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MAY/JUNE 2005

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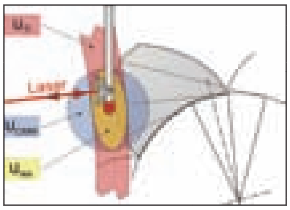

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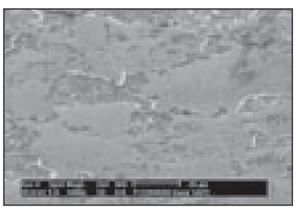

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GEAR TECHNOLOGY

The Journal of Gear Manufacturing

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Quietly Moving Mountains

A good friend was recently honored at the AGMA Annual Meeting. Marty Woodhouse received the AGMA's Lifetime Achievement Award, and I can't think of anyone more deserving.

Marty's efforts were recognized at the meeting, and he'll no doubt be mentioned in the AGMA's *Gear Industry Journal*. As his impact on the industry has been enormous, I'd like to recognize him here as well for his contribution.

I've known Marty for the better part of 40 years. He started his career at Fuller Transmission, but he's spent most of his professional career—beginning in 1968—as the face of Star Cutter Co. For many years, he has been its VP of sales.

Chances are, if you know Star Cutter, you know Marty. For his entire career, he's tirelessly traveled the world, representing his company at trade shows and on sales calls in Europe, China, India and Japan. And I'm not just talking about the big shows like IMTS and EMO. Every year, Marty has set up his booth at numerous smaller shows. Year after year after year, Marty has been in a car, on a plane, everywhere.

Many of you who have spent your lives in sales probably feel the same way. But in addition to the dedication he's shown his company, Marty Woodhouse had a vision of how the industry could work better. Through his perseverance and hard work, he's been able to make changes happen for the better. Marty has been a true leader of the gear industry, which is reflected in his dedication to and longtime involvement with the AGMA.

Thirty or forty years ago, the AGMA was a much smaller, more insular group than today, focused almost exclusively on its core membership, the gear manufacturers. Participation in the association by the suppliers was tolerated, but not encouraged. Marty was one of the first suppliers to the gear industry who broke into that club—for the betterment of the industry as a whole, as well as the gear manufacturers themselves.

Marty helped break down doors to get suppliers involved with the standards development process. Today, the machine and tooling people are very much a part of this process—as it should be.

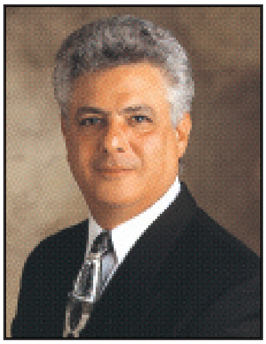
Over the years, Marty has served on a number of decision-making bodies related to the association, including the AGMA board of directors and its executive committee.

But perhaps nowhere has Marty's contribution been more evident than in his involvement with Gear Expo. He has been heavily involved with the planning and execution of Gear Expo since its beginning. Currently, Marty is chairman of the AGMA Trade Show Advisory Council, which helps guide the association in its trade show efforts. Those of you who have been going to the shows over the years can see how far it's come. In the early days of Gear Expo, the show included just tabletop exhibits, whereas today, it's an internationally recognized exhibition of the finest in gear machine tools and manufacturing technologies. A lot of the transformation of the show had to do with Marty.

In addition to his role in the industry, Marty has always been a good friend to me and to *Gear Technology*. About 22 years ago, I had an idea for an educational magazine specifically for the gear industry. At the time, there were a lot of naysayers who told me that the industry didn't need its own publication. But not Marty. He saw that what we were trying to do would help the industry, and he stepped up to become *Gear Technology*'s very first advertiser. He's been one of our biggest supporters ever since.

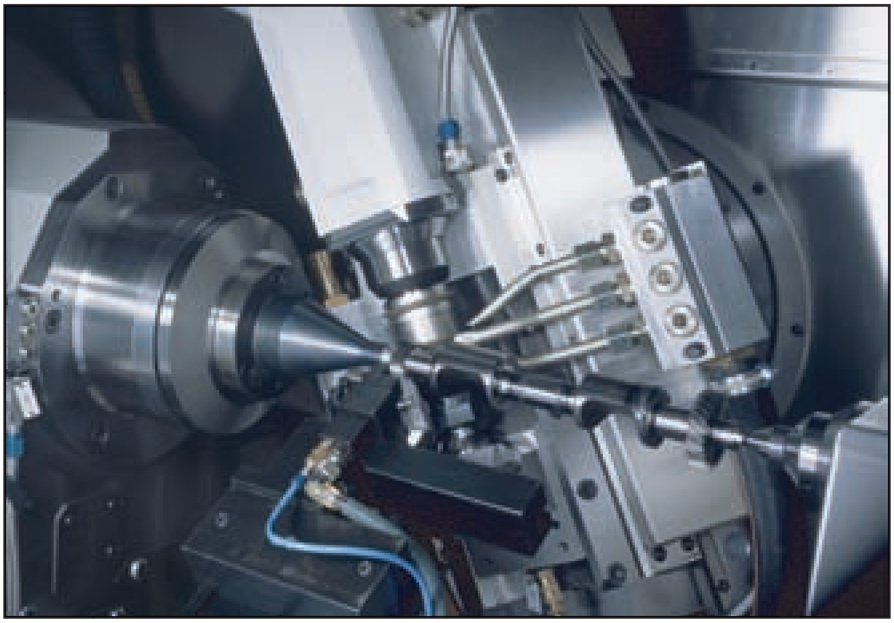
I know that Marty will be a little bit embarrassed by all of this attention. He's accomplished much, but he's never been one to toot his own horn. But he richly deserves the recognition for his many years of commitment, dedication and service to the gear industry.

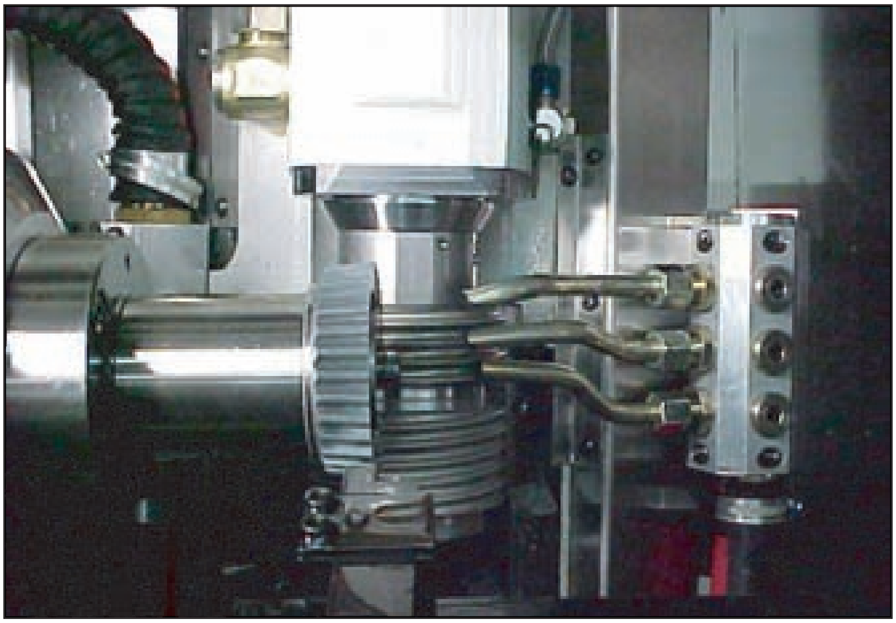
So, Marty, on behalf of *Gear Technology* and the worldwide gear industry, thank you for everything you've done. Your contribution has been enormous, and we wish you continued success.



Michael Goldstein, Publisher & Editor-in-Chief

New Hobbing/Grinding Machine from Gleason





The new P 90 G from Gleason was designed to fulfill a variety of job shop goals—from shortening lead times to increased flexibility to maintaining quality in harsh environments to occupying little floor space.

The machine can be used as both a hobber *and* a grinder. As a grinder, it can use either form wheels or threaded wheels.

"The main advantage of the new machine is its universality and high quality. Hobbing and grinding can be made on one and the same machine by the same operator," says Willy Häuptli, product manager at Gleason Corp.'s facility in Biel, Switzerland.

The machine is an upgrade of the company's P 60 and P 90 series of horizontal hobbing machines with a twist. It can be set up for gear hobbing, worm milling or gear grinding. While the P 90 G does have design aspects that are identical to its predecessor, like the headstock and hob head, its uniqueness can be found in its temperature stability and in the high speed range of its direct drive spindles, says Häuptli.

The P 90 G tool spindle operates at speeds up to 12,000 rpm and workpiece spindle operates at speeds up to 5,000 rpm. These high spindle speeds translate into shorter cycle times, Häuptli says.

"This is really the ideal platform for a grinding machine," he says. "Special adaptations for grinding have been made on the slideways, measuring systems and the sealing of the machine enclosure."

The machine controller incorporates use of a direct measuring system, which, according to Häuptli, is a highly accurate system that takes measurements on the slide.

Optimal arrangements are available for profile grinding or generating grinding with a worm-type wheel. The machine is designed to use non-dressable, CBN-plated grinding wheels.

According to Häuptli, the shorter cycle times and universality of the machine have been its main selling points. Though job shops are the most obvious beneficiaries of a product like this, its possible applications can reach industries like motor sports or aircraft.

Additional features include the P 90 G's small footprint—3.5 square meters—and its state-of-the-art Siemens CNC controller with Windows-based software interface and menu-assisted programming.

"Building this product from a proven base with proven parts by a motivated team makes it a reliable piece of production equipment from Day One," Häuptli sums up.

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A Leap in Gear Honing Productivity: Fässler's HMX-400

In May, a U.S. automaker will receive its first three HMX-400s, which are—at a minimum—50% faster than previous Fässler gear honing machines, says Roland Rütti, technical director for Fässler AG of Dübendorf, Switzerland.

"Today," he adds, "the gear honing process becomes an economical alternative to gear grinding."

Introduced in 2003, the HMX-400 was designed for automotive, truck, motorcycle and aerospace companies, as well as other businesses manufacturing high quality gears. In mid-2004, the first models were sold to companies in Europe's truck industry and America's automotive industry.

Fässler's latest gear honing machine can achieve cycle times of less than 30 seconds. Also, changeover times can be as little as three to five seconds, depending on the gear. According to Rütti, the cycle times—more than anything else—make the HMX-400 economical in high volume production.

The leap in gear honing productivity mainly results from two new features: a second workpiece spindle and direct drives for tool and workpiece spindles.

The machine's two workpiece spindles reduce both handling and honing times. While a gear is honed on one spindle, a second gear can be hydraulically clamped to the other spindle.

"With the HMX-400, you can machine in parallel where beforehand only sequential operation was possible," Rütti says.

Of the machine's nine axes, four use modern, dynamic direct drives. The four include hollow-shaft, linear direct drives for the tool and workpiece drives. The drives are used to meet demands for increasingly higher performance and machining accuracy from the honing process.

Also, the two workpiece spindles allow companies to automate the HMX-400 with a simple gantry loader system. Since introducing the machine, Fässler incorporated such an automated system, integrating it into the HMX-400's control system. The loader system is now a standard feature of the honing machine.

HMX-400 Technical Data	
Honing stone diameter	400 mm
Workpiece diameter, external honing	20–320 mm
Workpiece diameter, internal honing	50–350 mm
Maximum workpiece shaft length	400 mm
Machine dimensions (W x H x D)	2,200 mm x 2,150 mm x 3,000 mm or 7.2 ft. x 7.1 ft. x 9.8 ft.
Weight	8,500 kg or 9.37 tons
Maximum speed, honing stone drive	1,500 rpm
Maximum speed, workpiece drive	9,000 rpm
Slewing range, A-axis	+/– 45°
Slewing range, B-axis	+/– 10°

Moreover, with its spindles' drive system, the HMX-400 can perform single-flank honing that's process reliable. This ability allows for advantageous process strategies with certain workpieces, Rütti says.

The honing machine also saves time via its new integrated dressing roller. The dressing tool is diamond-coated and dresses honing flanks in the conventional manner, but it doesn't require clamping on a workpiece spindle.

"A fixed universal dressing ring, mounted on the tailstock, for dressing the inner diameter of the honing stone reduces the cost per workpiece and the dressing time," Rütti says.

The HMX-400 can make crowning and flank modifications, too. The maximum amounts of the modifications depend on gear geometry and tool design, but the minimums are 20 microns for crowning and 25 microns for flank modifications.

Also, the honing machine can improve pitch errors via its controls and direct-driven workpiece and tool spindles. Rütti explains that correcting pitch error depends on gear geometry, stock removal, and tooth thickness variation of the premachined gear, but the HMX-400 can generally improve pitch error to between DIN quality classes 6 and 2. The range roughly converts to Q11–15 using AGMA quality standard 2000-A88.

The HMX-400's two workpiece spindles also allow for online cleaning without increasing cycle times. Gears can be spun to remove oil before being unloaded.

The honing machine uses a Siemens 840-D control, with a graphical operating panel. Some gear data must be entered, but the HMX-400 can use its Fässler software to automatically calculate remaining data via process curves and complex algorithms.

Moreover, the honing machine can automatically optimize many process parameters, helping operators run the machine well without detailed background knowledge.

The HMX-400 includes new sensors to constantly monitor honing and other machine functions. Possible errors are shown graphically to simplify trouble-shooting, and a built-in modem permits direct Internet transmission of data for error diagnosis.

The machine also has a tooling recognition system to monitor the use of honing and dressing tooling. The system can simplify dressing during a tooling change because the last process and dressing data can be saved. “These data help the customer to manage reorders or make the setup easier,” Rütti says.

He adds that as a finishing machine, the HMX-400 can improve gear quality an average of four DIN classes.

“Depending on the premachining and gear geometry, we can achieve up to DIN 2 quality,” he adds.

That quality roughly equates to Q15 using AGMA standard 2000-A88.

And higher quality offers benefits. “Honed gears produce less noise and have a longer use life than other gears due to their typical surface structure,” Rütti says. “The structure of the surface of a honed gear, which resembles a fish skeleton, facilitates the formation of a lubrication film surface from the tip of the flanks to the pitch diameter and thereby positively inhibits the development of noise.”

A standard version of the HMX-400 costs about $840,000, or about €650,000. The standard version includes two workpiece spindles, force control, a fixed dressing ring on the tailstock, an integrated automation system, a Siemens 840-D control, a B-axis for flank modifications or tapered gears, and an easy-to-use operator interface.

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The SDZ broaching machines from Stenhøj Hydraulik.

Push-Pull Concept for Precision Broaching

MVS Metform, a division of MacLean Vehicle Systems, has recently installed a new type of broaching machine for high volume machining of internal splines in gear blanks. Located in Savanna, IL, Metform expects this technology, from Stenhøj Hydraulik of Denmark, to help it control the lead error on its parts, a critical factor in keeping its auto industry customers happy.

Most modern broaching machines are designed to pull the broach tool through the part. In some cases, broach tools may be pushed through the workpiece. But this new machine, Stenhøj's SDZ model, uses a simultaneous push-and-pull technique designed to help keep the broach tool perpendicular to the part.

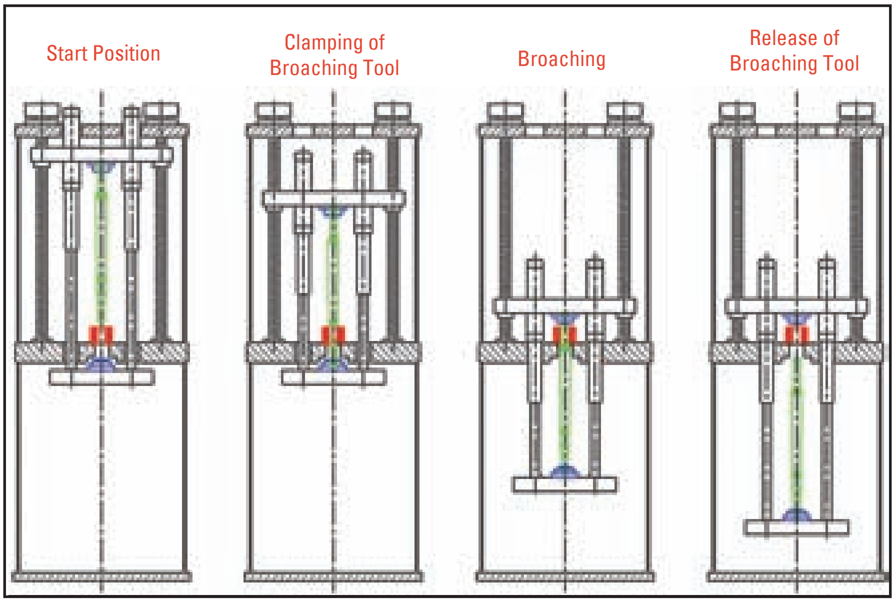
"The key unique factor of the machine is the push-and-pull bayonet collet system that actually very firmly controls the cutting action and the path of the broach tool," says Ken Nemec, president of Broachman LLC, Stenhøj's North American representative. "No other broaching machine has a system like this."

According to Nemec, the broach tool is held both top and bottom during cutting in hydraulically clamped collets. Those collets are mechanically linked so they move in unison.

"They're firmly being held and pushed and pulled simultaneously through the part, distributing all the power very evenly and keeping the broach on a firm, rigid path," Nemec says.

On a typical vertical broaching machine, Nemec says, nothing holds the top end of the broach, which can lead to tool movement on some parts.

For Metform, controlling such movement was a critical factor in



The patented push-pull broaching process from Stenhøj helps control lead error and improve tool life.

deciding on a broaching process.

"The most important feature of the Stenhøj Hydraulik broach machine is that the cutting force and drive mechanism are in alignment," says David Collier, product development engineer at Metform. "The push-pull feature helps maintain alignment of the tool to the part locator, for the full length of the cutting stroke. This helps hold the spline perpendicular to the locating face, which is a critical feature for our customer."

