Figure 7.

Certainly, the very minor damage shown in Figure 6 would not, at first review, seem serious enough to cause the very extensive, service-ending damage shown in Figure 7. After reviewing a number of gears from similar systems at various stages of progression, the authors were able to develop a history that clearly shows minor, initial damage leading to a catastrophic result.

Figure 8 shows two views of the same general region of micropitting on a helical gear tooth. The regions shown are magnified views of one of the micropitted regions denoted by the red arrows in Figure 6. This gear, which initially appeared quite similar to the one shown in Figure 6, eventually experienced many service-ending tooth fracture failures such as those shown in Figure 7. In order to examine the mechanism by which the seemingly mild micropitting distress progressed to a complete tooth fracture, we will examine this failure in detail. (*Authors' note: The figures used to illustrate this discussion were taken from several related, individual failure investigations conducted by the authors; thus, each figure does not necessarily show the same gear. Each figure was selected from the large number of images accumulated during the course of these investigations so as to best illustrate the point under discussion.*)

The Micropitting Mechanism

A visual examination of each tooth fracture surface displayed several zones of bending fatigue initiation and propagation. Fatigue was indicated by the many semi-circular beach marks, which are plainly visible. Bending fatigue initiated subsurface from the pitting/spalling and propagated up and over the tip from the drive side to the coast side of the tooth, resulting in removal of portions of the tooth tip. Fatigue characteristics are revealed in Figure 8—an enlarged view of the fatigue and rough surface topography shown in Figure 7.

As the micropitting progressed, it began to initiate small fan- or triangu-

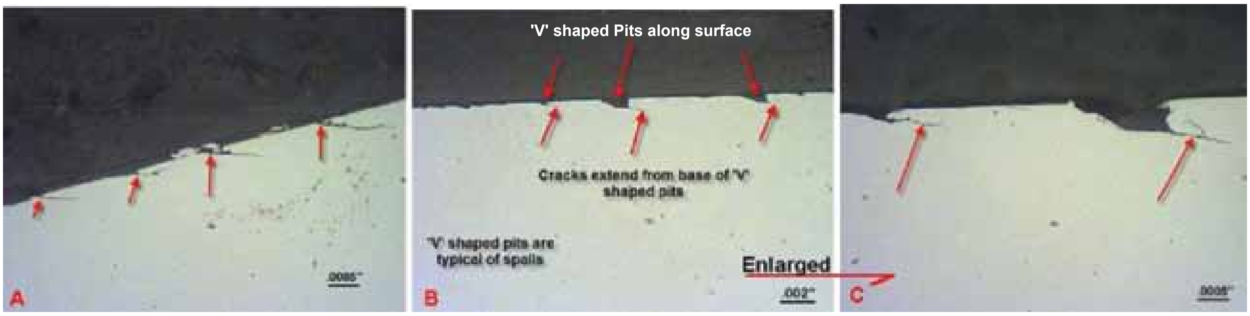

Figure 11—Small cracks propagating from spalls shown in Figure 9.

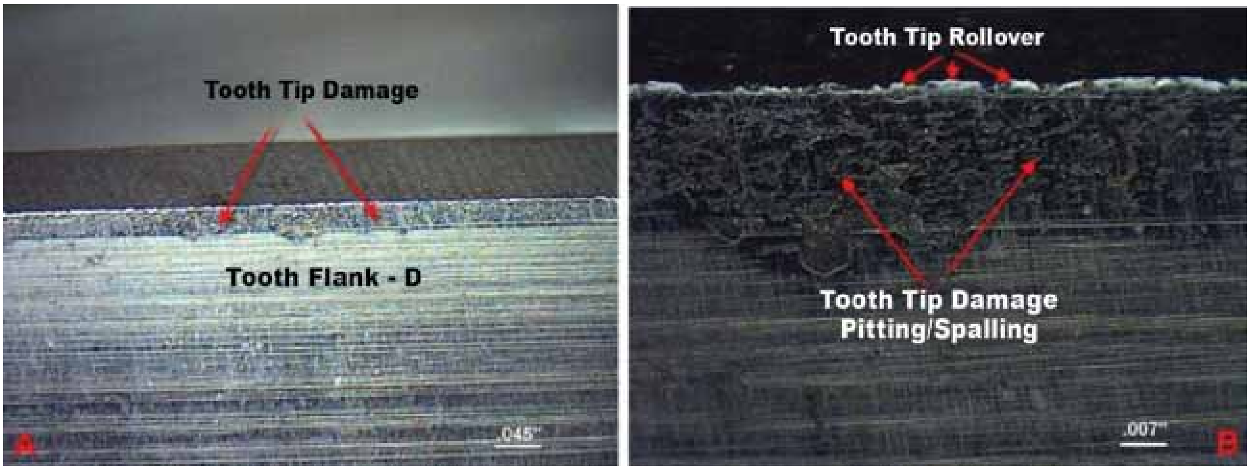

Figure 12—Micropitting at the tip of a gear tooth due to inadequate profile modification.

lar-shaped spalls that are not readily apparent through visual examination (Fig. 9A), but are visible with some additional magnification (Fig. 9B).

As the spalls continue to initiate and grow, they propagate by a crack mechanism shown in Figure 10. While these cracks are small, over time they progress and result in larger spalls occurring on the tooth surface. Continued propagation of these cracks into the body of the tooth (Fig. 11) led to the tooth fracture failures necessitating the gear's removal from service.