Controlling the lead error is critical for many broaching customers, Nemec says. "If the splines are straight up and down, the lead is good. If they have a tilt to them or an angularity to them, then it creates gearbox noise and premature wear in a gear, and that's what we're trying to avoid."

According to Nemec, the machine controls lead so well that even after heat treating, parts don't need any subsequent finishing operations. Often with other technologies, parts have to be hard turned or re-broached after heat treating. "This application makes both of those unnecessary," Nemec says, "because the lead error can be held so close."

Metform has been using the technology for more than a month. "So far, we have seen excellent results," Collier says.

Another important feature of the Stenhøj technology is that it helps increase tool life, says Nemec. The SDZ is an electromechanical machine, which results in smooth motion, as opposed to a hydraulically driven machine, which tends to be less smooth, Nemec says. "The hydraulic action almost acts like sandpaper on a broach. You can feel it when you touch a broaching machine. You can feel the bounce. That prematurely wears a broach tool."

In addition, because most broaching machines don't hold the tool as rigidly, that also affects tool life, Nemec says. "When it pulls off to one side or pulls off to the other, the broach tool gets uneven wear characteristics."

Between the smooth electro-mechanical motion of the machine and the way it rigidly holds the broach tool,

MVS Metform in Savanna, IL, recently installed a new Stenhøj broaching machine.

most customers can expect significantly increased tool life—in some cases double or more, Nemec says.

The machine at Metform is set up with two stations. In other words, it broaches two parts simultaneously. The SDZ machines can be set up for one, two or three stations.

All Stenhøj machines are equipped with an automatic shuttle table. The parts are placed on the table by an operator, robot or pick-and-place unit. The table shuttles the part into the machine, and then the tool is loaded and clamped both top and bottom. The part is broached, the tool is released and the part is shuttled out on the table for removal.

The broaching process is driven by planetary spindles, which, according to Nemec, are more accurate and rigid than ballscrews, which are commonly found on broaching machines. "The planetary spindle has virtually no backlash," Nemec says. "It is rated at having a one micron per foot backlash, which is virtually none."

The planetary spindles also have electronic error correction built into them, so the Stenhøj machine's twin spindles always rise and fall in unison. "Because they're using planetary spindles with a rigid drive system, the planetary spindles are always exactly lined up," Nemec says.

Also, the Stenhøj machines are equipped standard with a self-contained, maintenance-free coolant filtration system. "It makes maintenance a non-issue," Nemec says.

The Stenhøj machines are priced competitively, Nemec says. "We're right about in the middle of where the market is price-wise now," he adds. "When the euro and the dollar stabilize, we feel like we're really going to have an edge in the marketplace."

The Stenhøj machines come in a variety of sizes and configurations, with stroke lengths up to 72".

So far, the people at Metform are pleased with their results.

"The machine has performed well," Collier says. "It is very quiet and uses much less floor space than some other designs we considered. We are now anxious to study tool life to see if this also meets our expectations."

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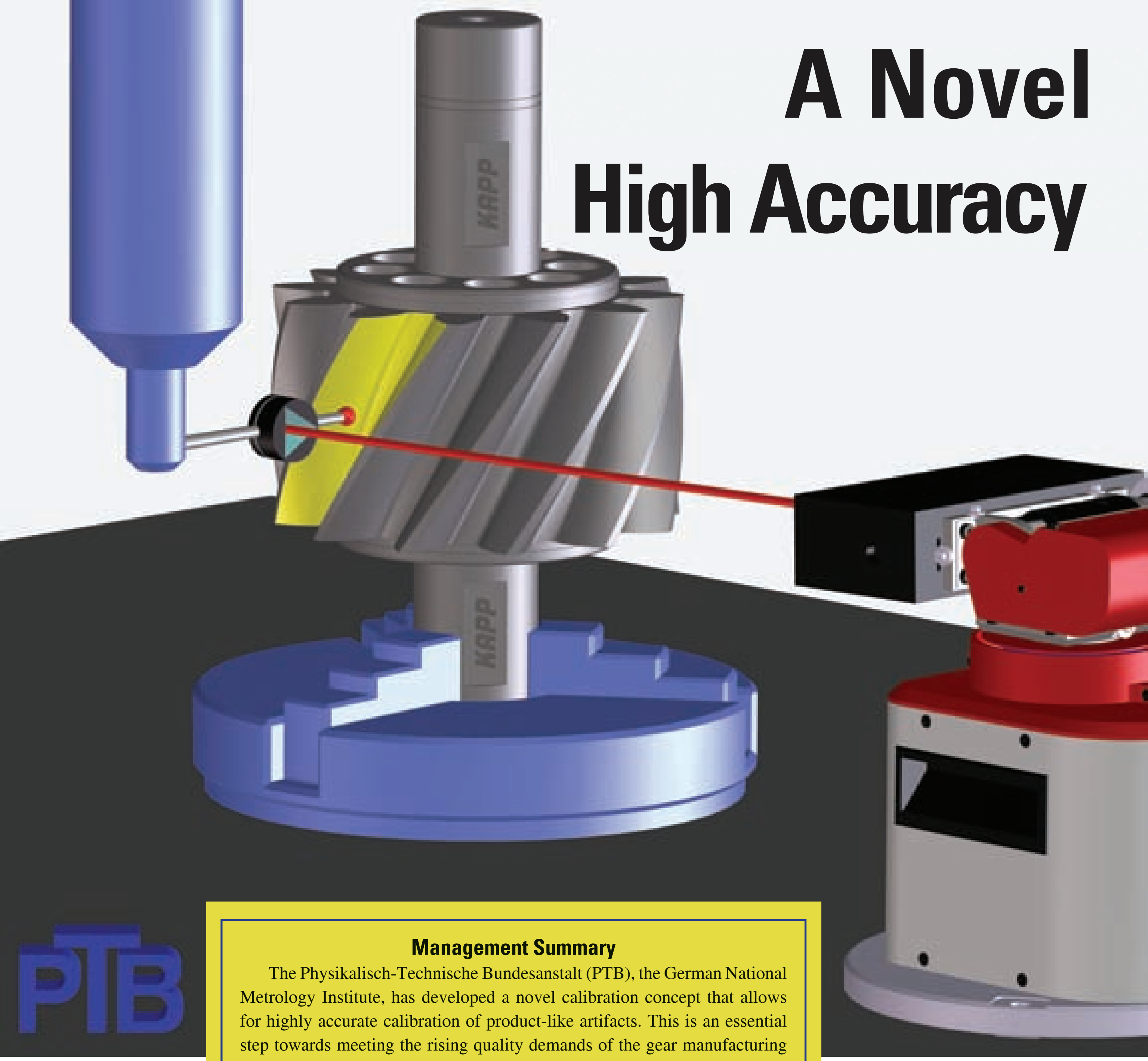
A Novel High Accuracy



Management Summary

The Physikalisch-Technische Bundesanstalt (PTB), the German National Metrology Institute, has developed a novel calibration concept that allows for highly accurate calibration of product-like artifacts. This is an essential step towards meeting the rising quality demands of the gear manufacturing industry by reducing the current calibration uncertainty of gear artifacts.

Recent national and international standards, such as AGMA and ISO, require gear manufacturers to account for measurement uncertainty. Accounting for it, gear manufacturers actually reduce their manufacturing tolerances from those specified on their prints. Consequently, they need highly accurate calibrations to make the uncertainty as small as possible, making their manufacturing tolerances as large as possible.

The measurement setup described is based on a coordinate measuring machine (CMM) equipped with a high-precision rotary table, a tracking interferometer (TI) for reading distance information and certified evaluation software. Both the measuring strategy for the complete measuring process and the reference algorithms, which provide a basis for a software test, were developed by PTB. Results on an involute profile artifact show that the measurement uncertainty of the new concept meets the high requirements.

Concept for Gear Calibration

By
Frank Härtig
Christian Keck
Karin Kniel
Heinrich Iven Schwenke
Franz Wäldele
Klaus Wendt

Introduction

Gear measurement tasks often require exceptionally high measurement accuracies. Today, specified tolerances for high quality gears often lie in the range of the uncertainty of the measurements. In these cases the quality of the products cannot reliably be assured (Ref. 1). A large part of the measurement uncertainties in industry can be attributed to the lack of highly accurate calibrated artifacts that embody the complex shape of industrial gears. Currently, the shapes of the national reference artifacts differ considerably from that of the industrial products. This makes the traceability via direct comparison with measurement results impossible. An increasing measurement uncertainty from the metrological institute down to the shop floor is the consequence (Ref. 2). Therefore, the PTB has developed a novel concept that can be used for the direct calibration of product-like artifacts.

Concept and Setup

All important measurement tasks of involute gears, like profile, lead and pitch measurements, are composed of a linear rotatory and a linear translatory motion. This special characteristic of gear kinematics can be used to minimize the influence of geometrical errors of machine guideways. The novel, high accuracy gear

Dr.-Ing. Frank Härtig *heads the work group for gear and thread metrology at the Physikalisch-Technische Bundesanstalt (PTB), the German National Institute of Metrology, located in Braunschweig, Germany. As group leader, he helps develop methods to determine and improve the measuring accuracy of national primary standards. Previously, he worked for several companies in coordinate measuring technology, specializing in gears, gearing tools and thread metrology. Härtig is also an active member of national and international standardization committees.*

Dipl.-Ing. Christian Keck *is investigating simulation and uncertainty assessment of coordinate measurements for PTB. An electrical engineer, he worked on the simulation of microelectronic devices and integrated circuits before joining the institute.*

Dipl.-Ing. Karin Kniel *works for PTB on coordinate measuring machines, laser tracking and gear metrology. A mechanical engineer, she helps develop methods to determine and improve the measuring accuracy of coordinate measuring machines.*

Dr.-Ing. Heinrich Iven Schwenke *is head of PTB's coordinate metrology section and this year became a corresponding member of the International Institution for Production Engineering Research (CIRP), which has its headquarters in Paris.*

Dr.-Ing. Franz Wäldele *is chief of the measuring instruments technology department at PTB. He holds 12 patents and is author of more than 130 technical papers. Wäldele is also a member of national and international standards committees pertaining to CMMs. Since 2003, he's been president of AUKOM e.V., the German association for training in coordinate metrology.*

Dr.-Ing. Klaus Wendt *works for PTB on new methods to determine and improve the measuring accuracy of optical 3-D coordinate measuring systems, especially in large-scale metrology. Before joining the institute, he worked in photogrammetry, the making of surveys and maps through the use of photographs. His doctorate is in geodesy, a field of applied mathematics concerned with measuring very large tracts of land.*

measuring device is based on this principle with the intention to achieve the most accurate measurement results (Ref. 3). The concept combines the flexibility of a CMM with the advantages of traditional measuring strategies. In the future this will allow calibration of 3-D product-like artifacts (Ref. 4) with almost the same accuracy as the 2-D national reference artifacts today. Figure 1 shows the different artifacts.

The new gear measuring device is based on four components: a high-precision, tactile Cartesian CMM, a rotary table, a tracking interferometer (TI) and certified evaluation software (see Fig. 2). The highly accurate rotary table is integrated into the machine table of the CMM. The geometrical errors of this rotary table are very small in comparison with those of a commercially available one. Furthermore, both the CMM and the rotary table are numerically corrected.

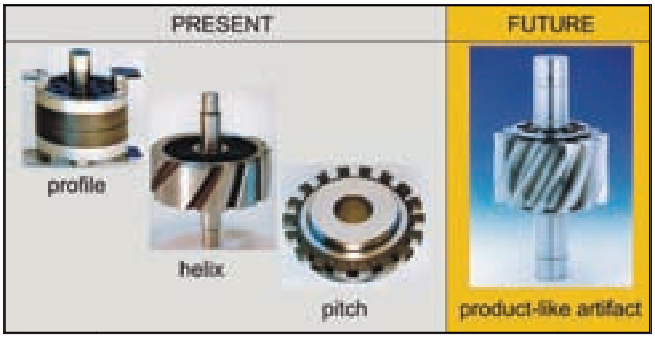
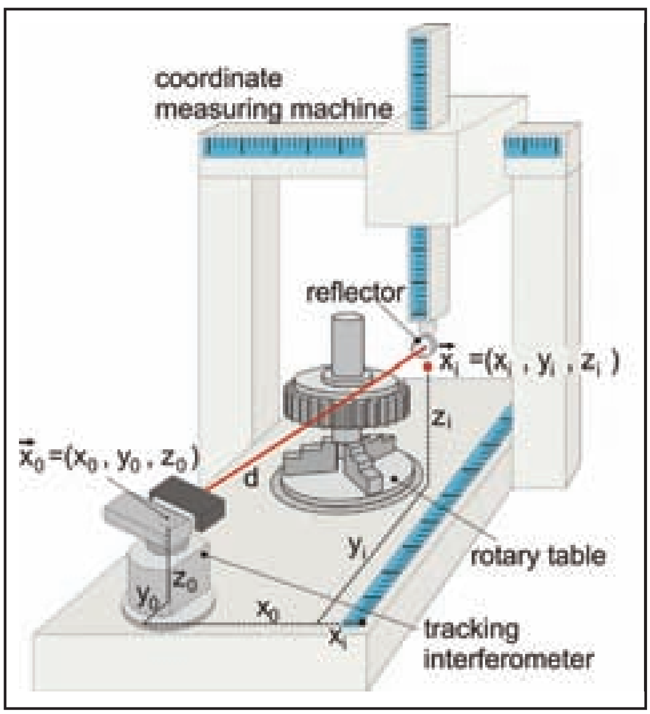


Figure 1—Current artifacts versus the new product-like artifact.



Component	Remark	Specification
CMM	MPE in µm (ISO 10360-2)	$0.7+1.7*10^{-6}L$
rotary table	angle position uncertainty in arc-sec.	0.08
	radial runout in µm	0.08
	axial runout in µm	0.03
TI	U(k = 2) in µm	$0.07+2.3*10^{-7}L$

Figure 2—The new gear measuring device (top) with technical specifications (bottom).

The TI is a development of PTB. Its laser beam follows a reflector mounted close to the probe tip. This allows evaluation of length information in the direction of the laser beam with interferometric accuracy.

Improved positions are obtained from a combination of the CMM and rotary table positions as read from the scales and of the distances measured by the tracking laser interferometer. All measurement information received from the machine components represents the measurement points with overdetermined numerical information. A patented algorithm (Ref. 3) is used to find improved positions. The temperature influence on the CMM and the TI is detected and corrected.

The measurement strategy and the evaluation algorithms for the complete measuring process were developed by PTB. The corresponding software was written in Java. For each single measuring point recorded in a static (non-scanning) mode, all readings of the components are triggered simultaneously by the CMM control.

Mathematical Background

The improved positions are calculated from the readings of the CMM scales and the distances measured by the interferometer on a point-by-point basis. This requires that the position $\vec{x}_0$ of the reference is known (see Fig. 2). To determine $\vec{x}_0$, the CMM has to be moved into at least four different positions ($\vec{x}_1$, . . . , $\vec{x}_4$) that must not lie on a common line, plane or sphere. In each CMM position $\vec{x}_i$, a measurement of the distance d_i is made. The unknown position $\vec{x}_0$ can be found by numerical minimization of the sum of squares errors:

$$\sum_i (|\vec{x}_i - \vec{x}_0| - d_i)^2 \longrightarrow \text{Min} \quad (1)$$

After the position of the TI has been determined, the actual measurement is performed. During a measurement, the probing system's signals, the machine scales and the interferometer length information are recorded simultaneously.

The calculation of the improved CMM position $\vec{x}'$ is performed as follows: The improved position $\vec{x}'$ and the position $\vec{x}$ read from the machine scales are assumed to have a difference of Δx. Their distances d and d' from the reference position differ by an offset Δd. The improved position is also related to the position $\vec{x}_0$ of the interferometer:

$$\vec{x}' = \vec{x} + \Delta\vec{x},\ d' = d + \Delta d,\ d' = |\vec{x}' - \vec{x}_0| \quad (2)$$

The coordinate and distance improvements can be found by mathematical optimization with a target function that puts a large weight on the distance measurements d' and a low weight on the position $\vec{x}'$. The reciprocal values of the estimated uncertainties of the CMM scale positions u_P and of the interferometric distance u_d are appropriate choices:

$$\frac{\Delta x^2}{u_P^2} + \frac{\Delta y^2}{u_P^2} + \frac{\Delta z^2}{u_P^2} + \frac{\Delta d^2}{u_d^2} \longrightarrow \text{Min} \ (3)$$

In principle, the optimization can be performed by any numerical method. As no directional information is drawn from the TI measurement, reduction of the uncertainty of the position measurement is achieved only in the direction of the straight line connecting the probing system and the interferometer position.

If the uncertainty of the original position $\vec{x}$ is assumed to have the form of a sphere, the uncertainty of the improved position $\vec{x}'$ will take the form of an ellipsoid u_{res} during a profile measurement, as shown in Figure 3.

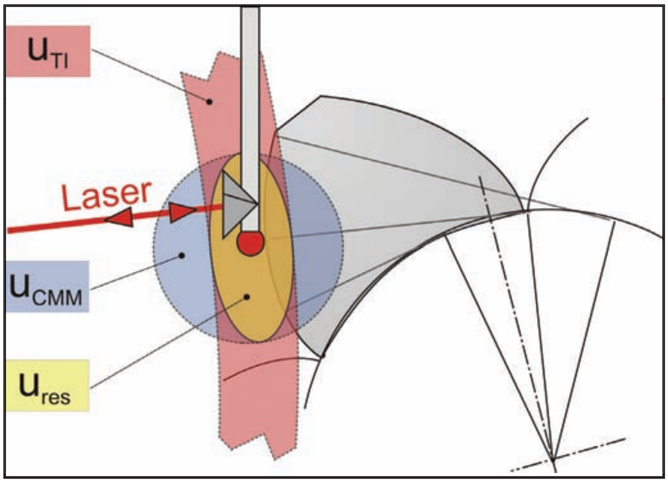


Figure 3—Reduction of the measurement uncertainty of the CMM u_{CMM} via additional length information (measurement uncertainty u_{TI}) to the resulting measurement uncertainty of the uncertainty ellipsoid u_{res}.