Micropitting also very often occurs when the amount of involute modification provided at the tips and flanks of a mating pair of gear teeth is inadequate to compensate for the deflections that occur under load. In this case, a very fine line of micropitting occurs on the tips of the teeth on one member and on the flanks of the mating member, very close to the lowest point of contact on the tooth. The appearance of this type of micropitting, shown on the tip of one tooth in Figure 12, is slightly

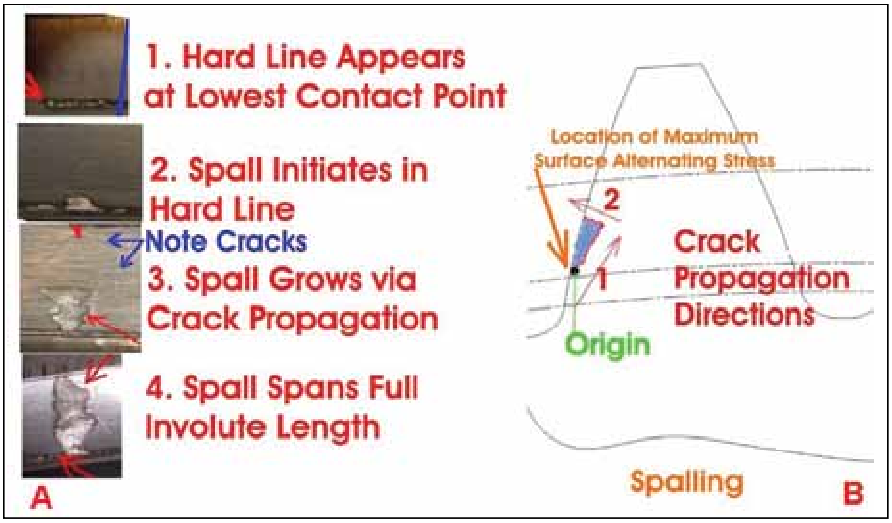

Figure 13—Initiation of a spall in a line of micropitting (the "hard line").

different from that typically observed on the tooth flanks in general, but the basic failure mechanism is quite similar.

A similar line of micropitting will be observed on the flank of the mating gear. This latter damage is often referred to as a "hard line." The presence of the hard line in the lower dedendum portion of the tooth—where the bending stresses are quite high—poses a particular danger of tooth fracture. The mechanism by which this occurs is shown in Figure 13.

The spalls progress from the hard line (Fig. 13A) via cracks that initiate at or near the surface in the micropitted region, then extending into the gear tooth body, until a piece breaks away

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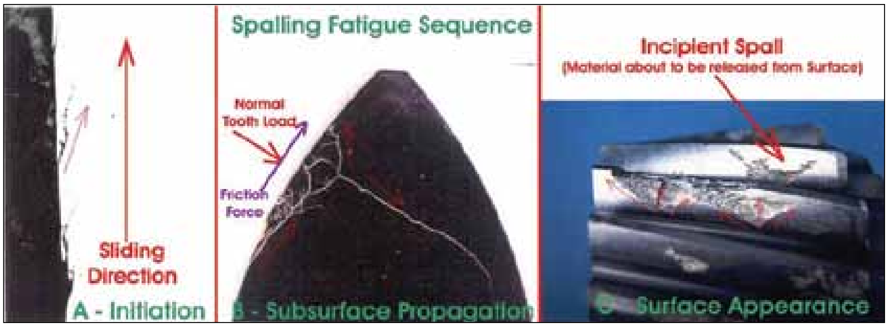


Figure 14—Micropitting-induced spall progression leading to a tooth bending fatigue fracture failure.

Figure 15—Partial tooth fractures resulting from spall crack progression.

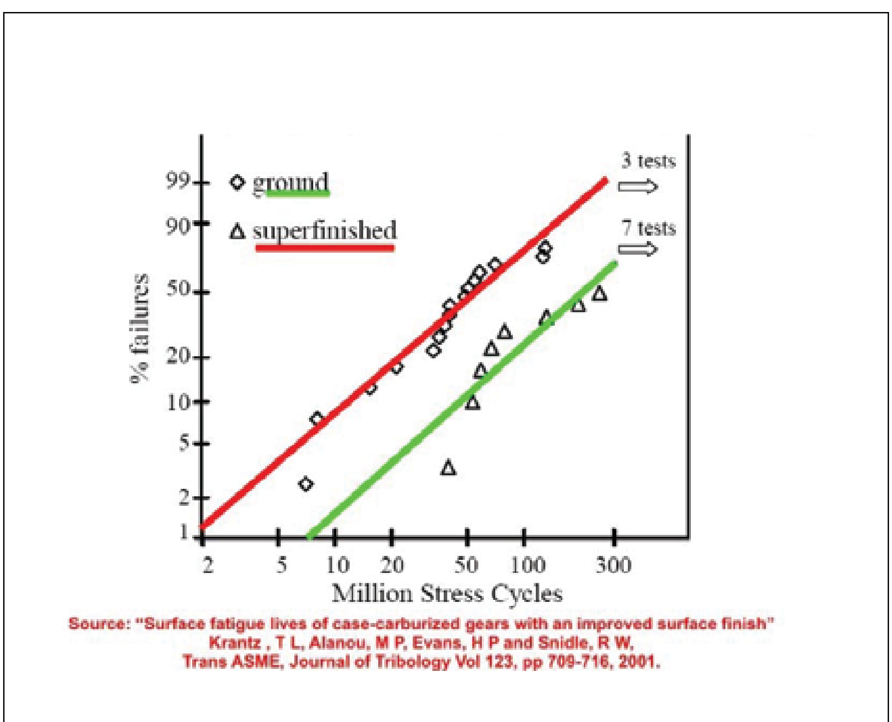


Figure 16—Results of micropitting fatigue testing on ground and superfinished gears.

from the tooth surface. This crack mechanism is shown schematically (Fig. 13B) and in sequence (Fig. 13A.)

The Profile Modification Connection

As noted, micropitting is often thought of as being related solely to lower-speed operation. This is not true. But the mechanism of the micropitting-induced failure takes on a somewhat different appearance. For higher-speed gears—especially those which experience significant tooth deflections—if the profile modifications (i.e., tip and/or flank modifications) are not sufficient to prevent hard contact near the extremes of contact (at the tip and flank of the tooth in the profile direction), the micropitting often first appears in the form of the very narrow hard line shown in Figure 12. Because this region is in an area of already very high tooth bending stresses—which are themselves already exacerbated by the very high tooth loading on the tooth profile due to the deflection- induced tip contact—very large spalls can occur very quickly, without the spread of micropitting, over even a large portion of the tooth profile.