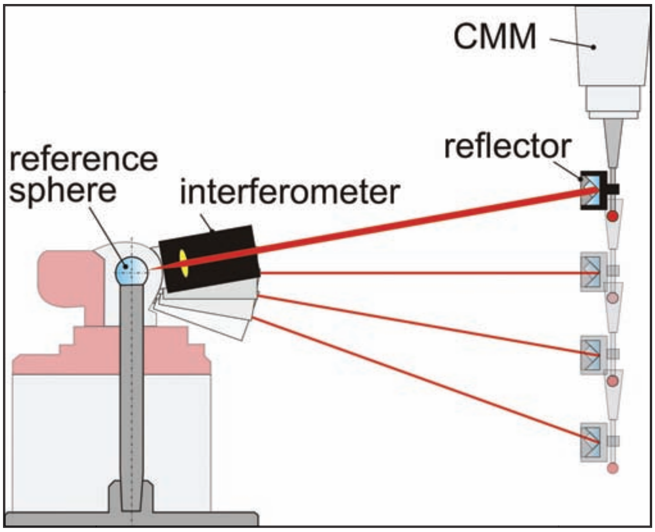


Figure 4—Tracking laser interferometer.

Tracking Laser Interferometer

The distance measurement uncertainty of the TI is the dominant uncertainty contributor of the system in the direction of the beam. The stability of the point of rotation is of especially great importance. As commercial laser trackers (Ref. 5) do not achieve distance measurement uncertainties in the submicron range, PTB has developed a new high-precision tracking interferometer. In its design, the gimbal-mounted interferometer moves around a fixed reference sphere serving only as the reference mirror for the interferometer (see Fig. 4). Due to this principle, radial and lateral deviations of the mechanical axes of rotation do not affect the measurement accuracy.

The accuracy of the TI length measurement depends significantly on the quality of the reference sphere surface and its unchanged position in space. To minimize its influences, the reference sphere has a form error of less than 30 nm. It is mounted on an invar stem to avoid any displacements due to thermal expansion. Atmospheric conditions, such as temperature, barometric pressure and relative humidity, are monitored to numerically correct the laser signal. As the TI is only 20 cm in diameter and 25 cm in height and has a weight of only 7 kg, it can be placed directly on the CMM table.

Reference Software

The new evaluation software allows evaluation of the measurement parameter of the modified flank geometries of product-like artifacts according to the definition of common gear evaluation standards and guidelines (Refs. 6, 7 and

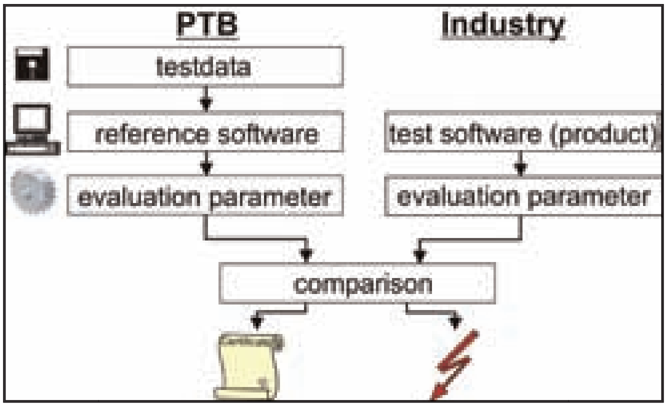


Figure 5—Certification of software algorithms.

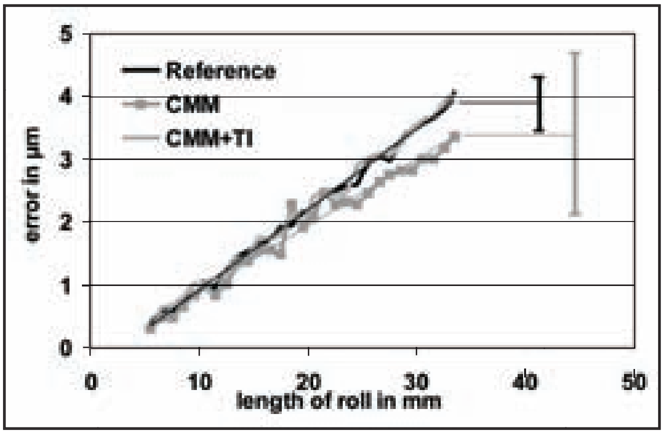


Figure 6—Results of an involute profile artifact.

8). Besides this application, the software can be used to compare the evaluation from PTB's reference software against the evaluations calculated by the industry. This allows the industry to certify its products. The principle of the software test can be seen in Figure 5.

Results

In order to verify the efficiency of the new approach on a gear involute profile artifact, comparison measurements were carried out. The high surface quality of the national reference profile artifact and measurement values with very small uncertainties provided excellent conditions for evaluating the new measuring method. The measurements were carried out according to the generative gearing principle.

The results in Figure 6 show very good agreement between the calibrated values of the artifact and the results of the new measuring device. Compared to measurement results obtained conventionally (CMM), it is demonstrated that the new method improves the measurement results considerably.

Conclusions and Outlook

PTB has developed a novel measuring device to calibrate gear artifacts. It is based on a high-precision Cartesian CMM with an integrated rotary table, a new tracking interferometer and certified software algorithms. Results show that the measurement uncertainty of the new gear measuring device complies with rising quality demands. Today it is possible to calibrate product-like gear artifacts.

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New Approaches

In Roll Testing Technology of Spiral Bevel and Hypoid Gear Sets

Heinz Eder and Christian Pahud

Introduction

The roll testing of bevel gears has existed as long as bevel gearing itself has existed. A device was required to check and confirm functionality, mounting distances and backlash to suit the future assembly condition of the gear set.

Single-flank and vibration checking have traditionally been widely accepted testing and checking methods for evaluating the quality of spiral bevel and hypoid gear sets. Mainly due to productivity reasons, the methods were limited to laboratory application, spot checks to monitor production and assembled gear sets.

Only the introduction of CNC roll testing equipment combined with PC-based evaluation technology dating back to 1990 enabled the breakthrough of this technology onto workshop floors in mass production applications (Ref. 1). Since then, this process has been automated, so it's now state-of-the-art technology, where the best assembly position for the gear set is evaluated, checking the quality characteristics for different mounting positions. This fulfilled the requirements of the automotive industry regarding the generation, recording and documentation of information about the quality level of its manufactured gear sets. However, the industry later required checking of the gear set characteristics over a wider range of positions. Checking a defined number of positions, though, was jeopardizing productivity. This is where the new continuous approach can be used to provide the required amount of information without compromising productivity.

Methods for Checking Spiral Bevel and Hypoid Gears

There are many reasons for checking spiral bevel gears and hypoid gear sets in production, such as monitoring production and documenting manufactured quality. However, in the pre-assembly stage, the main reason is to predict noise emissions, once the gear set is mounted in the carrier. The requirements for a testing device in a production environment are reproducibility of results, short setup and testing times, best possible simulation of "real" situation once the gear set is assembled, a straightforward good/reject identification and a reliable detection of components that do not fulfill the requested quality standards.

Methods to check individual components. There are numerous ways of checking individual components that will not be listed, as this paper is purely focused on the possible means of detecting and forecasting the noise behavior of spiral bevel and hypoid gear sets in automotive applications.

3-D coordinate measuring machine (CMM). On a suitable three-dimensional coordinate measuring machine that's measuring individual components of pinions and ring gears, pitch checks will indicate the indexing quality. Topography checks will indicate how close the actual microgeometry of the flank form approaches the theoretical nominal data or that of the master gear to be copied. However, these checks will give little indication about the future noise emission to be expected from an assembled gear set because only one component at a time is evaluated. In addition, usually not all teeth are checked for timing reasons and only a sample

Management Summary

This paper presents a new approach in roll testing technology of spiral bevel and hypoid gear sets on a CNC roll tester applying analytical tools, such as vibration noise and single-flank testing technology.

When assembling a spiral bevel or hypoid gear set in a carrier, two variables can usually be adjusted: 1.) ring gear mounting distance, to adjust required backlash and 2.) pinion mounting distance, to adjust contact pattern position and consequently running behavior.

The task is to reduce testing time compared to conventional roll testing while improving the amount of information generated to give indication for the best possible assembly position in the axle carrier.

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Figure 1—Oerlikon T60X tester (2003).

number of teeth is evaluated with the possibility of nonchecked teeth being not OK.

There is, however, a fairly new approach for checking bevel gears on 3-D CMMs. The approach, already realized for parallel-shaft gears (Ref. 2), is to scan the path of contact (POC) to find the possible causes for noise excitement whilst meshing individual teeth. The disadvantage of this method is that POC analysis will be made on the assumption that the matching member is perfect. Real components, however, will deviate from the nominal and will influence the POC.

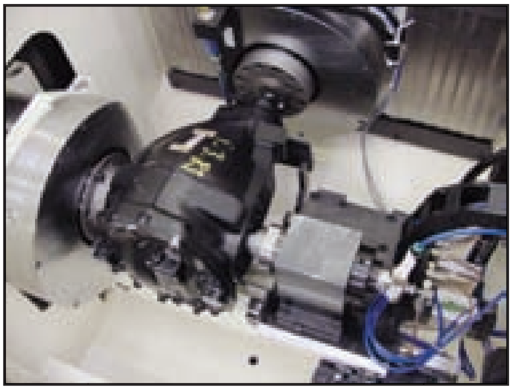

Figure 2—Typical mounting arrangement of bevel or hypoid housing on Oerlikon T60X.

Another possibility is the virtual meshing of a gear set after checking two matching components. After checking the topography of pinion and ring gear teeth, both members are virtually matched and a real "ease-off" can be generated. After evaluating a virtual, reproduced true ease-off, the ease-off condition, the tooth contact pattern (TCP), the POC and the transmission error (TE) can be analyzed, with the latter indicating noise emission capacity.

All of the checks available on a 3-D CMM are extremely accurate. However, testing is rather time intensive. Still, besides the latter method, checking one component only can hardly indicate the running condition of a gear set.

Therefore, the main application of 3-D CMMs in production is to monitor samples from cutting or grinding operations and to control topography when the machines' settings are changed automatically by means of software like KOMET® to ensure manufactured topography is as calculated.

Methods to check running behavior of matched sets. In the past, with the increasing role of finish-ground gear sets, the vast majority of spiral bevel and hypoid gears were lapped after heat treatment, depending on geographic region and application.

The lapping process necessarily involves a pairing of pinion and ring gear. Therefore, the obvious solution was to check the sets in pairs. Simulating the assembly of the gear set on a roll-tester was, and still is, the fastest quality check available in the pre-assembly stage.

Roll testing. What most roll testers have in common is that a gear set is clamped, brought into mesh and backlash is adjusted. After spraying or painting the gear sets, to avoid scoring, speed and torque are applied. The only difference between the numerous amounts of testers is the degree of automation developed over the years, starting from an all-manual tester with mechanical brakes to apply torque to the state-of-the-art testing machine that has fully automatic meshing and applies torques and speeds via electronically controlled drives.

Furthermore, testing as described has a high level of productivity, and typical testing time—not including clamping and unclamping—can be completed in the range of one minute.

A derivative of the T60, the T60X machine (see Fig. 1) was presented to the market in 2003 to meet customer demands, after realizing that meticulous testing of individual gear sets still leaves uncertainty in the assembly stage, where the gear sets are assembled in a carrier. Typically, the manufacturing tolerances of the housing, together with the evaluated best position on the pinion mounting distance, are compensated by shims (see Fig. 2). In production, wrong shimming caused by whatever reason will lead to a condition in which the perfectly evaluated gear set will be subject to potential noise emissions, if assembled incorrectly.

The arrangement of checking the gear set in an already assembled condition takes the detection of potential noise emitting one step further on the assembly line. The obvious nature of this checking arrangement is a purely OK/Not OK filtering before the carrier is released for assembly into the axle.

Another development in the automotive industry in recent years is a growing demand for bevel and hypoid gear sets deviating from shaft angles of 90°, mainly for low-floor, short-distance buses and because of new legislation to allow for softer hoods on motor vehicles, as a precautionary measure in car-to-pedestrian accidents. This requires space between the hood and the engine. This can only be maintained by moving the engine further back into the passenger room. In vehicles equipped with a longitudinal engine and front wheel drive, the space for the front passengers will then be sacrificed to move the gearbox back. To maintain the space for the front passengers, "slim line" gearboxes have been developed using a shaft angle smaller than 90° for the bevel gear set.

To satisfy that market requirement, the T60A machine was developed and presented in 2004. The T60A accommodates a shaft angle range of 90° +/– 11°.

Tooth contact pattern (TCP) analysis, conventional. After finishing the roll test of a gear set that has been sprayed or brushed with contact pattern paint, the contact pattern is visibly marked on the teeth. The created tooth contact pattern, is compared to a "master contact pattern" and judged by a trained individual. This check is performed on a "subjective" basis using the human eye as a measuring instrument. This process, involving the human factor, has disadvantages in repeatability and reproducibility and therefore creates difficulties in meeting modern quality control requirements. Consequently the clear choice is to replace it with "objective" checks.

To eliminate the human influence when judging the TCP, a camera-based TCP recognition system can identify and evaluate a contact pattern. This system compares a nominal TCP with the recorded TCP and supplies a straightforward Good/Reject message. Typical characteristics that are evaluated and toleranced are length, height, center of gravity, as well as area and orientation of the recorded TCP. Besides the elimination of subjectivity, such a device also enables the collection of statistical data and digital recordings of the TCPs on a fully automatic basis.

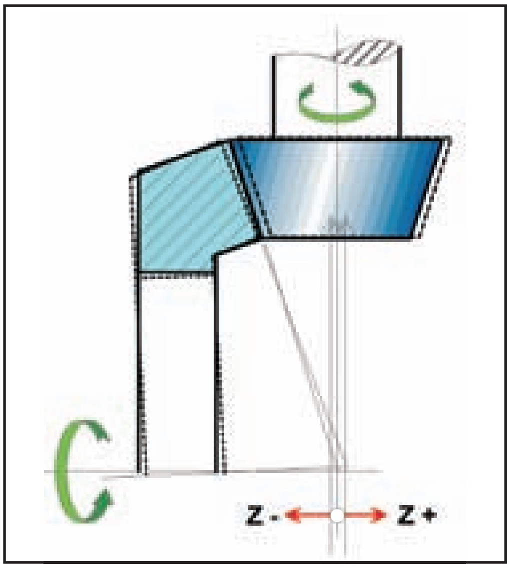

Figure 3—Principle of double-flank check on Oerlikon T60/L60.

Noise check, conventional. While running the roll test of a gear set, which has been sprayed or brushed with contact pattern paint or oil to avoid scoring, the running behavior is judged by a trained individual. As all checks involving the human factor, this check is performed on a "subjective" basis using the human ear as a measuring device. Besides lacking repeatability and reproducibility, this check has historically had a wide spread. Also users claim a reasonable ability of forecasting and correlation to vehicle noise. Nevertheless, this testing method as a final check is replaced by "objective" means of checking and evaluating.

Noise check, automatic (air noise). An air noise check is historically the logical step from judging the gear noise by listening to it with the human ear to judging it by using a microphone and setting the tolerance at a predefined noise level, typically a dB(A) rating. This evaluation method has not made a real breakthrough and has no real significance in testing and evaluating the running behavior of spiral bevel and hypoid gear sets.

Double-flank check. Double-flank checks in parallel shaft gear applications are usually performed by mating a member with a master gear or pinion and recording the axial deviations while running the set in a no-backlash situation. With spiral bevel gears, which are typically mated during the lapping process, this opportunity is not available. Instead the sets are double-flank tested in pairs as they are assembled (see Fig. 3).

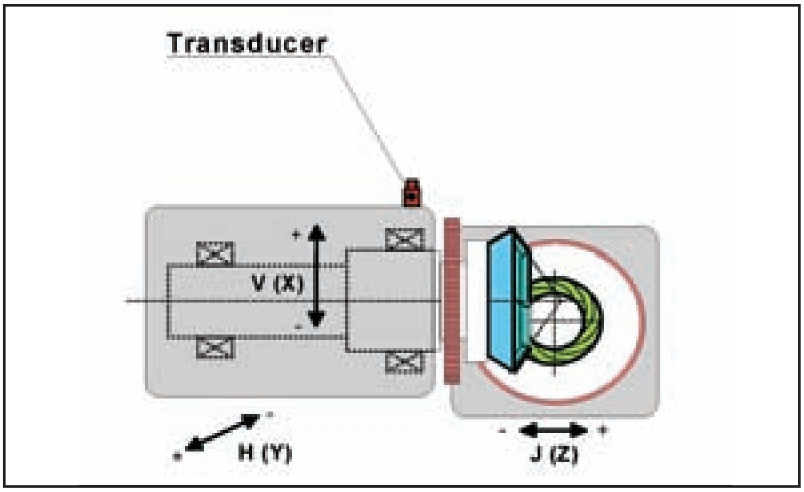

Figure 4—Typical arrangement of a vibration noise sensor on a bevel gear rolling tester.

Figure 5—Typical result of a vibration noise check referenced to pinion.

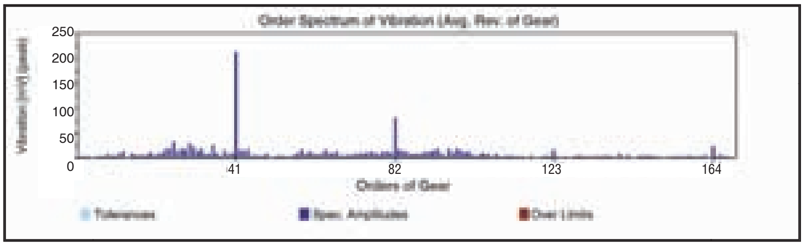

Figure 6—Typical result of a vibration noise check referenced to ring gear.

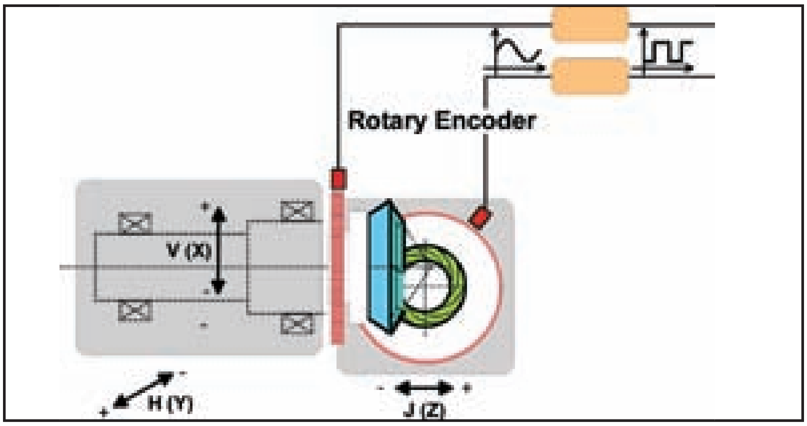

Figure 7—Principle of single-flank check on Oerlikon T60.

The test is performed in a no-backlash condition. While the ring gear is making one revolution, deviation of the pinion in ring gear mounting distance (deviation Z) is recorded. A fast Fourier analysis then evaluates rotary pinion and ring gear deviations separately. This test is usually performed in very little time. As this test does not represent the final assembled condition, which will have backlash, the test result cannot make a significant statement regarding running behavior.

However this test has established itself as a quick pre-check for CNC lapping and CNC testing to recognize runout errors on pinions and ring gears and clamping errors of mainly ring gears. Clamping errors will have an effect on runout qualities. This test avoids the possibility of pairs of gears being lapped or tested in an incorrect clamping position, thereby avoiding damage during lapping or misreading of testing results due to incorrect clamping.

Vibration noise check (VN). Typically a vibration noise sensor is mounted on a gear tester as close as possible to the meshing gear set to be tested (see Fig. 4). Preferably a CNC roll tester is used to apply torque and speed, to minimize influences of the roll testing machine itself, such as temperature deviations caused by mechanical brakes, torque variations due to manual application of torque, and speed variations due to influences of the applied torque—just to name a few.

The measured signal will then be amplified, synchronized with the spindle rpm and evaluated on a separate evaluation unit where typically a fast Fourier analysis will be carried out to divide the signal into the harmonic contents.

An advantage of this measuring principle is short measuring times due to the fact that comparatively high spindle speeds can be applied, typically allowing achievement of tooth mesh frequencies in the area of 300 Hz. Another advantage is the reduction of unproductive acceleration and deceleration times. Forecasting noise emission in the vehicle is reasonably good in the range of mesh frequencies. However rotational harmonic contents of pinion and ring gear can cause side band effects that cover or shift mesh frequencies, challenging their definite identification. Because vibration noise checking is a dynamic testing method, resolution for rotational harmonic contents is poor to nonexistent. Generating usable information for reliable forecasting of noise behavior is limited to the mesh harmonic contents of lower orders (see Figs. 5 and 6). The sum of its disadvantages compared with its directly competing measuring method, single-flank testing, has led to a decreasing application of vibration noise testing in the industry.

Single-flank transmission error check (SFT). For single-flank checking, high-resolution rotary sensors are mounted on pinion and gear spindle, typically as close as possible to the components to be analyzed (see Fig. 7). It is highly recommended that an NC control be used to apply torque and speed.

The digitized signal collected from the rotary encoders is recorded and fed into a PC-based analyzing system. By definition (DIN 3965), single-flank checking is a quasi-static checking method, hence it is basically free from dynamic influences. As a consequence, the equipment used, assuming measuring itself reaches an acceptable level, has no influence on the result itself. Due to the lack of dynamic influences, repeatability of SFT results is usually very good. In addition to the mesh transmission errors, which clearly correlate to vehicle noise behavior, rotational harmonic contents of the checked components can be obtained. A positive side effect of low checking speeds is fast acceleration and deceleration times for the checking procedure itself.

Due to the increased quality and quantity of characteristics and information provided by single-flank testing in comparison with vibration noise analysis, the former has reached a stage where it can be clearly called the "industrial standard" for pre-assembly running behavior checking of spiral bevel and hypoid gears.

Best position evaluation strategy, successively. All evaluation strategies named hereafter apply for both checking methods, vibration noise and single-flank transmission error, with all preconditions and characteristics mentioned in the sections *Vibration noise check (VN)* and *Single-flank transmission error check (SFT)*.

The vast majority of bevel and hypoid gears end up in vehicle applications. Typically the pinion cone distance (by shimming the pinion backface) and the backlash (by adjusting the ring gear mounting distance) are the two variables that can be adjusted in the assembly stage.

To ensure proper running behavior in the assembled stage, the set will be tested on a bevel gear roll test stand to evaluate the best running position, which will be set in the assembled carrier. Alternatively a known carrier displacement range will be imposed on the set and the transmission error tolerances will have to be kept over the entire range of displacement to ensure proper running behavior in the axle over the whole range of running conditions.

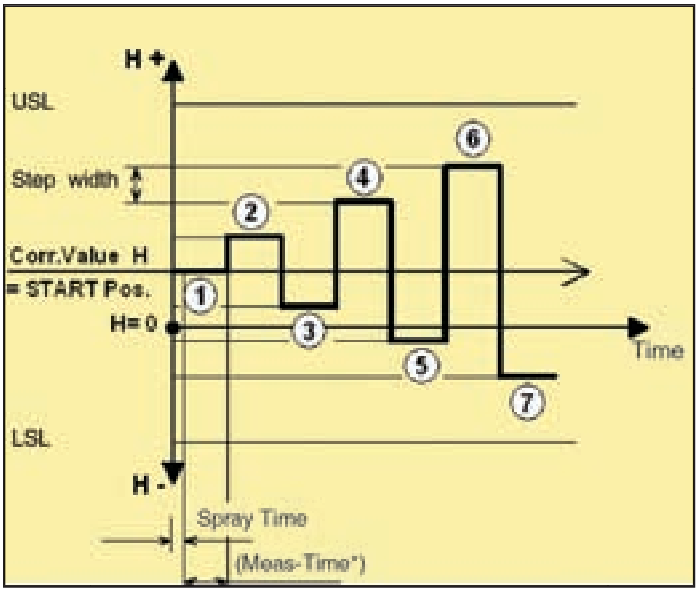

Figure 8—Classic best position evaluation procedure.

The typical approach to check the running position plus a wider range of possible assembly positions is to successively check a set number of individual positions for the pinion cone setting, followed by an individual evaluation of each position (see Fig. 8). The result for each individual setting position is an evaluation as mentioned in Figure 3. Application of this strategy is increasing the checking times for each individual position. Trying to optimize checking times consequently means reducing the amount of positions to be checked and thereby sacrificing the resolution over the entire range.

Best position evaluation, continuous. As the request was to get much more complete information of running behavior over an entire range of possible deflections in the gear carrier under load and temperature influences, the pre-evaluated and known gear housing deflections are simulated in the roll testing machine. Also, different from the incremental/successive approach, as explained in the section *Best position evaluation strategy, successively*, the deflections are now simulated on a continuous basis, thereby generating a wider range of possible information about the running behavior in only a fraction of the time previously required.

The result of a continuous measurement along a range of pinion cone settings deviating from the nominal mounting distance by +/–0.09 mm: the mounting distance is continuously increased, while data for either single-flank transmission error or vibration noise is collected (see Fig. 9). This data is evaluated by means of a fast Fourier Transformation evaluation.

In an example evaluation, a gear set ratio of 14:41 is evaluated, and an order analysis referenced to the pinion is displayed. Pinion orders along pinion cone setting, in this case single-flank transmission error for drive, are visible. Cross-referencing by pinion orders, the sample shows pinion rotational order: The 14th pinion rotational order equals the 1st mesh order, the 28th pinion rotational order equals the 2nd mesh order and so forth (see Fig. 10).

The displacement characteristic for each individual single-flank transmission error component can be extracted. The sum of information gained

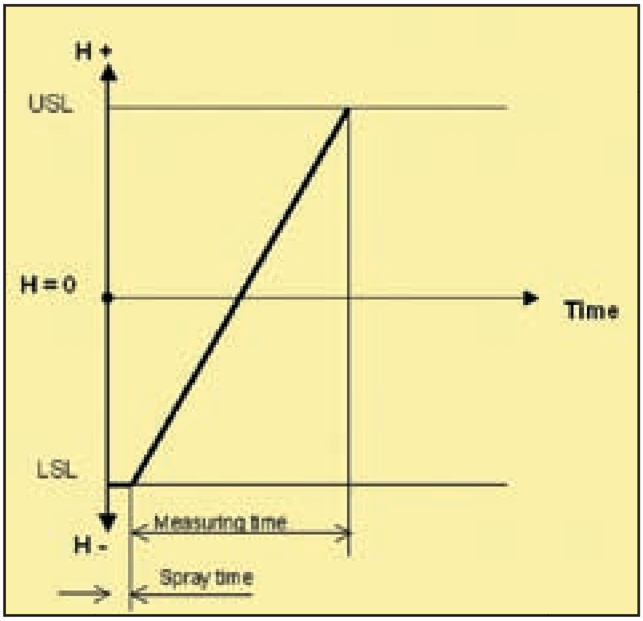

Figure 9—Continuous best position evaluation procedure.

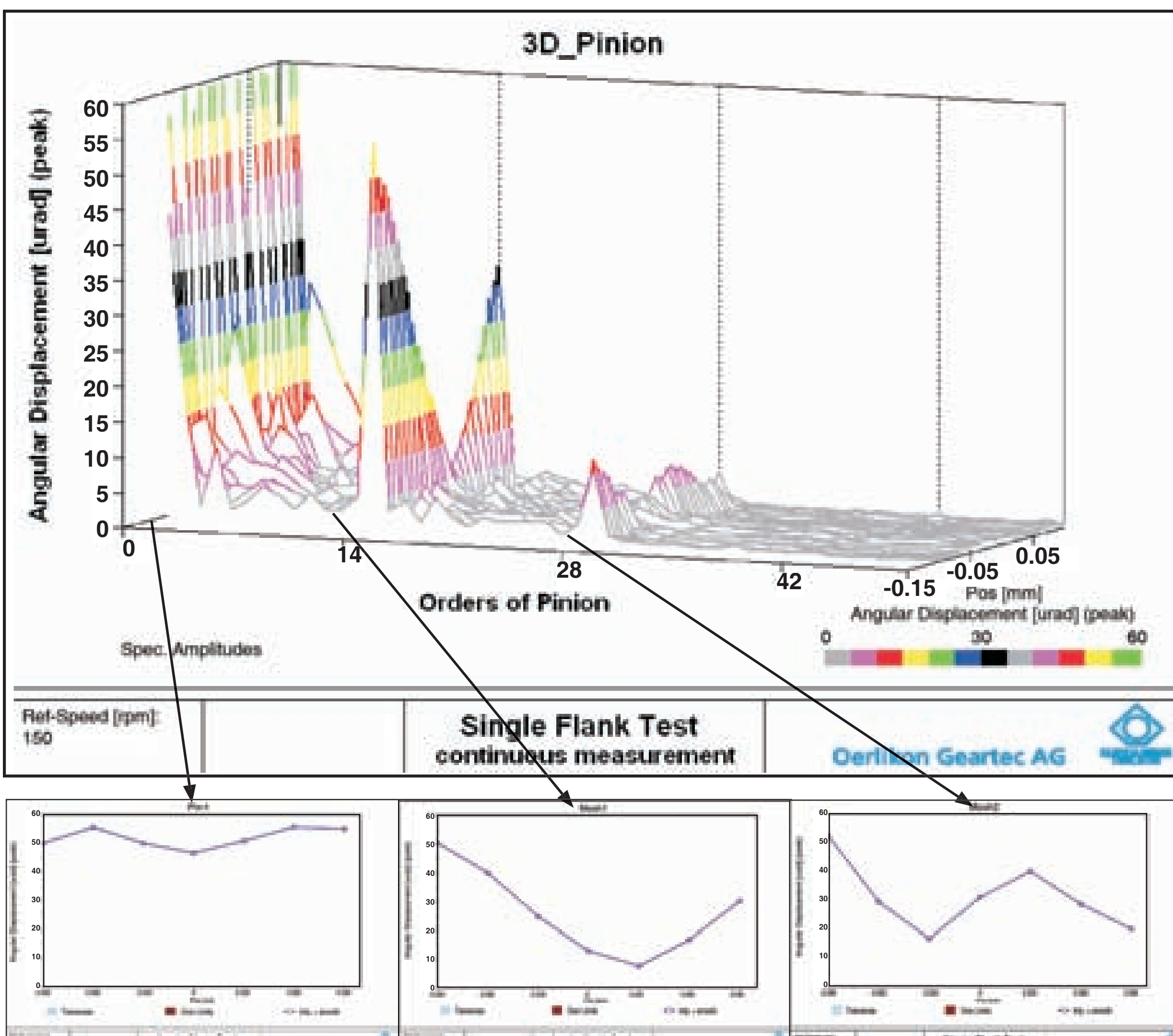

Figure 10—Continuous measurement evaluation result and extracts of pinion rotational orders 1, 14 & 28.

can then be used for evaluation, so different attachments of importance can be applied to different characteristics. This result will then be a clear indication of which pinion cone setting is the position having the desired transmission error characteristic. Alternatively the achievement of a desired transmission error characteristic can be checked and confirmed.

The application aspect of this new approach is as wide as the approach itself and can be applied in mass production using all evaluation tools with a simple Good/Reject result and the output of the best pinion mounting position. On the other hand, it is an ideal tool for the gear engineer to evaluate all possible means of bevel and hypoid gear characteristics in the development stage whilst gaining information for later application in mass production.

Test Series

A test series (see Table 1 for parameters) was conducted to show the capabilities of this new continuous approach.

All tests were conducted on an Oerlikon T60 gear testing machine equipped with capabilities for checking vibration noise and single-flank transmission error in both modes, the successive and continuous evaluation strategies. One set of ground hypoid gears was checked five consecutive times without clamping and unclamping in each method. Vibration noise and single-flank checks were also performed using both evaluation strategies, successive and continuous. All results and graphs in this paper represent averaged figures of five consecutive measurements. The range markers show the range of these five consecutive measurements to indicate the quality of repeatability for each characteristic.

Vibration noise checking results, successive. Analyzing the mesh harmonic contents of vibration noise, we get a result as shown in Figure 11. The amplitude of mesh 1 decreases from position 1 at 315 mV (pinion cone setting –0.09 mm) to position 5 at 45 mV (pinion cone setting +0.03 mm). This indicates that shifting the pinion cone position by 0.12 mm can reduce the significant amplitude for mesh 1 by 86%. A similar potential of improvement can be identified for mesh 2.

However, best positions for mesh 1 and mesh 2 do not coincide. Also, depending on the best position evaluation strategy, which has to be correlated with actual noise emission in the vehicle, the "correct" best position can vary from application to application. Repeatability for meshes 1–4 is at an acceptable level. For meshes 5 and 6, the range of measurement results is in the area of the signal size itself and therefore is not suitable for further evaluation.

Table 1—Parameters for Test Series.

Ratio	14:41
Axial Offset	30 mm
Axial Backlash	0.16 mm
Checking Speed for Vibration Noise (Pinion Spindle)	1,100 min^{-1}
Checking Speed for Single-Flank Test (Pinion Spindle)	150 min^{-1}
Torque	15 Nm
Increments of Pinion Cone Settings Referenced to Nominal Pinion Mounting Distance (7 positions)	Pos.1–7: –0.09 mm; –0.06 mm; –0.03 mm; 0 mm; 0.03 mm; 0.06 mm; 0.09 mm
Checking Duration per Increment, Successive	5 Ring Gear Revolutions
Checking Duration per "Increment," Continuous	2 Ring Gear Revolutions

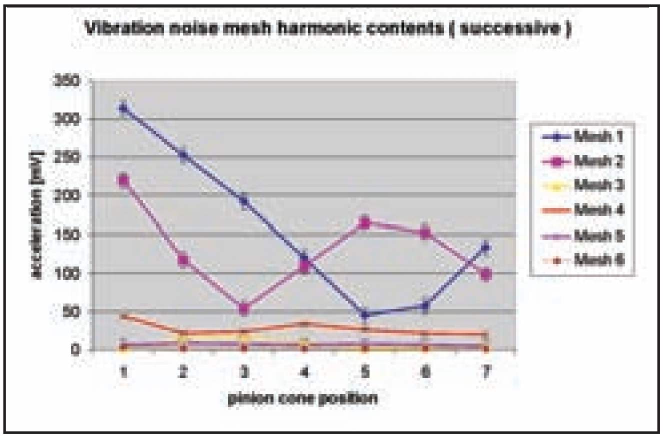

Figure 11—Mesh harmonic contents of vibration noise signal; checking method successive.

It has to be emphasized that, for this study, ground gear sets have been used. As these sets fulfill high quality standards, as all heat treatment distortions are removed by this process, there are no sideband effects. Consequently, mesh harmonics can clearly be identified.

To prove the known fact, that vibration noise analysis is not a feasible method to detect the rotational harmonic contents in reference to the gear, gear rotational harmonics were extracted from the measured signal by FFT detection. As expected, the quality and repeatability of the result was not suitable to give any indication because the range of the measured signals (see Fig. 12) was wider than the averaged signal itself. This is mainly due to factors as explained in the section *Vibration noise check (VN)*.

Vibration noise checking results, continuous. The continuous vibration noise measurement (Fig. 13) shows almost identical results to

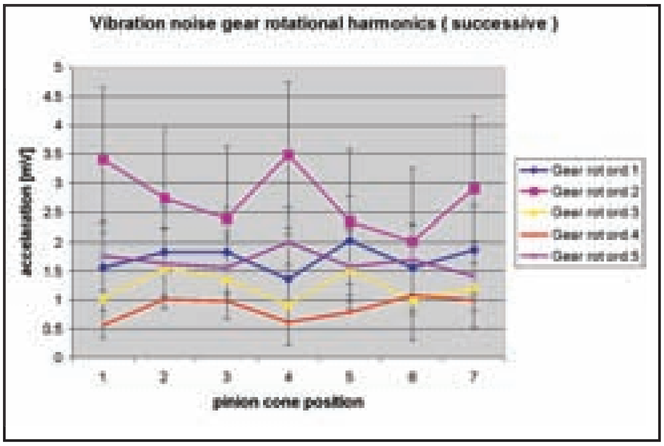

Figure 12—Gear rotational harmonic analysis of vibration noise signal; checking method successive.