The real danger in this mechanism is the fact that it occurs in an area of high bending stress. It is thus very likely that one of the spall cracks will progress through the tooth body, causing a tooth bending fatigue failure (Fig. 14).

The initial spall cracks (Fig. 14A) are rather small, and initiate at or near the surface. As these cracks progress, they result in rather large spalls—becoming apparent on the gear tooth surface (Fig. 14C)—since the cracks are initiating at the surface and progressing into the body of the tooth in a relatively short time. One or more of the cracks will progress through the tooth body (Fig. 14B).

When a crack progresses through the tooth body, partial tooth fractures (Fig. 15) will result. But unlike the fractures that occur due to extensive pitting damage, spall-induced fractures are likely to quickly occur after even a small amount of spalling has occurred.

The large spalls shown in Figure 14C all initiate very low on the tooth profile in a region well below the region of single tooth contact (in the transverse plane) where the tooth loads should be very close to zero. The high loading in this region at the tips of the teeth is due to inadequate tooth profile modification, thus rendering the load at engagement and disengagement to be very high. Because of the large spalls, such micropitting-induced failure modes are much more serious than those in which micropitting gradually destroys the tooth profile. This is due to the relatively quick progression of cracking into the tooth body and the larger partial—and often total—tooth fractures that ensue.

Sliding Velocity, Friction and Finish

Despite the absence of a clear explanation for micropitting phenomena, it is clear that there are several major factors that contribute to the occurrence (or non-occurrence) of this failure mode. The literature provides indirect evidence that, in addition to basic loading and elastohydrodynamic film conditions, sliding velocity, friction coefficient and tooth surface finish (which is certainly interrelated with both friction and sliding as well as the film thickness) are all major factors.

For example, testing conducted by Krantz, et al., found that the micropitting fatigue life of carburized and ground gears was improved quite measurably by superfinishing the gears after grinding. A sampling of the data from that work (Fig. 16) clearly shows this effect for the gears tested. The testing was accomplished with gears that were otherwise identical, thus the life improvement shown can be attributed to the application of the superfinishing process.

Conclusion

As we have seen from this discussion, the anatomy of a micropitting-induced tooth fracture failure is a somewhat complex event that may take many forms. The authors hope that this short discussion of the general nature of this process helps designers to better understand this mechanism, thus permitting them to successfully design against its occurrence in real-world applications.

Steve Cymbala *was a 34-year employee of the Boeing Company where he held the position of staff engineer with the CH-46 Drive Systems Group at the Philadelphia Integrated Defense & Space Group until his retirement in 2003. He joined the Boeing Vertol Division in 1966 as a mechanical engineering technician in the Model CH-46 Equipment Group where he supported design efforts of the various equipment projects, most notably the Rescue Hoist personnel retrieval. In 1968, he transferred to the CH-46 Drive Systems Group where he supported design and sustaining engineering efforts of the CH-46 helicopter transmissions and shafting until his departure from Boeing in 1970. That year, Cymbala accepted a design engineer position with General Technical Services. While there, he was responsible for all mechanical aspects of a space lab-bound biological experiment—Arabidopsis—sponsored by the University of Pennsylvania. In 1973, he returned to Boeing where he resumed his position in the CH-46 Drive Systems Group. Cymbala has served as a senior drives engineer for Drive Systems Technology, Inc. since 1976, performing complete design functions, as well as client drawing reviews. He also performs field gearbox failure investigations. He has co-authored three technical papers that have been presented at the Mill Gearing Technology Symposium, American Gear Manufacturers Association Fall Technical Meeting and Association of Iron & Steel Technology (AISTech) Technical Meeting.*

Ray Drago, chief engineer of Drive Systems Technology, Inc. *is active in all areas of mechanical power transmission. These activities include the design and analysis of drive systems for such diverse areas as large, high-speed paper, printing and cardboard machinery; commercial marine drives; heart pumps; large oilfield valves; high-speed cable climbing devices; high-speed gas turbine/generator sets; special automotive racing gearboxes; artificial limbs; mine shaft hoists; air- and water-cooled condensers; miniature gear motors (120 in-oz torque range); automatic bolt torquing devices; very large mining and mill gears; municipal and industrial water and waste water processing system drives and small private helicopter conversions (piston to turbine engines).*

Roy J. Cunningham *earned a master's degree in materials–metallurgical engineering from Drexel University in 1970 and a bachelor's degree in metallurgical engineering from the Drexel (University) Institute of Technology in 1967. He possesses more than 35 years' experience as both professional engineer and engineering consultant, beginning at Boeing Vertol Co. (1967–1973). From 1974–1991, he worked at Boeing Vertol Company as senior staff metallurgical engineer. From 1991 until his retirement in 2000, he worked at Boeing Helicopter Company, serving as senior manager-materials engineering. Programs he worked on included the Chinook, Sea Knight and V22 Osprey aircraft, the Comanche helicopter and JSF aircraft. Cunningham has also served as subcommittee chairman of the Penn State (State College) ARL Advanced Gear materials program for the development and testing of advanced gear materials. He holds one patent and has served on a number of AGMA and other association committees. Cunningham has also produced some 20 technical papers and presentations.*

Gear Applications

ALL THE RAGE AT WINDPOWER 2010

Capitalizing on a burgeoning new technology where gears are of great import, the gear community gathered en masse at the American Wind Energy Association's Windpower Expo 2010.

Dallas hosted some 20,000 visitors for AWEA's Windpower 2010 show, the largest conference for wind in the world (Courtesy AWEA).

Some 20,000 attendees came to Dallas to see the latest wind energy trends from almost 1,400 exhibitors over an expo space spanning six football fields. Windpower is the largest energy trade show in America and the worlds' largest wind energy conference.

Some of the familiar gear industry faces exhibiting included GE Drivetrain Technologies, Hansen Transmissions, Gleason Corporation, Brad Foote Gear Works, Fairfield Manufacturing, Ingersoll Cutting Tools, Moventas, Liebherr, Romax, Winergy Drive Systems and ZF Services North America. Following is a summary of what a few gear industry exhibitors had on display.