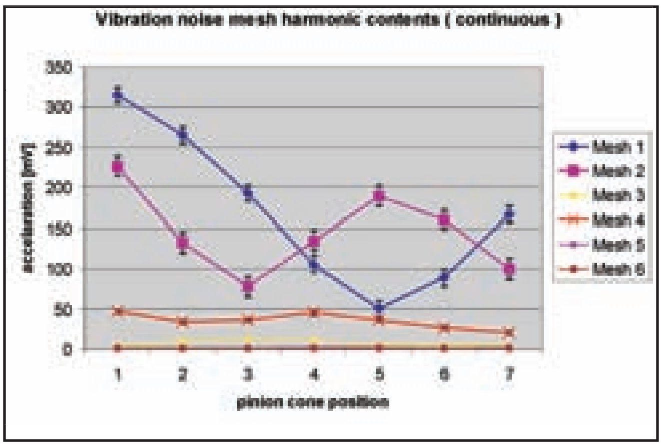

Figure 13—Mesh harmonic contents of vibration noise signal; checking method continuous.

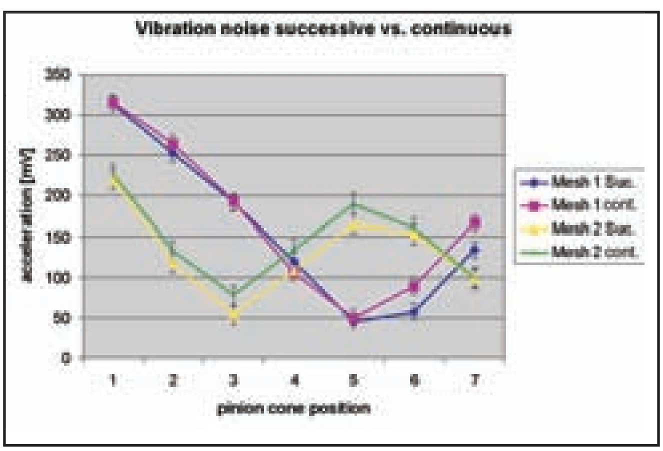

Figure 14—Vibration noise successive checking vs. continuous checking.

Table 2—Correlation Coefficient Vibration Noise, Successive Method vs. Continuous Method.

Characteristic	Correlation Coefficient VN, Successive vs. Continuous
Mesh 1	98.49%
Mesh 2	98.34%
Mesh 3	89.87%
Mesh 4	86.22%

the successive measuring (Fig. 11). It has to be noted, though, that the checking time could be reduced by 35% using the continuous checking approach.

Correlation of successive check with continuous checks of vibration noise. Visualized for mesh 1 and mesh 2 (see Fig. 14), the correlation of both checking methods can be recognized.

Correlating the successive and continuous checks and performing a correlation study, the results shown in Table 2 can be obtained.

Correlation coefficients for meshes 1–4 reach a satisfying level that proves: Using the new continuous approach, an identical level of quality for results can be obtained, with checking times simultaneously reduced by 35%. Consequently the new continuous approach is qualified for replacing the successive approach in applications where vibration noise is an indicator for future vehicle noise emissions.

The reduction in checking time allows for obtaining a wider range of information without a reduction in productivity. Alternatively productivity can be raised while obtaining a similar amount of information at a similar quality level.

Single-flank checking results, successive. Evaluating the single-flank transmission error in successive mode, a result, as displayed in Figure 15, was obtained. Repeatability reaches an acceptable level for meshes 1–6. The pinion cone position with the highest figure for mesh 1 is position 1 at 49 μrad. The lowest mesh 1 figure is position 5 at 7 μrad. Very similar to the vibration noise evaluation, this difference indicates that by shifting the pinion cone position from position 1 to position 5, the significant amplitude for mesh 1 can be reduced by 86%.

The best position for mesh 2 is position 2 at 4.8 μrad whereas the highest output position for mesh 2 is position 1 at 9.3 μrad, followed by position 5 at 8.4 μrad. Depending on the best position evaluation strategy—which has to be correlated with actual noise emission in the vehicle—and attaching different importances to the obtained results, a "best position" for the assembly of this particular gear set can be determined.

Different from the vibration noise evaluation, the repeatability of single-flank checking results for the rotational orders is acceptable (see Fig. 16). Therefore analyzing the rotational harmonic contents of single-flank transmission error in reference to the ring gear indicates rotational harmonic behavior, like runout, ovality, triangularity, squareness and other rotational harmonic influences. Gear rotational harmonics can be extracted from the measured signal by FFT. Applying single-flank transmission error evaluation, side effects from rotational harmonic components moving mesh harmonic components into sidebands are non-existent. Consequently there is nothing to challenge their clear identification from vibration noise.

The sum of advantages for SFT evaluation, as intimated in the section *Vibration noise check (VN)*, has led to SFT's increasing application in mass production of spiral bevel and hypoid gears.

Single-flank checking results, continuous checking. The continuous single-flank measurement shows a pattern of harmonic mesh content results identical to that of successive measurement (see Figs. 15 and 17). However, checking time using the continuous method was approximately 65% of that using the successive checking method.

Correlation of successive with continuous check of single-flank evaluation. In Figure 18, the correlation of both checking methods is visualized. Displayed are the results for mesh 1 and mesh 2, for both cases.

No significant difference in the two approaches can be identified. The corresponding curves have a good correlation in both absolute amplitudes and patterns along the pinion cone positions, leading to the conclusion that applying the continuous method leads to identical results compared with the successive approach and can be qualified as a suitable replacement. Advantageous is the time reduction while gaining identical output.

Carrying out a correlation study for all mesh harmonic components from meshes 1–5, the results in Table 3 can be obtained. The entire range of meshes 1–5 shows acceptable correlation between the two checking methods.

Correlation between vibration noise & single-flank checking results. As in many applications with lower mesh harmonic contents, meshes 1–3 are the primary indicators for future vehicle noise emissions. Also, checking vibration noise can be a reasonable approach for testing bevel gears to predict vehicle noise.

However, higher mesh orders can indicate surface finish problems caused by surface roughness itself or feedmarks produced when generating a pinion. Also, higher rotational harmonic contents can indicate "wow-wow"

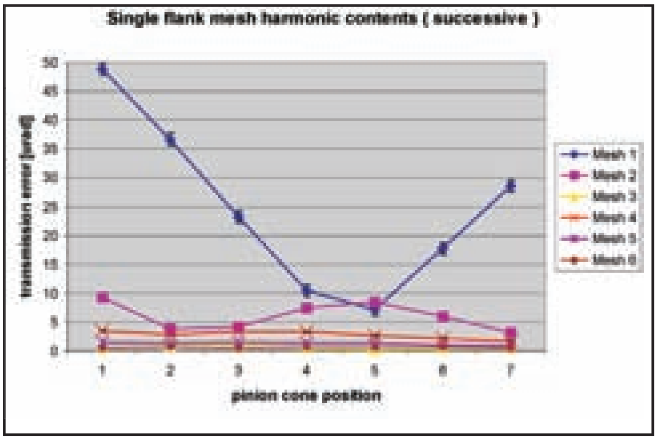

Figure 15—Mesh harmonic contents of single-flank transmission error; successive checks.

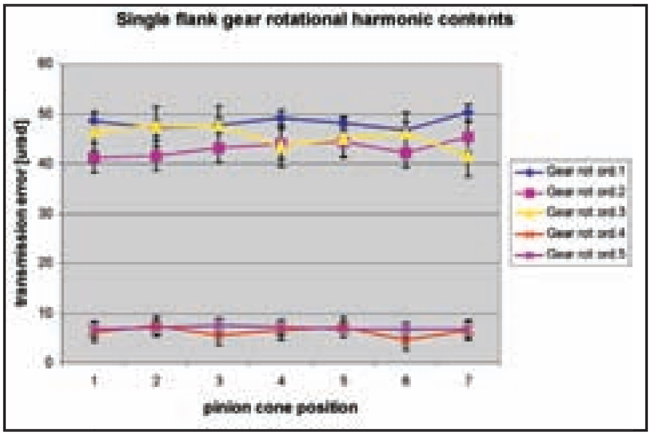

Figure 16—Gear rotational harmonic contents of single-flank transmission error; successive checks.

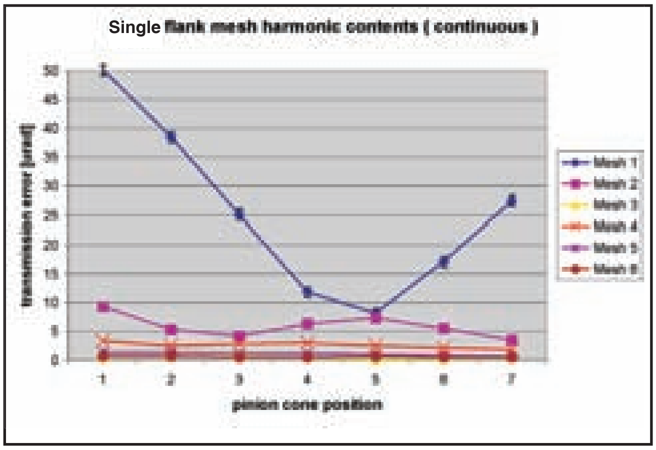

Figure 17—Mesh harmonic contents of single-flank transmission error; continuous checks.

sounds. Consequently, not recording and evaluating these higher orders and contents leaves a significant risk of overlooking these problems.

To show that single-flank transmission error can provide similar information compared to vibration noise, a correlation study between the two checking methods was undertaken and is shown in Figure 19.

Visualizing the mesh harmonic contents of meshes 1–3 on a logarithmic scale, the pattern of the behavior along pinion cone setting is similar, proving that single-flank transmission error checks are able to replace vibration noise checks.

Conclusion

The continuous evaluation process fulfills two different demands for the manufacturers of spiral bevel and hypoid gears, demands that—until today—were contradictory: short cycle times and full information on running behavior.

Fulfilling these demands ensures reliable statements about the noise behavior that can be expected. Applying the continuous method, which provides information identical in quality to that of the non–continuous checking method, helps manufacturers avoid assembling gear sets that are likely to fail due to unwanted noise emissions in the vehicle. Also, the continuous approach helps them in less time than the successive method, thereby reducing costs.

Recent development of roll testing after gear set assembly helps to further reduce the number of noise failures of assembled carriers by evaluating the quality of transmission, thus allowing manufacturers to filter inaccuracies in the gear set assembly stage.

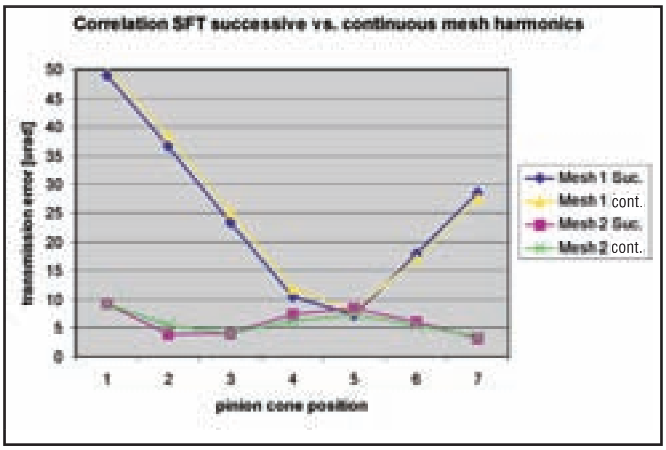

Figure 18—Single-flank transmission error successive checking vs. continuous checking.

Table 3—Correlation Coefficient Single-Flank Check, Successive Method vs. Continuous Method.	
Characteristic	Correlation Coefficient Single Flank, Successive vs. Continuous
Mesh 1	99.68%
Mesh 2	93.57%
Mesh 3	94.64%
Mesh 4	96.93%
Mesh 5	95.08%

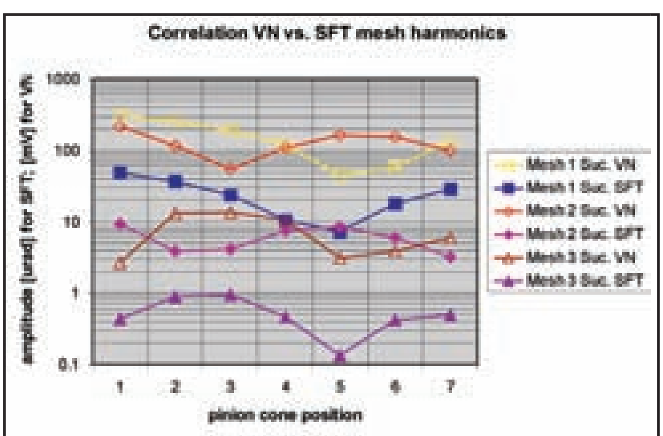

Figure 19—Vibration noise successive checking vs. single-flank successive checking.

Outlook

The new approach, enabling continuous collection of measurement data, offers options for further developments and additional analytical approaches by varying characteristics other than pinion cone setting only. The options include scans with continuously variable amounts of backlash and vertical offset. Furthermore torque- and speed-scans measuring the continuous variation of SFT and/or VN will improve the analytical capabilities of gear engineers both in the development stage and in production. With an angular tester with V, H and J deviations, angular displacements—which will necessarily occur on a bevel gear set under load—can now be simulated, opening up another variable for better research and development.

An earlier version of this paper was presented at the International Conference on Gears, held March 13–15, 2002, in Munich, Germany. It was also published by VDI Verlag GmbH in the conference's proceedings, VDI report 1665. It has been updated by the authors and is republished here with VDI's permission.

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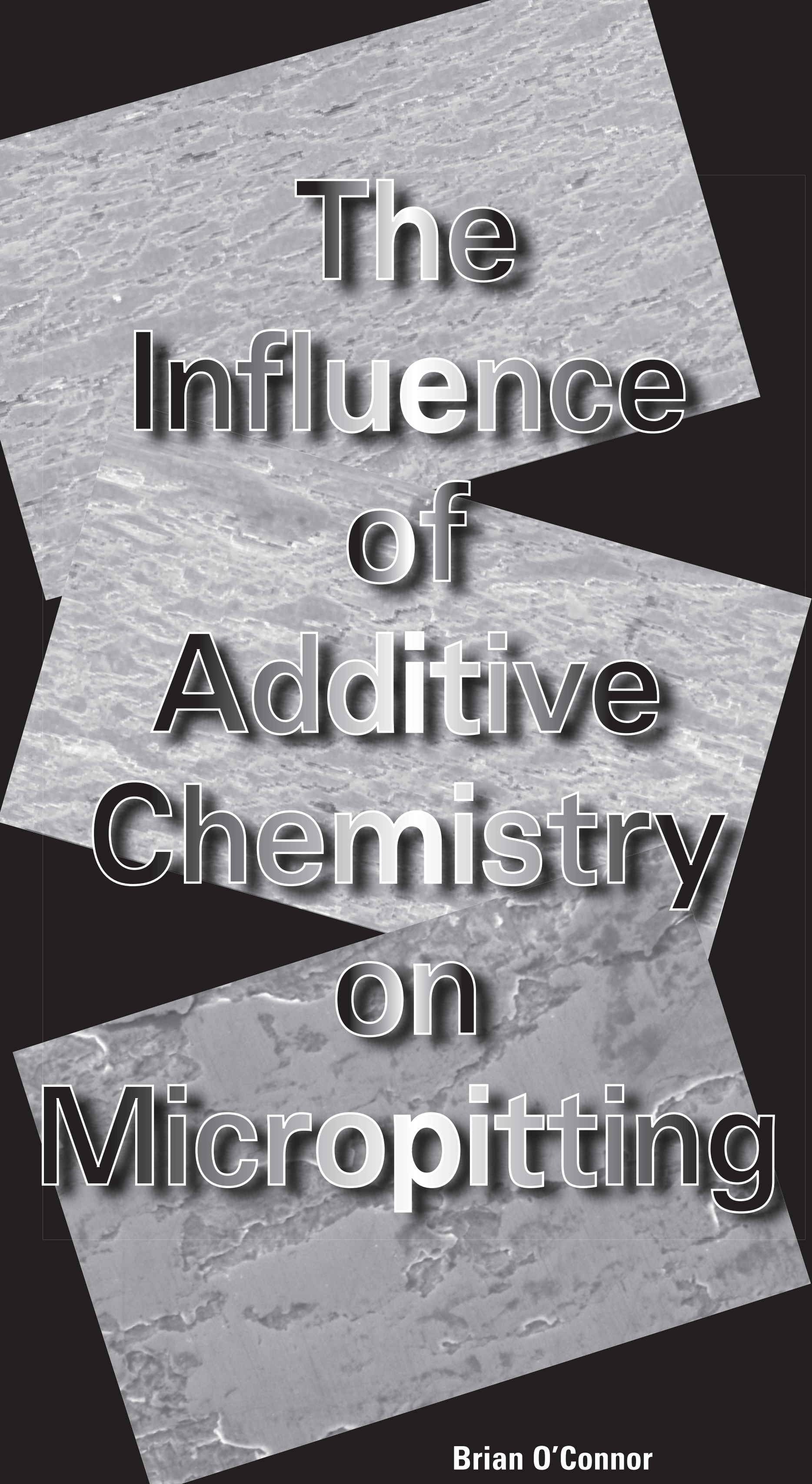

The Influence of Additive Chemistry on Micropitting

Brian O'Connor

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Introduction

Micropitting is a form of surface fatigue that appears to be benign, but can cause significant problems in drivetrains. It is not a new issue, but more recently, micropitting has been receiving increased attention as a serious mode of failure in many large industrial drives and also some automatic drives. Micropitting has become a significant issue in the wind turbine industry as turbine outputs have increased. What was thought to be harmless discoloration (gray staining) of the gear teeth is now recognized as a damage mode that can impact gear tooth accuracy, leading to increased noise and vibration and reduced gear life. The phenomenon has been studied from several perspectives, including kinematics, surface finish, metallurgy and lubrication (Refs. 1–5). The mechanisms behind micropitting are not completely understood, but it appears clear that it is affected by operating conditions, surface roughness and lubricant.

Lubricant studies have generally been limited to evaluating different commercial fluids in the marketplace or simplistic systems put together with available additives (Refs. 6–7). From this, some broad conclusions have been drawn, mostly suggesting that higher viscosities are more effective at reducing micropitting. This is helpful, but the problem of micropitting has not been studied in depth from the perspective of the chemical additive system. This work begins to address that issue and focuses on the impact various additive chemistries have on the micropitting form of damage. Typically, the additive is not well documented because of the proprietary nature of many of the components used. Nonetheless, the additive is an integral part of the lubricant formulation and is responsible for protecting gear and bearing surfaces from scuffing, catastrophic wear and corrosion in addition to minimizing oxidative degradation, minimizing foaming, and enabling water separation in many applications. The chemical additive system can then be a complex mixture of several different components, each used to provide a different performance function.

They must also be compatible with each other and not diminish performance in areas outside their intended use. Thus, it becomes a careful balancing act to provide a broad functional system for the typical industrial application. When a new performance issue, such as micropitting, is introduced, the lubricant and its additive system must be re-examined to determine how its various components impact and help alleviate the problem.

As mentioned, one approach to improve micropitting performance through the lubricant is simply to increase its viscosity. This should increase the effective film thickness in the contact and reduce the amount of asperity contact, that is, increase the lambda ratio (film thickness to surface roughness ratio). This has been demonstrated to be an effective approach in some cases, but, in others, additive effects can still override the higher viscosity (Refs. 4, 8). Higher viscosity can also contribute to increased churning losses and reduced energy efficiency. This begins to have an impact on the economics of wind turbines in that there is less power being delivered to the grid due to increased losses in the transmission. Another approach would be to look at altering the additive chemistry while maintaining or reducing the viscosity of the fluid.

A typical industrial gear additive package consists of a number of individual components, each designed to provide a specific performance function. Many of these components are polar compounds, which absorb or react with the metal surfaces they are trying to protect. Examples would include antiwear (AW) agents, extreme pressure (EP) or antiscuff agents and corrosion inhibitors. There are at least two types of corrosion inhibitors—one for preventing rust of ferrous components and the other for the prevention of corrosion of non-ferrous surfaces, such as copper or copper-based alloy components. The copper-based alloy components are usually referred to as metal deactivators or metal passivators (MP). Other compounds used for control of oxidative degradation, deposit control, foam inhibition and demulsibility act more through interactions in the bulk field.

Management Summary

Gear micropitting has been a highly visible issue in selected applications in recent years, most notably in large wind turbine transmissions. Various industry groups have addressed the problem from their own areas of expertise. This has included evaluation of the gear design characteristics, surface finishing, the use of special coatings and lubrication. A common approach to improve the lubrication has been to increase the viscosity and create thicker films, which, in turn, reduce the amount of surface asperity interaction. Another approach from the lubricant side has been to alter the additive chemistry to effect a change in the wear properties of the system.

This paper discusses the potential effects observed for different antiwear and EP chemistry on the micropitting of cylindrical gears. Tests were conducted in an FZG test rig, which has been used by the industry as a guide for general gear performance. Fluids were examined in a series of experimental designs, which served as the iterative process leading toward an optimized additive system. The results show that the EP, or antiscuff, agent was the most effective component at reducing the level of micropitting.

For the purpose of this study, a generic industrial gear additive system was created that basically took the most common components used to meet a basic set of performance requirements such as those outlined in AGMA 9005-E02 (Ref. 9). This package comprises an antiwear agent, EP agent, metal passivator, rust inhibitor, demulsifier, deposit control agent, friction modifier and foam inhibitor. The study began with the premise that the micropitting would likely be influenced by those components that reacted with the metal surface. This included the antiwear and the EP components of this formulation. In addition, experience has shown that the deactivator or metal passivator component can be very surface active and, in some cases, interfere with the primary function of the antiwear agent or the EP agent or both, and so this component was included in the assessment. Thus, the variables would be the AW, EP and MP, while the balance of components remained constant in the experiments. Additional studies followed where the changes were limited to varying only the antiwear and later only the EP agent, all other components being held constant. It became clear from these experiments that the EP agent had a greater effect than the antiwear agents. Further, there was evidence in the performance of the formulation with respect to micropitting performance.

Experimental

Despite the growing importance and performance implications of micropitting as a damage mode on gear drivetrains, there are no standardized tests available to the lubricant industry. Thus, part of the effort here was to develop a screening method that would reproduce the micropitting phenomenon and have relevance to the application of interest. The equipment used in these studies is the standard FZG four-square rig with the method evolving from a brief study involving different combinations of speeds and loads (torques). The gears are the standard "C" profile FZG gears generally used in pitting evaluations with this test rig. The lubricants are based on generic industrial gear oil and encompass the typical key components that are used in commercial formulations today.

Test Rig. The FZG test rig is well known in the oil industry for measuring the scuffing load capacity of many types of fluids and is the basis for several test standards (Refs. 10–12). The FZG tester is a recirculating-power, four-square configuration rig. The basic test rig has been demonstrated to have sufficient versatility to evaluate a variety of wear modes, such as low speed wear, scuffing, pitting and micropitting (Ref. 13).

The principal parts of the rig include a

Table 1—Blends for Matrix 1: ISO VG 32 Mineral Base.

Oil Code	A1	A2	A3	A4	A5	A6	A7	A8
Additive*								
AW–1	+	+	+	+	0	0	0	0
EP– 1	+	+	0	0	+	+	0	0
MP	+	0	+	0	+	0	+	0
	*Balance of additive package contains appropriate levels of dispersant, demulsifier, rust inhibitor and foam inhibitor.							
KV 40°C[cSt]	30.2	30.3	30.3	30.3	30.2	30.3	30.2	30.4
Elemental								
P	338	338	338	338	0	0	0	0
S	7,451	7,451	3,179	3,179	7,062	7,063	2,790	2,791
N	218	155	218	156	126	63	126	64

Note: A "+" symbol indicates normal level and a "0" symbol indicates not present.

test gearbox, a slave gearbox, a load clutch and a torsional shaft. Power is supplied by a variable speed 5.7 kW DC motor with an effective speed range from 50–3,000 rpm. The rig is designed to evaluate parallel-axis cylindrical gearing (primarily spur gears) having a center distance of 91.5 mm. The standard torsional shaft (23 mm diameter) will permit torques to at least 550 Nm on the test gears. The gears are loaded by applying torsion to a shaft through a slip clutch by means of weights or a scanner device. The locking bolts on the clutch ensure the torsional load is maintained during the running period.

Test Gears. The evaluations discussed here were conducted using two standardized test gears available for the FZG rig. One is known as the "C" profile and the other is identified as the "C-GF". These gears are typically used for pitting and micropitting evaluations, respectively, in the FZG rig. Both gear types are case carburized 16MnCr5 steel with a tooth width of 14 mm. The primary difference is in the finish, with the "C" type gears having an average roughness value of Ra = 0.30 +/– 0.05 μm and the "C–GF" gears typically with an Ra value = 0.50 +/– 0.10 μm. These gears do not have any tip relief or lead modification, as might be found in typical automotive or industrial applications, but they still serve as a useful test tool for relative comparison within their known limitations.

Test Methods. Although no officially sanctioned test method exists, the most widely accepted method for micropitting performance today is described in the FVA Information Sheet 54/I–IV (Ref. 11). This is basically a summary of the testing protocol used by Schoennenbeck in the early 1980s in his studies of micropitting (graufleckigkeit) at the Technical Univesity of Munich (Ref. 4). This is a very long and tedious test method and requires special gear checking equipment to measure the profile deviation along the involute of the tooth. Many test laboratories do not have the special equipment required to carry out the profile deviation measurement. There is, however, a general relationship between weight loss and profile deviation that we have used in our internal screen testing. Care must be maintained to minimize macropitting, as this can distort the response.

In order to evaluate a relatively large number of lubricant modifications in a timely and cost-effective manner, a screening procedure was developed from a short study of different operating conditions. The objective was to minimize the onset of macropitting while maximizing the wear that would occur from just a micropitting mode of damage. From previous experience, it is known that macropitting would occur with torques greater than 302 Nm (standard load stage 9) applied to the rig. Most industrial lubricants were capable of running for at least 100 hours before macropitting would occur. The operating condition study involved comparing the response of a single reference fluid using two speed variables (cycling multispeed vs. constant speed) and two torque variables (sequential step load vs. constant load) in a simple 2 x 2 matrix. The results showed that the maximum wear without significant macropitting was achieved with the constant speed, constant load combination of operating conditions. This is similar to the screening method used by Thiessen (Ref. 14). Thus, for the evaluations presented here, the test conditions used were: pitchline velocity = 6.25 m/s; pinion torque = 300 Nm, and duration = 72 hours. Type "C" profile gears were used in the screening method presented here. Also, in these experiments, the temperature was intentionally not controlled but rather allowed to seek its own equilibrium. Since many applications do not control the lubricant temperature, this was also applied to the experiments. It is an attempt to get closer to actual practice and affords some additional information about the thermal characteristics of the lubricant under test. At the end of each test, the gear is rated for area damaged by micropitting (averaged over 16 pinion teeth), macropitting (sum total over 16 pinion teeth) and wear by weight loss observed for the pinion and gear.

Following the screening evaluations, testing was conducted with a modified test matrix in the test known as the FVA 54/I micropitting test (Ref. 15). This is a two-part test conducted in a standard FZG test rig using jet spray lubrication. The first phase of the test involves a series of six, 16-hour increasing step load stages. At the end of each 16-hour stage, the gears are measured for profile deviation. The criteria for acceptability is ≤ 7.5 μm average profile deviation over three teeth on the gear set. The second part of the test is the durability phase and consists of a series of 80-hour stage runs at constant load. After each 80-hour stage, the gears are checked for profile deviation. In this phase, the criteria is ≤ 22.5 μm average profile deviation for acceptable performance. The test is then rated on a load stage achieved in part one, and the length of testing is achieved in part two. An overall rating with respect to the micropitting performance is assigned based on load stage, durability life and general condition of the gears.

Test Lubricants. Lubricants used for many wind turbine applications today are typically ISO 320 viscosity grade. Since the objective of these studies was to identify potential additive response, a lower viscosity lubricant was chosen to increase the probability of asperity contact and accentuate the influence the additive may have on micropitting performance. The initial studies were done with a mineral base blend meeting the ISO VG 32 characteristics. Later studies were done with mineral base fluids meeting the ISO 150 viscosity grade to address other issues and will be reported on in the future.

For the ISO VG 32 blend, the base oil was a solvent-refined 150 neutral oil meeting the characteristics of an API Group I Stock (Ref. 16). The additive was noncommercial but designed to be representative of a typical industrial gear additive formulation meeting the requirements of AGMA 9005-E02 (formerly 9005-D94) (Ref. 9). Although the primary interest was in the antiwear (AW), antiscuff (EP) and metal passivator (MP) components, it is important to work with an otherwise complete package to determine if interactions may occur that might not be observed when evaluating isolated components. The balance of the additive package consisted of a dispersant for deposit control, demulsifier for water shedding capability, rust inhibitor and foam inhibitor.

In the first group of experiments, the focus was on the AW, EP and MP components. These were either present at their conventional treatment levels or at zero levels. A simple three factor-two level factorial design was created to evaluate the main effects and potential interactions of these components as outlined in Table 1. The physical and basic characteristics are provided in the table. As a follow up to those experiments, a series of evaluations were conducted where only the antiwear agent or the EP agent was varied to ascertain the response of different chemistries for the same performance function. The general characteristics for the alternate antiwear and EP blends are described in Table 2. The alternate antiwear and EP components were chosen to provide a range of different chemical functional groups or activity levels. They are generically described in Table 3.

Table 2—Blends for Antiwear and EP Studies.

Oil Code	A1	AW2	AW3	AW4	EP2	EP3	EP4
Additive*							
AW–1	+				+	+	+
AW–2		+					
AW–3			+				
AW–4				+			
EP–1	+	+	+	+			
EP–2					+		
EP–3						+	
EP–4							+
MP	+	+	+	+	+	+	+
*Balance of additive package contains appropriate levels of dispersant, demulsifier, rust inhibitor and foam inhibitor.							
KV at 40°C [cSt]	30.2	30.3	29.9	30.1	29.4	29.8	30.7
Elements							
P [ppm]	338	340	340	340	338	338	338
S [ppm]	7,451	7,046	7,050	7,048	7,454	7,453	7,446
N [ppm]	218	289	285	126	218	221	982

Table 3—Description of Antiwear and EP Chemical Components.

Component	Chemical Description	Function
AW–1	Medium-chain alkyl dithiophosphoric acid ester, amine salt	Antiwear (8.5% P)
AW–2	Long-chain alkyl phosphoric acid ester, amine salt	Antiwear/friction modifier (5.0% P)
AW–3	Medium-chain-length alkyl phosphoric acid ester, amine salt	Antiwear (7.7% P)
AW–4	Long-chain alkyl phosphite	Antiwear/friction modifier (5.8% P)
EP–1	Alkyl disulfide	Antiscuff (43% S)
EP–2	Alkyl polysulfide	Antiscuff (45% S)
EP–3	Alkyl polysulfide	Antiscuff/cutting agent (54% S)
EP–4	Experimental mono- and disulfide	Antiscuff/antioxidant (40% S)

Results and Discussion

As a first approximation, a simple 2^3 factoral design was evaluated to determine if the chosen variables were contributing to the micropitting mode of damage. The variables addressed in this matrix were the antiwear (AW), antiscuff (EP) and the metal passivator (MP). These were thought to be among the more surface-active components with reaction potential with the surface. To increase the emphasis on the effect coming from the additive system, a very light viscosity grade was chosen in order to maximize the surface asperity interaction. The nominal roughness value for the "C" profile FZG gears used in the early studies was approximately 0.3 μm. Using

Table 4—Results with Matrix 1.								
Oil Code	A1	A2	A3	A4	A5	A6	A7	A8
Base Fluid	ISO VG 32 (100% Solvent Refined 150 N)							
Additive*								
AW–1	+	+	+	+	–	–	–	–
EP–1	+	+	–	–	+	+	–	–
MP	+	–	+	–	+	–	+	–
*Balance of additive package contains appropriate levels of dispersant, demulsifier, rust inhibitor and foam inhibitor. A "+" symbol indicates standard treat level, and a "–" symbol indicates not present.								
FZG Micropit Screen Test								
Micropit area [mm²]	17.9	23.4	24.4	24.8	18.7	9.1	N/A	N/A
Macropit area [mm²]	0	0	0.2	52.4	0	8.9	N/A	N/A
Weight Loss [mg]	22	29	37	102	49	47	12,309	4,562
Tmax [°C]	107.4	115.6	111.9	125.1	108.9	103.2	148.6	143.5
Tavg [°C]	103.5	110.6	106.2	116.7	100.7	98.9	119.0	107.7

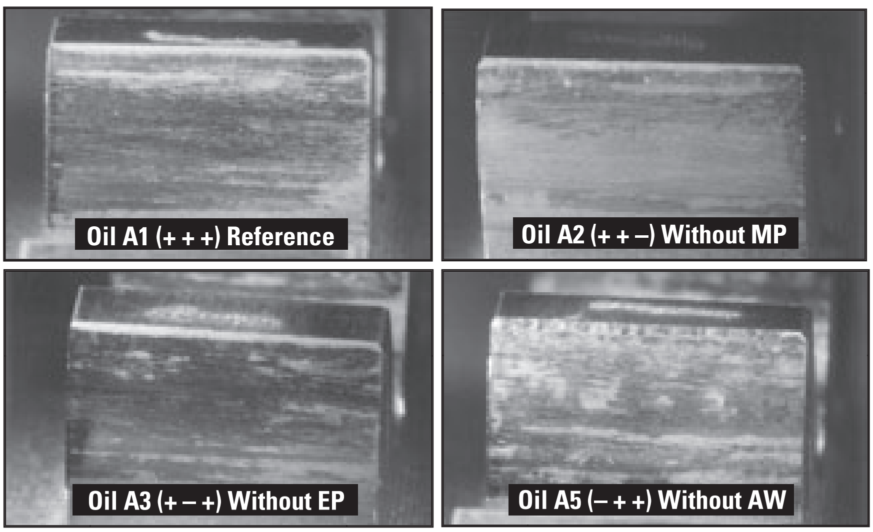

Figure 1—Comparison of micropitting damage from FZG Micropit Screen Test – Matrix 1.