Gleason Corporation (*www.gleason.com*). Wind turbine gears produced by Gleason gear production machines and cutting tools are estimated to supply over 50 percent of wind turbines worldwide. The company displayed examples of the Opti-Cut family of indexable carbide-insert milling, hobbing and shaping cutters, which are designed to reduce wind power gear cutting costs by up to 50 percent. Visitors to Gleason's booth also learned about the series of quick-change workholding equipment for large production machines, such as the Gleason X-Pandisk fixture system, which automatically aligns workpieces weighing up to 2,000 kg to reduce changeover time by up to 70 percent.

Klüber Lubrication (*www.kluber-solutions.com/wind*). The Klüberplex BEM 41-141 is a beige grease that features a special blend of base oil and additives to cover the varying lubrication requirements of the individual bearing applications within wind power stations. These include pitch and yaw bearings (high stresses, oscillations, vibrations), main bearings (low rpm, high stresses, vibrations), and generator bearings (high rpm and temperatures).

Also on display was the Klüberplex AG 11-462, which is a gear grease that provides adhesion and protection against high loads and corrosion. The white grease lubricates the control gears for pitch and yaw systems while reducing the risk of migration inside the nacelle and onto the tower.

Ingersoll Machine Tools (*www.ingersoll.com*). In a major diversification of its activities, Ingersoll introduced two product lines specifically designed for the wind industry, supported by a $5 million grant awarded through the Green Industry Business Development Program, a component of the Illinois State's Energy Plan, administered by the Department of Commerce and Economic Opportunity and funded by the American Recovery and Reinvestment Act. According to Tino Oldani, president and CEO, "Ingersoll's activities are tailored to meet the new manufacturing requirements of the wind power generation industry and foster an evolution that will propel the U.S. manufacturing in a leading position in the global market."

The MasterWind Lean Manufacturing Center is a large, multipurpose milling machine that is introducing lean machining processes for the large wind components: gearboxes, hubs, upper and lower plates. Nacelles will be completely machined in one setup with cost reduction and improved quality and process reliability. The first MasterWind will be in operation in the third quarter 2010 from Ingersoll's headquarters in Rockford, IL. The other major product funded from the grant is a Wind Blade Demonstrator for the automation of blades production.

Sage Oil Vac (*www.sageoilvac.com*). The Gear Oil Exchange System for wind turbines features a flush system that improves fluid changes on gearboxes hundreds of feet above the ground, which can be operated from the ground. The unit can deliver ISO 320 viscosity grade gear oil at a rate of 15–22 liters (4–6 gallons) per minute while used gear oil can be vacuumed directly from the tower gearbox at a rate of 4–8 liters (2–4 gallons) per minute.

The flush system has a 454 liter (120 gallon) tank with a 100.5 meter (330 foot) hose, hose reel and pump, and it allows operators to winch the used oil hose, fresh oil hose and flush fluid hose up at the same time. The flush system works in conjunction with the Gear Oil Exchange System's standard operating features. It is available in skid, open trailer or enclosed trailer configurations. The system features two 946 liter (250 gallon) or 1476 liter (390 gallon) tanks. Longer hose lengths are available for taller towers.

Brevini Wind (*www.breviniwind.com*). On display by Brevini Wind was its portfolio of pitch and yaw drives and glimpses of its main drives under design. The company offered updates on its ongoing investment in a new production plant in Yorktown, IN, which will manufacture a complete range of main gearboxes for wind turbines ranging from 0.9 MW to 3.5 MW. Phase one of the $50 million investment will have capacity for 1,000 main gearboxes a year, which will expand to up to 2,000 main gearboxes a year. Production is scheduled to begin in the fourth quarter of 2010, and job opportunities were the buzz for Brevini, looking to fill 450 jobs in Indiana. According to Jacopo Tozzi, Brevini Wind president, "So this will be a gradual buildup of employees that will last for the next three or four years."

Brevini also expressed great optimism for the market potential in wind energy. "We are preparing ourselves for a robust market around the corner. We have the wind, we have the technology and, thanks to the support of the state of Indiana, the local authorities and the U.S. Department of Energy, we have the opportunity," says Renato Brevini, president and founder of Brevini Group. "That is why I am absolutely confident that the U.S. wind market will be the biggest in the world, and Brevini Wind will be a major player."

Parker Hannifin Corporation (*www.parker.com*). A new lubricating system from Parker Hannifin is a turn-key solution for wind turbine gearboxes. The complete system package includes pumps, filters, coolers, tanks, sensors and piping integrated for installation directly to the gearbox. The system includes manifold block lubricating filters and the icount PD for monitoring the condition of the system oil. The design addresses the filtration challenge of high viscosity, up to 30,000 cSt, oils experienced during wind turbine startups in the harshest environments.

Liebherr (*www.liebherr.com*). As a system supplier, Liebherr can provide bearings as well as drive units and control technology. The harmonization of its components was demonstrated by a powered rotor blade adjustment system consisting of the Liebherr DAT 300 planetary gear and a two-row interior-toothed KUD 128 four-point bearing.

The DAT 250 rotary drive with angle transmission was designed for the blade adjustment of a 2 MW system, and the angle format serves as a space-saving arrangement. The DAT 400 is used for the azimuth adjustment of a 3 MW system and features a compact design combined with low weight. Liebherr emphasized how it manufactures the teeth arrangements on the large roller bearings and gear and transmission systems on teeth milling and shaping machines of its own brand name.

Bonfiglioli (*www.bonfiglioliusa.com*). The focus for Bonfiglioli is fully-integrated systems, and on display at Windpower 2010 was its full range of products for wind businesses: gearboxes, motors and inverters; and specifically, the VER/S regenerative active front end (AFE), 700T Series yaw and pitch drive for wind turbines and the ACTIVE solution control drive.

As part of the Bonfiglioli regenerative system, the VER/S AFE is the first of two stages that transfer energy to the grid connection as an application demands. The VER/S regenerative AFE stage interfaces with the electrical grid while the ACU vectorial Field Oriented Control (FOC) stage provides active current control of the current from the permanent magnet synchronous generators (PMSG) in the gondola.

The 700T Series yaw and pitch drive controls functions like yaw and pitch drives and are used in the latest state-of-the-art wind turbines. The 700T series planetary speed reducers feature flange mount, output shaft: splined or with integral pinion, rugged construction, high torque capacity and output shafts supported by heavy duty capacity bearings.

The ACTIVE solution control drive features a full series of flexible solution drives, control for high performance and advantages in scalability and compact size.

"Our approach was well-received at Windpower 2010," says Greg Schulte, president, Bonfiglioli USA. "We experienced very positive responses to our product lineup, and we were very pleased with our booth traffic. We will absolutely attend the event again in 2011 and are already hard at work preparing the solutions we'll introduce next."

Some of the many gear products on display at Windpower 2010 included (from top to bottom) the 700T Series yaw and pitch drive from Bonfiglioli, Gleason's Opti-Cut family of tools and the ACTIVE solution control drive also from Bonfiglioli.

June 27–30—PowderMet 2010. The Westin Diplomat, Hollywood (Ft. Lauderdale), FL. The 2010 International Conference on Powder Metallurgy and Particulate Materials is the main event of the powder metallurgy (PM) industry in North America. Over 170 worldwide industry experts will present the latest in PM and particulate materials. The technical conference consists of 34 sessions where three papers will be presented. The corresponding trade exhibition consists of 100 booths showcasing suppliers of PM processing equipment, powders and products. Special conference events include guest speakers, luncheons, Sunday evening's welcome reception and Tuesday evening's dinner and main social event. Attendance is open to powder metallurgists; educators and students; design, mechanical and materials engineers; technicians; production personnel; management and other persons interested in any aspect of PM, particulate materials and related technologies. For more information, visit *www.mpif.org/Meetings/2010/10_gateway.htm*.

July 12–16—Coordinate Metrology Systems Conference. World-Class Grand Sierra Resort, Reno, NV. The 26th annual Coordinate Metrology Systems Conference (CMSC) is organized by the Coordinate Metrology Society (CMS), the membership association for measurement professionals. This five-day event is the only North American conference that caters solely to professionals using portable 3-D coordinate measurement technology on manufacturing factory floors and in science laboratories. Attendees include expert and novice quality professionals, metrologists, manufacturing executives, scientists, students, teachers and more. In addition to white paper presentations, the conference also features workshops, standards seminars, user group meetings and networking events. For more information, visit *www.cmsc.org*.

July 26–28—Basic PM Short Course. Penn Stater Conference Center Hotel, State College, PA. This three-day course is designed for users of powder metal (PM) parts and those looking for an introduction to PM, to update knowledge on recent developments in PM, to broaden background in the field and to enhance advancement opportunities through expanding knowledge. Attendees do not need a technical background to benefit from this basic short course. It is designed for engineers, tool designers, product designers, metallurgists, supervisors, purchasing agents, technicians, managers, hands-on workers, administrators, quality control personnel or office personnel. Topics covered include the history of PM—including current and future developments, why PM is a viable method of producing metal parts, why use is widespread in industries, designing for PM, how metal powders are produced, different designs used in compacting tools, how sintering develops the functional properties, metal injection molding, secondary operations, MPIF standards, special tests for powders and more. Attendees receive over $400 worth of publications. For more information, visit *www.mpif.org/meetings/2010/2010_Basic_sc.pdf*.

August 17–18—NFPA Industry and Economic Outlook. Westin Chicago North Shore Hotel, Wheeling, IL. AGMA members are invited to join the National Fluid Power Association (NFPA) at the intersection of marketing and strategy for the Industry and Economic Outlook Conference. The event offers hard economic data and expert analysis along with additional focus into the technology breakthroughs likely to impact mobile and industrial markets. The conference includes analysis of markets critical to AGMA members and gear manufacturers: industrial, construction, heavy trucks and agriculture/farm machinery. Familiar past-AGMA speakers will provide macro-level analysis and forecasts, including Jim Meil, Eaton Corporation, Eli Lustgarten, ESL Associates and Alan Beaulieu, Institute for Trend Research. Prior to July 9, AGMA members can register for this conference for $750 ($850 after), by registering as "Invited Guest" at the conference website, *www.nfpa.com/Events/2010_IEOC_ProgramDetails.asp*.

Sept 13–15—Gear Failure Analysis Seminar. Big Sky Resort, Big Sky, MT. AGMA's Gear Failure Analysis Seminar examines various types of gear failure, including macropitting, micropitting, scuffing, tooth wear and breakage. The possible causes of these failures are presented along with suggestions on how to avoid them. Lectures are paired with slide presentations, hands-on workshops with failed gears and Q&A sessions designed to provide comprehensive understanding of reasons gears fail. Attendees are encouraged to bring their personal failed gears or photographs of them to discuss. The seminar aims to help solve everyday problems faced by gear engineers, researchers, maintenance technicians, lubricant experts or managers. For more information, visit *www.agma.org/events-training/detail/gear-failure-analysis-seminar/*.

Gleason-M&M Calibration Lab

COMPLETES A2LA ASSESSMENT

The Gleason-M&M Precision Systems' Calibration Lab has received accreditation to ISO/IEC 17025 following a successful recertification assessment by the American Association for Laboratory Accreditation (A2LA). This is the seventh consecutive year the lab has achieved this certification, and it has not been granted to any other lab for gear and spline measurement, according to Gleason's press release.

"Most of the lab's work involves calibration of master gears and spline gauges," says Edward Lawson, chief metrologist and program leader at Gleason-M&M. "Periodic recertification is important because normal wear and tear on these masters can lead to false rejection of production parts."

The lab also calibrates reference involute, lead and pitch masters that are used worldwide to calibrate and verify gear inspection instruments. The A2LA accreditation includes the Gleason-M&M Precision Field Service organization, which provides calibration services for all makes and models of gear involute profile and lead measuring instruments. Following ISO 18653 methods, this procedure involves estimation of U95 measurement uncertainty as the preferred method for instrument calibration and evaluation. Lawson says that measurement uncertainty methods are essentially equivalent to common SPC methods, except as applied to measurement operations. The resulting calibration report provides data that helps the user understand and give due consideration to the reliability of gear and spline measurements.