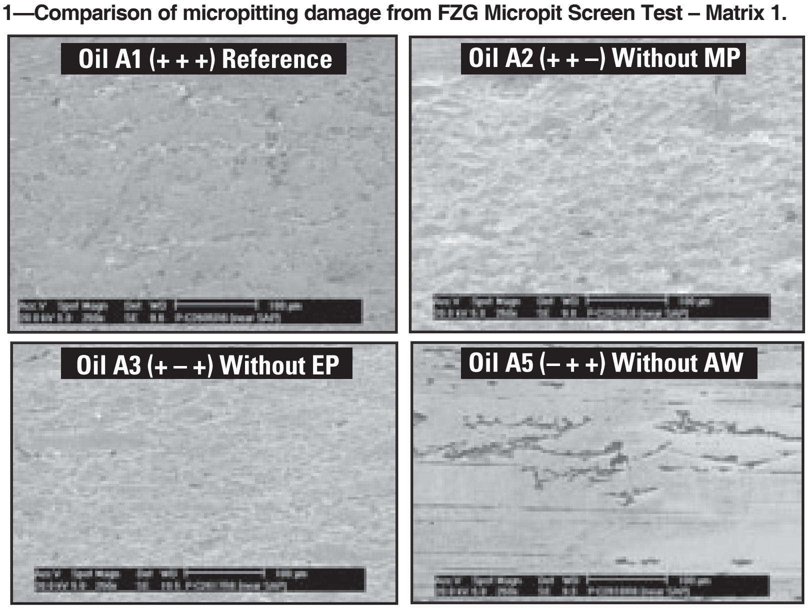

Figure 2—Influence of Main Effect Components (AW, EP, MP) on micropitting from Matrix 1 (all micrographs taken approx. 2 mm above SAP).

the Dowson-Higginson formula for film thickness in EHD line contact situations shown in Equation 1, it was clear that the typical ISO VG 320 viscosity used in many industrial applications would provide a very thick film and limit the possible additive interaction with the surfaces (Ref. 17).

$$h_{min} = 2.65 * \frac{R * G^{0.54} * U^{0.7}}{W^{0.13}} \qquad (1)$$

Where:
h_{min} = minimum film thickness
R = reduced radius of curvature for the mating components
G = dimensionless materials parameter
U = dimensionless velocity parameter
W = dimensionless load parameter

It was desired to reduce the lambda ratio to well below 1.00 to provide an adequate forum for the additive interaction with the surfaces. Based on the calculations for the minimum film thickness using the Dowson-Higginson equation above and the typical surface roughness of the gears, an ISO VG 32 blend should provide a lambda ratio of approximately 0.6.

The results of the first test matrix are summarized in Table 4. A complete mathematical analysis of the results could not be carried out due to the severe wear encountered with the two tests run without the antiwear and EP components (blends A7 and A8). This clearly points out the value of these components in a loaded sliding contact. Because of the extremely high wear, the gears could not be rated for micropitting damage. The remaining six tests did provide some direction. The results suggest that there are likely interactions between the EP agent and the antiwear and metal passivator, which detract from performance. If one compares oil A6 (EP agent only) to either oil A2 (the comparable blend with the antiwear present) or to oil A5 (the comparable blend with the metal passivator present), both cases result in more micropitting.

Sometimes, one must look beyond empirical results to see difference. If one compares oil A1, A2, A3, and A5, the average area of micropitting damage is similar, i.e. 17.9, 23.4, 24.4 and 18.7 mm^2 respectively. The typical visual assessment shown in Figure 1 confirms that these appear similar. However, as one examines the surfaces more closely, as in Figure 2, there is a distinct difference in the appearance of the micropitting damage for oil A5 compared to the other three. This change in appearance suggests that the antiwear component present in A1, A2, and A3 may be affecting performance in a negative fashion, since oil A5 was constructed without the antiwear component. The micropits on the surface of the gear run with oil A5 are larger in size, but the surface around them is much smoother, which suggests a possibly lower wear with increased running time, a point that was not examined in this study.

The previous exercise evaluated one antiwear agent and one EP agent in the matrix. The antiwear was a medium-chain-length alkyl dithiophosphoric acid ester and the EP was an alkyl disulfide. In two sets of evaluations, a series of simple substitution experiments were conducted to determine if the response (micropitting) would be altered if the chemical functionality were changed. There are still interactions to consider, but this limited work was a pilot to see if any effect could be observed. Using blend A1 from Matrix 1 as a baseline or reference, the alternate components were substituted on an equal chemical (phosphorus or sulfur) basis for the reference materials now dubbed as AW-1 and EP-1. A list of alternate components is shown in Table 3.

Two approaches are considered here to address the micropitting issue. One is to reduce the friction at the surface and thereby reduce the tangential stress acting on the asperities that form the micropits. The other approach is to actually induce a high rate of wear to rapidly remove the asperities and thus minimize the long-term damage from micropitting. The latter is considered more as a chemical break-in approach. If reduced friction is an important aspect in the mechanism of the micropitting formation, then the two long-chain alkyl phosphorus derivatives, AW-2 and AW-4, should help based on their performance in automotive applications. For the case involving high, chemically induced wear, the more active antiscuff components, EP-2 and EP-3, were chosen to accomplish this. These components are generally more active than the EP-1 baseline component and should provide a higher rate of wear, thereby reducing the surface roughness more rapidly. As part of the investigation, an antiwear component of similar alkyl chain length but different functionality (AW-3) and an experimental alkyl disulfide (EP-4) were also included simply to look at different chemical functional groups.

The results shown in Table 5 do not necessarily support either the reduced friction or increased wear approaches to reduce micropitting, at least for the components chosen. Of the two long-chain

Table 5—Results with Alternate Antiwear and EP Components.

Oil Code	A1	AW2	AW3	AW4	EP2	EP3	EP4
Base Fluid	ISO VG 32 (100% Solvent Refined 150 N)						
Additive*							
AW–1	+				+	+	+
AW–2		+					
AW–3			+				
AW–4				+			
AW–5							
EP–1	+	+	+	+			
EP–2					+		
EP–3						+	
EP–4							+
MP	+	+	+	+	+	+	+
*Balance of additive package contains appropriate levels of dispersant, demulsifier, rust inhibitor and foam inhibitor.							
Micropit area [mm^2]	17.9	30.9	12.6	12.4	38.8	39.4	6.9
Macropit area [mm^2]	0	7.5	0.6	27.4	0	0	4.9
Weight loss [mg]	22	41	40	48	52	60	28
Tmax [°C]	107.4	113.4	106.4	111.1	117.4	115.5	106.9
Tavg [°C]	103.5	108.2	100.9	103.6	114.5	111.0	103.7

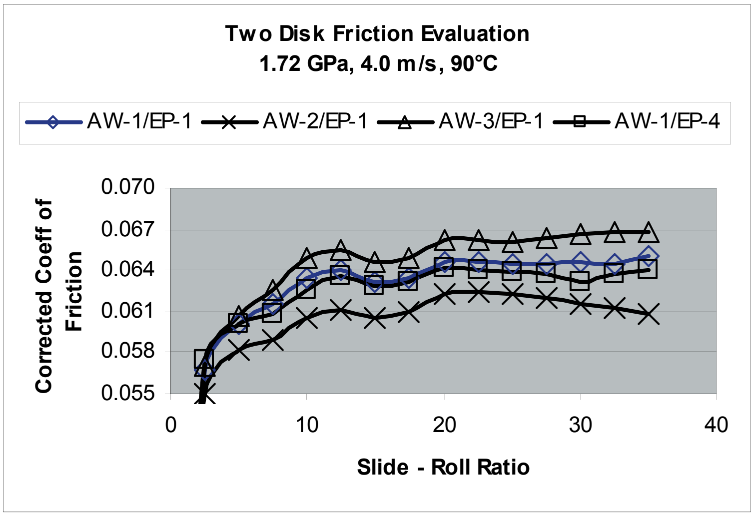

Figure 4—Two Disk Friction Response vs. Slide-Roll Ratio.

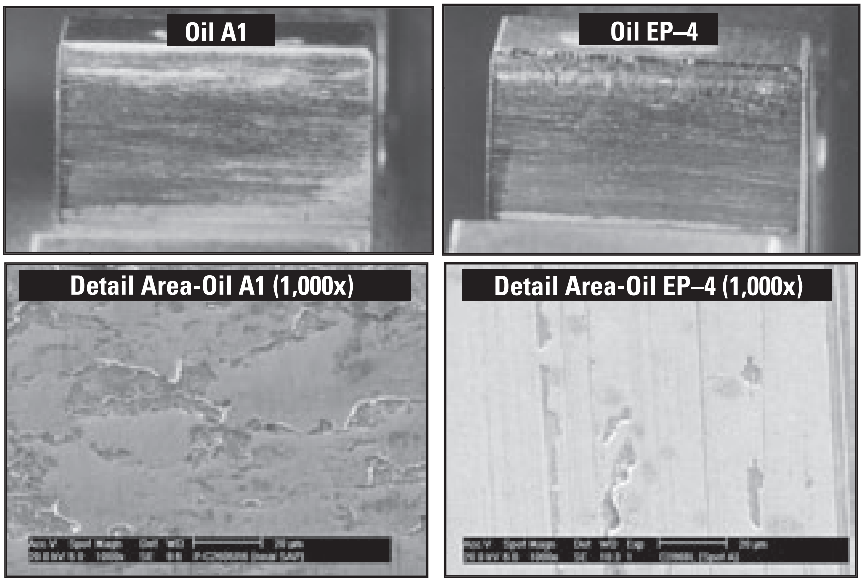

Figure 4—Comparison of micropitting damage from FZG Micropit Screen Test.

Table 6—Evaluation of Matrix 2.

Oil Code	A1	A2	B1	B2	A5	A6	B3	B4
Base Fluid	ISO VG 32 (100% Solvent Refined 150N)							
Additive*								
AW–1	+	+	+	+	–	–	–	–
EP–1	+	+	–	–	+	+	–	–
EP–4	–	–	+	+	–	–	+	+
MP	+	–	+	–	+	–	+	–
*Balance of additive package contains appropriate levels of dispersant, demulsifier, rust inhibitor and foam inhibitor.								
FZG Micropit Screen Test								
Micropit Area [mm²]	17.9	23.4	6.9	23.7	18.7	9.1	N/A	0.1
Macropit Area [mm²]	0.0	0.0	4.9	45.3	0.0	8.9	0.0	0.9
Weight Loss [mg]	22	29	28	93	49	47	248	17
Tmax [°C]	107.4	115.6	106.8	109.0	108.9	103.2	100.2	97.5
Tavg [°C]	103.5	110.6	103.7	105.7	100.7	98.9	95.0	94.5
Comment				Macropit fail			Severe wear—could not rate	

alkyl phosphorus compounds that were aimed at reducing friction, only the AW-4 material showed a reduction in micropitting. The medium-chain alkyl phosphoric acid ester, AW-3, also showed a similar reduction in micropitting. It is interesting to note that the other long-chain phosphoric acid ester (AW-2), which was expected to have a much lower surface friction, did not perform very well. Using a similar two-disk apparatus, the friction properties of selected alternate component blends were also examined. Figure 3 shows that the response of friction as a function of slide-roll ratio is very similar for these fluids regardless of their gear micropitting performance. This suggests that a different mechanism is controlling the micropitting response.

From the theory of increased wear, neither of the more active sulfur compounds, EP-2 or EP-3, performed as expected. In fact, their performance was detrimental with regard to micropitting protection. The experimental alkyl disulfide, however, provided a significant reduction in micropitting compared to the baseline EP–1 formulation. Figure 4 highlights the comparison between oil A1 and oil EP–4 in the critical region near the start of the active profile (SAP) on the pinion gear. There is clearly a difference in the amount of micropitting and the surface topography of these two runs. The original machine marks are still visible in the test with EP-4, whereas with A1, the surface in the same region is void of detail beyond the micropitted damage.

While the focus of this study was to examine and reduce the amount of micropitting formed through the lubricant, the alternative antiwear components that did show a benefit, AW-3 and AW-4, were found to have deficiencies elsewhere that limited their long-term use. Thus, the next iteration would only include further evaluation of the EP component, EP-4, which showed a benefit in the initial screening. Again, it was desired to look for interactive effects between the potential components of interest. A modified version of the first matrix was then set up and evaluated. In this case, the blends were first evaluated in the short screen test and then later by the FVA 54/I method.

The Matrix 2 design and results for the FZG screen test and full length FVA 54/I tests are shown in Tables 6 and 7, respectively. From the available data, one can examine trends with respect to the response of the main effects, i.e., the presence or absence of AW-1, use of EP-1 vs. EP-4, and the presence or absence of the MP. From the screen test results, we find that the presence of AW-1 in the formulation leads to higher amounts of micro- and macropitting and increased maximum and average oil temperatures during the testing. Component EP-1 resulted in higher levels of micropitting and higher oil temperatures than EP-4, but had less macropitting on average than EP-4. There was no real difference in the measured parameters when the metal passivator was present or not. If one examines the FVA 54/I test data in a similar fashion, it shows the antiwear component produces, on average, higher amounts of micropitting along with higher levels of profile deviation. This is consistent with the trends observed for the screen test. For the EP and metal passivator (MP) components, the FVA test did not show any notable separation for the profile deviation, which is the critical measurement of that test. It is interesting to note that despite the use of a very low viscosity base fluid (ISO VG 32), there were several cases of high micropit classification. This is encouraging from the standpoint that perhaps lighter fluids may be used in the future, if the additive system provides adequate protection.

Conclusion

The work presented in this study is part of a larger program to investigate and understand lubricant chemical response toward micropitting of gears. This initial work shows that the choice of additive chemistry can have an impact on performance. Additionally, it is clear that there are variations of performance within a given functional family. Therefore, it may not be prudent to arbitrarily declare a given functionality, such as antiwear or EP, as being more beneficial or detrimental over the other, owing to the many possible chemical types that fall within a given performance functional group. This work has also looked at friction and wear as factors in the micropitting process, but the results did not support the premises. Additional work is being undertaken to explore the mechanism involved.

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Table 7—Evaluation of Matrix 2 by FVA 54/I Method.

Oil Code	A1	A2	B1	B2	A5	A6	B3	B4
Base Fluid	ISO VG 32 (100% Solvent Refined 150N)							
Additive*								
AW–1	+	+	+	+	–	–	–	–
EP–1	+	+	–	–	+	+	–	–
EP–4	–	–	+	+	–	–	+	+
MP	+	–	+	–	+	–	+	–
*Balance of additive package contains appropriate levels of dispersant, demulsifier, rust inhibitor and foam inhibitor.								
FVA 54/I Micropit Test								
Overall Rating	High	Middle	N/A	Low	High	Middle	Middle	High
Part 1: Step Load								
Fail LS	10	10	10*	9	>10	9	9	>10
Profile Dev. [μm]	11.1	9.0	7.5	8.7	2.7	8.0	8.0	7.5
Weight Loss [mg]	21	45	24	65	18	34	27	19
Part 2: Durability								
Duration [h]	480	320	N/A	160	160	240	160	240
Profile Dev. [μm]	19.0	22.5	N/A	22.5	14.3	18.4	22.5	21.0
Comment			*Scuff failure	Macropit fail	Macropit fail	Macropit fail		

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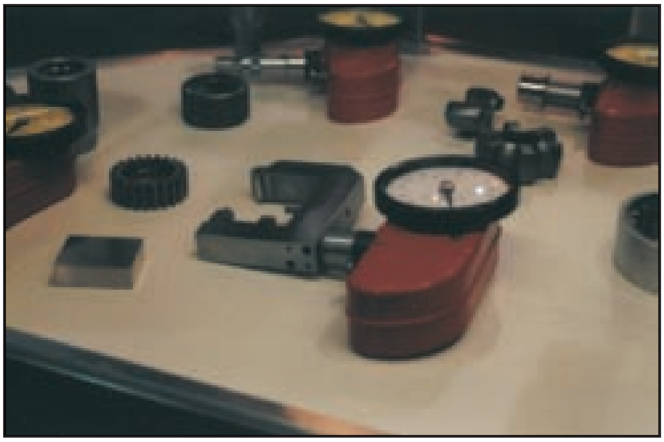

Quality Expo Exhibits Gear Measuring Equipment

Dedicated gages for measuring pitch diameter, a flexible bench system for measurement over balls, and nests for measuring features of straight bevel gears.

These were among the many gear-related products featured at Quality Expo, held April 19–21, at the Donald E. Stephens Convention Center in Rosemont, a Chicago suburb. Held for more than 20 years, this year's expo displayed inspection, testing and measurement equipment, software and services from more than 200 exhibitors.

Pitch diameter gages were the main gear products exhibited by Comtorgage Corp., based in Slatersville, RI. The handheld gages are for use on the shop floor, in high volume production of gears and splines.

In such production, employees may be required to make frequent, accurate measurements of dimensions at the machines to monitor quality. Comtorgage specializes in dedicated gages, each one measuring a specific dimension of a part of specific type and size.

"The gage is dedicated to the application and is not adjustable for a wide variety of sizes," said Kim Gradolf, a Comtorgage regional sales manager. "Using a gage designed for only one dimension, for a high production part, will be far more accurate and repeatable than an adjustable gage."

Comtorgage's pitch diameter gages cost about $1,500–$3,000.

Gradolf said the gear industry mainly uses Comtorgage's gages to measure bore size, major diameter, minor diameter, outside diameter and pitch diameter of spur, helical and ring gears and most types of internal and external splines.

Comtorgage also designs and manufactures standard and customized gages for measuring threads, bores, keyways and other features. Measurements can be viewed via analog dial or digital readout or can be transmitted directly to computers or data collectors.

At the Marposs display, flexibility was a major feature of its main gear product, a bench system for measurement over balls. The system is retoolable, allowing it to measure gears with a variety of diameters.

Its other major feature was the cushioning mechanism for the retractable ball. The mechanism can be adjusted so if a person lets go of the retractable arm, the ball will slowly settle against its gear, not slam into it.

"It can be used on a shop floor, or it can be used in a lab," said Gary Sicheneder, Marposs Corp.'s manager–new market development.

The system can be attached to a column for amplifying and displaying results, to a computer or to a dial or digital indicator. The system, with a column, costs $6,000–$7,000.

The bench system is part of the M62 product line, which covers all of Marposs' gear-related products. The company also exhibited a number of master gears and handheld spline gages.

Located in Auburn Hills, MI, Marposs manufactures and supplies products for applications requiring measurement, control, and data management at each stage of the production process.

At Euro-Tech Corp.'s exhibit, bevel gear nests were a featured item among its gear-related products.

Made by Frenco GmbH of Altdorf, Germany, the ground nests can be used to measure back face runout, pitch diameter, O.D. roundness and shaft concentricity in the case of a bevel gear shaft. The nests are made so straight bevel gears rest on their pitch diameters and reference those diameters for machining or inspection.

"The tooth-to-tooth index repeatability of a Frenco ground nest is second to none in accuracy," said Jerry Kowalsky, president of Euro-Tech, which is located in Menomonee Falls, WI.

A nest costs about $2,400–$3,000, depending on bevel gear size and quantity produced.

Euro-Tech also displayed indicating spline gages for internal and external splines and clamping systems for toothed profiles.