The Gleason-M&M Precision Systems calibration lab is the only A2LA-accredited lab in the United States for gear and spline measurement.

Gleason-M&M welcomes visitors to this facility in suburban Dayton, Ohio. Lawson says, "None of the lab's services are more important than sharing our experiences with customers."

For more information or to arrange a visit, call (800) 237-5433.

British Gear Association

ANNOUNCES TWO RESEARCH PROJECTS

The first of two ongoing research projects the British Gear Association (BGA) is working on focuses on reducing the micropitting wear rate and increasing the micropitting threshold stress in gears. The previous two phases of this project enable BGA consortium members to gain a better understanding of the micropitting phenomenon in gears. The next phase will concentrate on investigating the most influential variables linked to micropitting, using back-to-back rig testing. Key areas for investigation include surface engineering (coatings, superfinishing, shot peening), surface texture, lubrication and materials.

The second BGA project focuses on materials for enhanced gear bending fatigue performance. This project is a continuation of a series of research projects aimed at improving the fatigue properties of gears, which dates back to the mid-1990s. The latest phase will be strongly materials-focused and will concentrate on evaluating gear tooth bending fatigue strength using single-tooth pulsator testing, as has been used in previous phases of the project. The variables to be investigated include the base steel type, heat treatment method and post heat treatment processing.

BGA is actively seeking additional consortium members. For further information about these projects, contact Andy Harry, at BGA, by phone: + (44) 01283 51 5521, or e-mail: *andy@bga.org.uk*.

Kahraman

PRESENTED 2009 ALUMNI AWARD

From left to right: E. Gordon Gee, Ohio State University president, Dr. Ahmet Kahraman, Joseph A. Alutto, provost, and Archie Griffin, president of the OSU Alumni Association.

Dr. Ahmet Kahraman was recently awarded the 2009 Alumni Award for Distinguished Teaching from the Department of Mechanical Engineering at The Ohio State University.

Kahraman joined Ohio State in 2003 after working at the University of Toledo as an associate professor and director of the Center for Gear Research. During his tenure at Ohio State, he has taught numerous courses on the dynamic behavior of mechanical systems. In addition, he serves as the director of the Gear and Power Transmission Research Laboratory. Prior to becoming a teacher, Kahraman worked for ten years as a researcher.

Award winners are nominated by current and previous students as well as their colleagues. Kahraman will receive a cash award, an increase to his base salary and will be inducted into the University's Academy of Teaching. His selection marks the second year in a row that a Mechanical Engineering faculty member has been honored with this award.

Carl Zeiss

OPENS WEST COAST TECH CENTER

Carl Zeiss Industrial Metrology celebrated the grand opening of the West Coast Tech Center in Irvine, CA on April 6–7. Set up as a production inspection facility with metrology systems in a support role, the two-day event offered visitors demonstrations on palletizing applications and investigative metrology work.

The official ribbon cutting ceremony took place April 6. "The goal in opening this 3,800-square-foot facility in Irvine, CA is to get closer to our customers in this region while providing local support in growing markets," says Drew Shemenski, manager of the West Coast Tech Center. "Not only does this facility allow us to offer traditional hardware support, but it can also help us focus on a higher level connecting machines together through software to manage inspection requirements and data."

The center offers a range of metrology technology including optical, touch scanning, CT X-ray and measuring software. It also has a variety of surface form and geometry systems, in-house measuring services, software training and application support.

Romax

APPOINTS CHIEF OPERATING OFFICER

Graeme Walford

Romax Technology Limited, a technical consultancy providing design and analysis services for gearboxes, bearings and drivetrains, announces the appointment of Graeme Walford to the position of chief operating officer. Walford, who assumed his position at the beginning of 2010, will support CEO Dr. S.Y. Poon with his future ambitious growth plans for the company. Walford graduated from Loughborough University with a degree in mechanical engineering. He began his career with Rolls-Royce before moving to MascoTech as engineering director. In 1999, Walford joined GKN Driveline where he set up the new GKN Torque Technology business unit.

"There are tremendous opportunities for Romax, not only within its core business streams, automotive and wind energy, but in many other new areas," Walford says. "I hope that through the experience and knowledge I have gained throughout my career, I can help Romax in the next phase of their development, maintaining leadership throughout their core business, but also spreading expertise into new areas, which I believe is the next big step for Romax in the future."

U.S. Gear Tools

BRINGS TWO MANAGERS ON BOARD

Adam Lambert

U.S. Gear Tools, Inc. recently announced that Adam Lambert has joined the company as its new vice president and general manager. Lambert, a longtime senior manager with the Anderson Cook Company, has more than 25 years of spline rolling machine manufacture, tool design and manufacturing management experience.

"Adam brings us the background and experience we were looking for to manage and operate our tool design and manufacturing facility located in Swannanoa, NC," says George Simon, president of U.S. Gear Tools. "While some in our market are retrenching and shrinking, we are aggressively moving to expand our presence and capabilities in the global marketplace for spline and thread roll tooling."

U.S Gear Tools designs and manufactures precision tooling for the spline and thread rolling marketplace. It also designs and manufactures gear hone tooling and gear shaver tooling. U.S Gear Tools and its sister company Roto-Flo, a spline and thread roll machinery company, combine to supply integrated solutions to the spline and thread rolling industries throughout the world.

Mike Callesen has also joined U.S. Gear Tools as sales and marketing manager. Callesen has over 30 years' experi-

continued

ence in the sales and application engineering of spline and thread rolling tools and machines, serving most recently as vice president of sales for the Anderson Cook Company. He will be located at the parent company's headquarters on Hoover Road in Detroit.


Mike Callesen

"We are excited to have attracted one of the most experienced and notable sales executives in this industry," Simon says. "Mike is widely known throughout the industry for his comprehensive, on-the-floor understanding of the spline and thread rolling process, a critical aspect of selling an engineered product such as spline and thread roll tooling. This hire, along with other recent investments in personnel and equipment, further supports our strong commitment to serving the roll forming marketplace by building a world-class organization for spline and thread roll tools and machinery."

Solar CEO

RECOGNIZED AS SMALL BUSINESS EXPORTER

The U.S. Small Business Administration's (SBA) Philadelphia District Office awarded William R. Jones the 2010 Eastern Pennsylvania and Region Three Small Business Exporter of the Year. Jones is chief executive officer of Solar Manufacturing Inc. of Souderton, PA.

Jones was nominated for the award by Patricia J. Kratz, president of Univest National Bank and Trust Co. The award is presented on a district, regional and national level. Region Three consists of Pennsylvania, Delaware, Maryland, Virginia, West Virginia and Washington, D.C. National Small Business Week was observed in Washington, D.C. May 23–25. It is an annual recognition of the small business community's contribution to the American economy.

Dave Dickson, SBA's Philadelphia district director, presented the award to Jones on May 6, at the annual SBA Day at the Ballpark. "Every year, the SBA's Philadelphia District Office awards the Small Business Exporter of the Year award to an individual who uses creative overseas marketing strategies and effective solutions to export-related problems to grow their business," Dickson says. "As this year's award winner, William Jones more than appropriately joins the roster of award winners from previous years and across the country whose enterprising initiative has benefited not only their own business and employees, but the community at large. With this award, the SBA applauds Mr. Jones for his exemplary contributions to this nation's business community and economy."

AFC-Holcroft

RELOCATES EQUIPMENT

The dismantling, relocation and reinstallation of multiple pusher furnace lines and companion equipment was ordered by an automotive supplier customer of AFC-Holcroft's. The equipment will be moved from the United States first to AFC-Holcroft's licensee MATTSA, in San Luis Potosi, Mexico, where it will be cleaned, inspected, rebuilt, cold-cycled and repainted before being sent to the customer's facility in Mexico.

A total of three furnaces plus companion equipment and accessories will be relocated in this project. "A move of this scope is not something to be taken lightly," says Mark Johnston, sales engineer at AFC-Holcroft. "There are, for example, international logistical and import/export complications, as well as language differences to take into consideration. AFC-Holcroft has a great deal of experience with these types of moves, having done many in recent years. Having local support in Mexico from our partner MATTSA will benefit us greatly in this project."

Several new pieces of equipment are part of the order, including loaders, pre-washers, preheat furnaces, 13,500 cfh E-Z Series Endothermic Generator, oil cooling systems and other accessories. AFC-Holcroft will provide formal class-

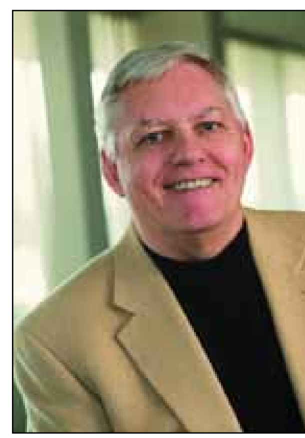
continued

room instruction and basic operator training to the customer's operators, maintenance and administrative personnel. The operators will be involved in the start-up and dry-out phase of the reinstallation. The relocation process began in March 2010 and is scheduled to be completed by December 2010.

SAE

AWARDS OUTSTANDING CONTRIBUTION

Jack Champaigne, president of Electronics Inc. and publisher of *The Shot Peener*, received an Outstanding Contribution Award from SAE International at the 2010 SAE World Congress in Detroit in April.



Jack Champaigne

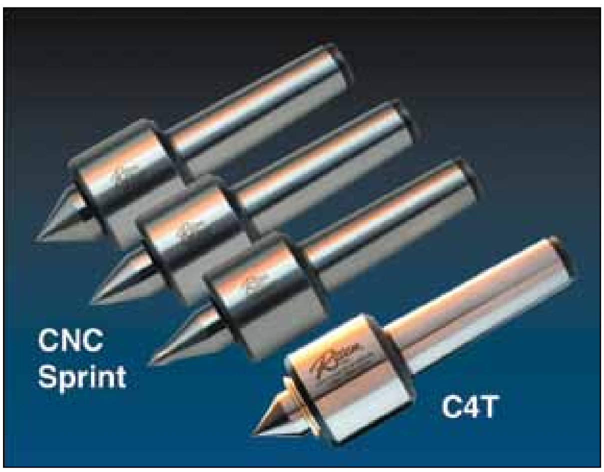
The annual award was established in 1953, and it recognizes outstanding service and leadership in the technical standard boards of the organization for engineering professionals in automotive, aerospace and commercial vehicle fields.

Champaigne has been a member of the SAE International Materials, Processes and Parts Council since 1986, and he currently serves as committee chairman of the SAE Surface Enhancement Committee, which is responsible for developing and revising surface treatment standards used in the manufacture of metal components. Under his leadership, the committee has updated and created metal surface treatment standards that address rapid advances in technology and special applications for the automotive industry.

Electronics Inc. (EI) manufactures and distributes products that improve the quality and control of shot peening.

Applied Technical Products

REPRESENTS RITEN IN MID-ATLANTIC



Riten workholding products are now represented in the Carolinas, Virginia and West Virginia by Applied Technical Products Inc. (ATP), a manufacturer's representative agency established in 2002.


Tom Wright

ATP represents six cutting tool manufacturers and four workholding products companies. The agency is headed by Tom Wright, who has more than 25 years of sales and training experience in the metalworking industry. He has held outside sales positions with several machine tooling companies and has extensive knowledge of current machining technology. He operates from southwestern Virginia and can be reached at *twright4321@comcast .net.*

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Metal Finishing News	79	(212) 633-3100	*metalfinishing@elsevier.com*	*www.metalfinishing.com*
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Bacteria Turns Microgears in Bio-Inspired Experiment

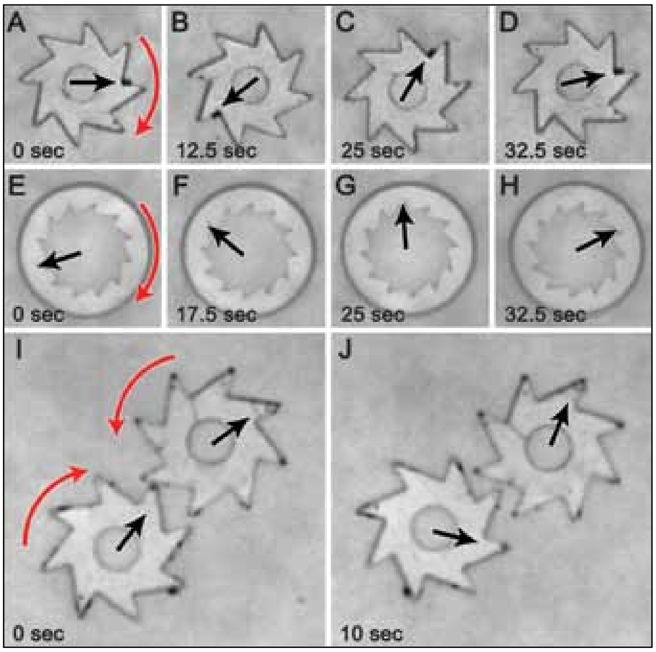
Who knew what a few hundred bacteria could do with a little cooperation? Andrey Sokolov of Princeton University, Igor Aronson from the Argonne National Laboratory and Bartosz Grzybowski and Mario Apodaca from Northwestern University found out after placing microgears (380 microns long with slanted spokes) in a solution with the common aerobic bacteria *Bacillus subtilis*. The scientists observed that the bacteria appeared to swim randomly but occasionally collided with the spokes of the gears and turned them.

"In our experiment, the gears turned for about five to seven minutes, then the bacteria runs out of food, film evaporates, etc." says Igor Aronson, an Argonne materials scientist. "In principle, the constant flow of a micro-fluidic device in rotation can be sustained over much longer time."

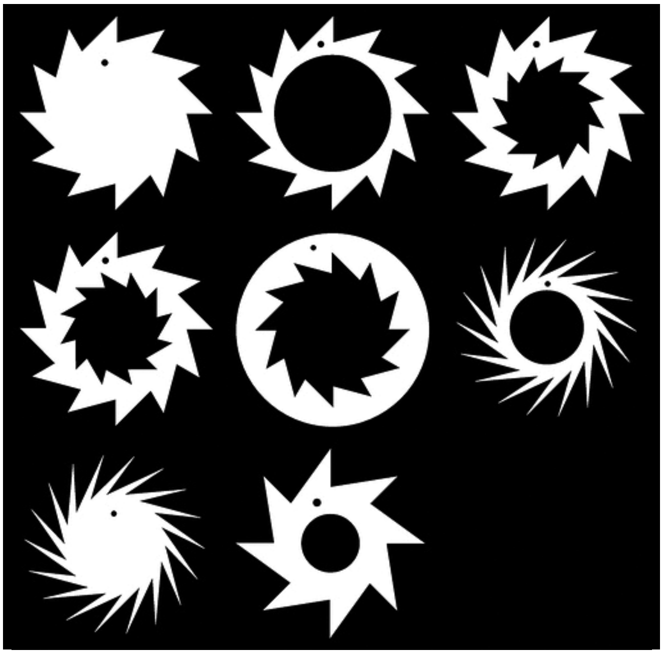
The ability to harness and control the power of bacterial motion is an important requirement for further development of hybrid mechanical systems driven by microorganisms, according to Aronson. When multiple gears are placed in the solution with the spokes connected, the bacteria will turn both gears in opposite directions, causing the gears to rotate in synchrony for long stretches of time.

"There exists a wide gap between man-made hard materials and living tissues; biological materials, unlike steel or plastics are 'alive,'" Aronson says in an Argonne Laboratory press release. "Our discovery demonstrates how microscopic swimming agents, such as bacteria or man-made nanorobots, in combination with hard materials, can constitute a smart material, which can dynamically alter its microstructures, repair damage or power microdevices."

The speed of the gears can be controlled through the manipulation of oxygen in the suspended liquid. By decreasing the amount of oxygen, researchers can slow down the gears' movement while eliminating the oxygen halts the movement entirely. If the oxygen is reintroduced, the bacteria "wakes up" and begins swimming again.



This diagram tracks the movement of the gears turned by the bacteria (courtesy of Argonne National Laboratory).



Silhouettes of several gear designs that could be turned by *Bacillus subtilis* bacteria (courtesy of Argonne National Laboratory).

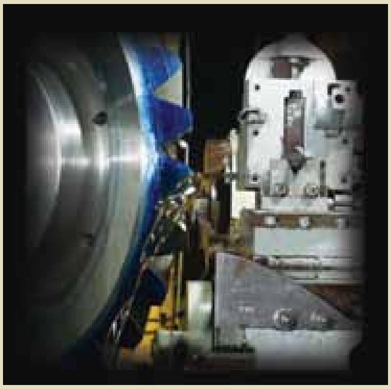
Bacillus subtilis is a bacterium commonly recovered from water, soil, air and decomposing plant residue and does not possess traits that cause disease. It is not considered pathogenic or toxigenic to humans, animals or plants. But it may hold the key in the future for bio-inspired materials that can be controlled, manipulated and used as energy.

"The fact that bacteria, working together, can power gears million times heavier than themselves was one of the most significant findings in the experiment," Aronson says.

In addition to its energy use, the discovery could be developed as a natural means to repair damage. The bacteria possess nutrients and skin tissue qualities that are able to adapt to the environment and heal themselves to a certain extent.

The research at Argonne was supported by the Department of Energy's Office of Science (SC), and the work at Northwestern University was supported as part of the Non-Equilibrium Energy Research Center (NERC), an Energy Frontier Research Center also funded by SC.

Before Argonne National Laboratory began powering gears via bacteria, its researchers have helped millions of travelers fight jet lag, invented a method to help save heart attack victims by injecting their lungs with a slurry of fine ice crystals and helped prove that Beethoven suffered from lead poisoning. Argonne scientists, including the founder of the laboratory, Enrico Fermi, have won three Nobel Prizes in physics. For more information on this and other Argonne research projects, visit *www.anl.gov*.



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