Euro-Tech, a sales and engineering company, represents European-made gages and tooling, including arbors, chucks, drills, measurement systems, taps and accessories.

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Web: ***www.eurotechcorp.com***

EVENTS

Solving and Avoiding Gear Failures: AGMA Offers 14th Annual Seminar

"Gear failure can lead to company failure," says gear consultant Robert Errichello. "Whether your company manufactures gears, sells lubricants or uses gears, you need to know how to prevent gear failures and how to correct them if they occur."

Consequently, the American Gear Manufacturers Association is sponsoring the 14th Annual Gear Failure Analysis Seminar. The seminar is taught by Errichello and gear failure analyst Jane Muller, both of GEARTECH, located in Townsend, MT.

Attendees will learn gear failure modes, what causes them, how to fix them, how to prevent them and what to watch for. Students will be able to examine sample gears showing the modes. Also, they can bring samples or photographs of their own failed gears and discuss them during the seminar's workshop.

The seminar includes a written test and a practical test with real gear failures, allowing attendees to practice failure analysis. They then present their analyses to the class.

"What we teach is directly applicable to everyday problem solving," Errichello says.

Past students included gear engineers, users and reasearchers, maintenance and lubricant technicians, and managers.

The seminar will be held twice in 2005: June 20–21 and Sept. 19–20. Each offering is limited to 30 people.

Charlie Fischer, AGMA's manager–technical division, expects the June offering to sell out by early May. Fischer handles registration for the seminar, which has sold out for several years running.

The seminar costs $625 per AGMA member, $845 per nonmember. The cost includes a 272-page manual, which has copies of seminar presentations, reference technical papers and an atlas of 36 photographs showing all failure modes and briefly explaining each mode.

The seminar will be held at Big Sky Resort in Big Sky, MT. Attendees can reserve rooms by calling the resort and can obtain a special room rate, $125 a night for a single or double room, by mentioning the AGMA during reservation.

To register:
Charlie Fischer
AGMA
500 Montgomery Street, Ste. 350
Alexandria, VA 22314-1581
Phone: (703) 684-0211
Fax: (703) 684-0242
Internet: ***www.agma.org***
E-mail: ***tech@agma.org***

For other information:
Jane Muller
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Phone: (406) 266-4624
Fax: (406) 266-4625
E-mail: ***rlegears@aol.com***

PM² TEC Conference

The streets of Montreal will be abuzz with metallurgy talk this summer when the International Conference on Powder Metallurgy & Particulate Materials hits the Palais du Congres.

The conference, held June 19–23, includes special sessions that could be of interest to gear designers and manufacturers. On June 21, Special Interest Session 4 will cover P/M Solutions for the Next Frontier: Gears and Driveline Components, a program that will review the state-of-the-art in gear manufacturing technologies and the appropriate powder metallurgy response. Presentations will debate the performance of powder metal gears as compared to traditional wrought gears. Other discussions include "A Predictive Model Development for P/M Gear Rolling," "Rolling Contact Fatigue of Surface Densified Gears," and "Trends in Gear Manufacturing Technology."

Another feature of the event will be the exposition, with 130 exhibitors showing off their products. The Modal Shop, a manufacturer of structural and acoustical sensing systems for engineers, including many in the gear industry, will be there. Among the products The Modal Shop will exhibit is a nondestructive test system based on resonant inspection. The system can be used on powdered metal parts for end-of-line 100% inspection.

Scott Sorensen, marketing manager at The Modal Shop, believes the powder metallurgy conference is becoming increasingly important for the marketplace.

"As powdered metal parts become more widely used and find their way into more and more consumer products, the industry is poised to grow, and this show helps spread the word," he says.

Admission prices range from $75–$1,300, depending on the number of sessions to be attended.

For more information:
Metal Powder Industries Federation
Phone: (609) 452-7700
Internet: ***www.mpif.org***

EVENTS

Learn to Lessen Noise: Ohio State University's Gear Noise Short Course

Whether in the housing of an electric toothbrush or the transmission of a luxury sedan, gears should be quiet. If they aren't, then companies face two problems: gear noise and dissatisfied customers.

To solve the first, and thereby solve the second, companies need to know about gear noise, from its causes to how to minimize it.

To learn that, The Ohio State University, located in Columbus, offers the Basic Gear Noise Short Course. The course, which will be held Sept. 13–15, is for gear designers and noise specialists who encounter gear noise and transmission design problems. Past students also included manufacturing engineers.

Course attendees learn about the types of gear noise and their causes, especially the main cause: transmission error. They also learn how to measure, analyze and reduce gear noise. Prevention is taught as well, with students learning to design gears to minimize the major causes of noise. They also learn to predict transmission errors from design and manufacturing data. Other topics include shaft and gear tooth dynamics, transmission dynamics, and housing dynamics and acoustics.

The course includes lectures, demonstrations and a workshop. Laboratory and software demonstrations illustrate gear noise measurement and analysis techniques. Many of these demonstrations use the resources of two university facilities, the Acoustics & Dynamics Laboratory and the Gear Dynamics & Gear Noise Research Laboratory, also known as the GearLab.

In the workshop, attendees can bring tapes of measured gear noise data for examination via spectrum analyzers.

The course is taught by Dr. Donald R. Houser and Dr. Rajendra Singh. Houser is director of the Gear Dynamics & Gear Noise Research Laboratory. Singh is director of the Acoustics & Dynamics Laboratory.

The course costs $1,390 per person. The cost includes continental breakfasts, lunches and a dinner.

Attendees must register in advance, no later than Aug. 31. Hotels and their telephone numbers are listed on GearLab's website. Attendees are responsible for their transportation from Columbus' airport.

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Internet: ***www.gearlab.org***

May 24–26—Decision Tools for a Lean Manufacturing Environment.

TechSolve facility, Dayton, OH. Concentrates on the collection of machining data and utilizing it to make lean manufacturing decisions, communicating solutions to upper management and managing lean manufacturing projects across interdependent company departments. $795 for TechSolve members and $895 for non-members. For more information, contact the organization by telephone at (800) 345-4482 or on the Internet at *www.techsolve.org*.

May 24–26—EASTEC 2005 Advanced Productivity Seminar.

Eastern States Expo Center, West Springfield, MA. Regional event bringing together buyers and sellers of machine tools and metalworking technology. Pricing information is available by request from the Society of Manufacturing Engineers. The society can be contacted by telephone at (800) 733-3976 or on the Internet at *www.sme.org*.

May 24–26—Fundamentals of Parallel Axis Gear Manufacturing.

Pheasant Run Hotel & Conference Center, St. Charles, IL. Seminar includes computer-based visual aids, text and interactive presentations on the topics of gear nomenclature, basic mathematics for manufacturing personnel, gear hobbing, gear shaping, cutting tools and proper hob maintenance, inspection techniques and the AGMA standard, production estimating, gear finishing processes, and troubleshooting. $795 includes meals. For more information, contact Koepfer America by telephone at (847) 931-4121 or on the Internet at *www.koepferamerica.com.*

June 5–7—Machine Components 2005.

Shanghai International Exhibition Centre, Shanghai, China. The 2005 Gear Technology Exhibition for China and the 2005 International Fastener Technology Exhibit for China. This show encompasses the fastener, gear, chain transmission, spring, powder metallurgy, hydraulic and pneumatic industries. For pricing and registration information, visit the exhibition's website at *www.macomponents.com*.

June 6–9—KISSsoft Calculation Programs.

KISSsoft facility, Zürich, Switzerland. The first day is an overview of KISSsoft and shaft/bearing calculation methods. June 7–8 are dedicated to the theory of geometry and strength calculations for gears as well as gear design determination and optimization. Finally, a seminar titled "KISSsys: Modeling a System of Machine Elements" will take place June 9. €400 or $516. For more information, contact KISSsoft by e-mail at *info@KISSsoft.ch* or on the Internet at *www.KISSsoft.ch*.

M&M Precision Announces A2LA Accreditation

M&M Precision Systems Corp. began operations late last year as the world's first and only A2LA-accredited commercial gear inspection lab.

The goals of the A2LA are achieving customer satisfaction through meeting laboratory and user needs for competent testing and calibration, improving the quality of laboratories and their data, and increasing the acceptance of accredited laboratory data to facilitate trade.

"Accreditation can be defined as a procedure by which an authoritative body [accreditation body] gives formal recognition that a conformity assessment body fulfills specified requirements and is competent to carry out specific tasks. This is always third party," says Roger Brauninger, senior lab services officer of the Association for Laboratory Accreditation.

In other words, A2LA accreditation gives customers added reassurance that M&M is competent in the field of gear measuring.

According to Todd Griffieth, product manager at M&M, the company has been registered to ISO 17025 for years, which also demanded consistent measurements over a long period of time.

The difference, says Brauninger, lies in the fact that ISO 17025 is one of the quality standards considered as a basis for the A2LA accreditation. It is the most appropriate standard for quality control testing labs, he says, but there are many more quality standards which accreditation bodies utilize.

The idea to go one step further in the accreditation status was initiated by Ed Lawson, M&M's director of metrology. He sat on several AGMA committees with employees from the U.S. government's metrology center in Oak Ridge, TN, who convinced him of the need in the commercial market for A2LA accreditation.

Oak Ridge also supplies gear metrology services, but the focus of that facility is on government standards and tends to be more expensive for the customer. Yet, for a long time before M&M's recent accreditation, Oak Ridge was customers' only option.

Griffieth explains: "Their focus is slower, extremely expensive and just not designed for commercial application. Yet there was no need being met for the commercial marketplace."

M&M's accreditation is a result of a process that spanned two years, required tens of thousands of dollars (half for the initial certification and half for the yearly renewal) and the use of an outside consulting service.

According to Griffieth, the end result has justified the efforts. For starters, the Big Three (Ford, DaimlerChrysler and General Motors) stipulate that their suppliers must be accredited to A2LA. Tier One suppliers typically follow suit in those cases, says Griffieth. A multitude of components are used in building a car and all need to meet specifications for quality. Being accredited to A2LA saves the automobile manufacturers the chore of testing each of the components themselves, says Brauninger.

Post-accreditation, one of the biggest challenges has been

communicating the discrepancy between their data figures and those of a non-accredited company to their customers. In many cases, the two final numbers are very similar.

"One stipulation is that you can't advise a customer whether a measurement is good or bad. Every measurement has some amount of error, and our goal [in getting accredited] is to minimize the gray areas," says Griffieth. "A2LA says that it's not our job to justify the result [of our measurement] or apply it to someone else's business."

With time, this issue should sort itself out as the gear industry collectively familiarizes itself with the specifics of A2LA. Griffieth expects the industry to eventually embrace A2LA in the same manner as it did ISO.

"This kind of thing usually gets momentum from the top," he says. "People initially took the ISO stipulations for quality pretty lightly and now it's the expectation. We estimate that the same will happen with A2LA in less than five years."

Rexnord to Buy Falk for $295 Million

Rexnord Corp. announced that it has entered into a definitive agreement to purchase The Falk Corp. from Hamilton Sundstrand, a subsidiary of United Technologies Corp., for $295 million. The transaction is expected to close in the second quarter of this year.

Rexnord, headquartered in Milwaukee, WI, is a worldwide manufacturer of power transission components with revenues of approximately $800 million. Falk, also headquartered in Milwaukee, is a manufacturer of gears and couplings, with annual revenues of approximately $200 million.

"By combining two successful companies that have complementary products and technologies, we create a bigger, stronger business with combined annual revenues in excess of $1 billion," says Robert Hitt, Rexnord's CEO, in the company's press release. "This acquisition is consistent with Rexnord's growth strategy, enhancing our capabilities and allowing us to better serve our customers."

"Falk Corp. has a strong market presence with substantial brand equity and a significant installed base," says Dave Doerr, Falk's president. "Falk looks forward to joining with Rexnord to offer our customers the best solutions to their power transmission needs."

Star SU Consolidates Sales With Bourn & Koch, Winco

A mutual agreement has been reached for sales and marketing between Star SU and Bourn & Koch for their machine tool product lines.

This enterprise will be owned and managed by an executive committee of members of both organizations.

Star SU's comprehensive line of gear machine tool products will now be enhanced by a complementary line of gear hobbers, grinding machines and Fellows shaping machines as a result of this merger.

A separate agreement between Winco and Star SU has been reached for consolidation of sales activities of each company's gear tool product line. The intention of this agreement is to consolidate all sales activities under Star SU LLC. The enterprise, effective July 1, will be owned and managed by members of both companies.

The merger creates a significant addition to the existing Star SU gear tool product line of PCD and CBN inserts and cartridges, reamers, special cutters and integral shank tooling for high volume transfer machining systems throughout North America.

The combined enterprise allows chip-making manufacturers to use a single supplier of precision round tools and gear tools and of support service for them.

American Wera Exec Dies in Plane Crash

Jim and Deanna Eaton

Jim Eaton, vice president of sales for American Wera Inc. in Ann Arbor, MI, and his wife Deanna, died March 30 in a plane crash.

The two were headed to Sarasota, FL, to move Deanna's 85-year-old mother back to Midland, MI, for the summer when the Rockwell Commander 114B that Eaton was piloting crashed into the Gulf of Mexico. They were just a few miles from the airport.

Eaton was a graduate of Ball State University. He is survived by his mother, Catherine Burnett of Logansport, IN, and his daughter, Genessa Eaton of Saline, MI.

Walter Friedrich, president of American Wera, worked with Eaton at Liebherr for years before forming American Wera. "For us, he was very involved with hobbing and the one who pushed the first gear honing machine in the U.S."

Siemens Acquires Flender Holding GmbH

Siemens AG has acquired Flender Holding GmbH of Bocholt, Germany, for €1.2 billion in order to expand its business in industrial drive technology.

According to a company press release, Flender's activities will be integrated into the Siemens Automation and Drives Group as its 11th division.

Flender, a supplier of mechanical and electrical drive equipment, has sales of €1.012 billion and employs 6,700 employees at 80 locations.

The Siemens Automation and Drives Group, located in Nuremberg, Germany, is a leading manufacturer of automation and drives.

This transaction is subject to the approval of anti-trust authorities.

Northstar Aerospace Awarded Rolls-Royce and U.S. Army Contracts

Northstar Aerospace has received three aerospace contracts totaling $17 million from Rolls-Royce plc and the U.S. Army.

According to the company's press release, Northstar has been contracted for $9 million of work in developing and manufacturing internal gearbox components used in the Trent 1000 engine. The gearbox components will power the Boeing 787 Dreamliner wide-bodied jet that will begin service later this decade.

Two contracts were awarded by the U.S. Army's Aviation and Missile Command, which develops, acquires, fields and sustains Army aviation and missile weapons systems. The first contract has an estimated value of $4 million and entails an overhaul of the forward transmissions used in the twin-turbine, tandem rotor CH-47 Chinook transport helicopter. Also valued at $4 million, the second contract is for providing spare parts for the AH-64 Apache attack helicopter and the CH-47 Chinook.

Ritchie Moves to Star SU


Mark Ritchie

Mark Ritchie was hired as a gear tool project engineer at Star SU LLC. He has held a similar position at Gleason for the past six years. Prior to that, he worked at Atwood Mobile Products for four years.

According to the company's press release, he specializes in the design, manufacturing and application of gear hobs, shaper hobs, shaper cutters, and non-generating hobs. He has also been responsible for testing HSS materials and coating combinations for customer satisfaction. Ritchie has experience in lean manufacturing and Kaizen implementation, has been involved in ISO 9001/ISO 14001 as a lead quality auditor and is familiar with developing, linking and applying lead quality systems.

Among his new responsibilities will be providing gear tool technical service and technical support.

Gleason, Harbin Form Joint Venture

Gleason Corp. announced that it is in the process of forming a joint venture with Harbin No. 1 Tool Corp. for the production of precision gear cutting tools.

Both companies plan to produce high precision gear cutting tools and provide service to end-user markets. The joint venture will be named Gleason Yi Gong (Harbin) Cutting Tools Co. Ltd.

In the mid-1980s, Gleason licensed Harbin for certain tool technologies. Gleason will now contribute and license its latest technology, including proprietary equipment and software, as well as provide support in the form of technical know-how and training.

A letter of intent has been signed detailing the terms of the joint venture, which is slated to begin in the third quarter of this year. Gleason and Harbin No. 1 will own 70% and 30% of the joint venture, respectively.

Dana and Dongfeng Motor Sign Agreement

Dana Corp. and Dongfeng Motor Co. Ltd. signed an agreement to form a joint venture company to develop and produce commercial vehicle axles in China.

According to Dana's press release, the 50/50 joint venture will be called Dongfeng Dana Axle Co. Ltd. At a future date, the partnership may begin producing driveshafts and other products for commercial vehicles.

Arrangements will be finalized in the third quarter of this year, following government approvals.

Dana will invest approximately $60 million in an existing Dongfeng subsidiary, which is China's largest commercial vehicle axle manufacturer. Headquartered in Xiangfan, China, the joint venture company will employ approximately 8,000 people in production facilities in Shiyan and Xiangfan as well as a research center to be established in Wuhan.

Dongfeng Dana Axle will continue to primarily supply Dongfeng Motor, which is one of the world's largest truck producers, while expanding other product offerings. Projected annualized sales for the joint venture company are expected to be approximately $400 million.

Cowley Named Sales Manager of Process Equipment


Bruce Cowley

Bruce Cowley was hired as a sales manager for Process Equipment Co.'s metrology systems division.

According to the company's press release, Cowley has more than 20 years' experience in gear metrology and gear processing companies such as Sheffield Measurement, M&M Precision, David Brown Engineering—Sykes division, Mahr Federal and Gleason.

In his new position, Cowley will lead the sales and distribution activities for the Next Dimension Series CNC elemental systems, special gear and gear tool-related inspection systems and contract inspection.

Lambert-Wahli Make Merger Official

Lambert Ltd. and Wahli Ltd. merged their operations on April 1.

According to a press release, the two companies have been operating under the same management, at the same headquarters for several years. All addresses and telephone numbers will remain unchanged.

GM Invests to Build New Transmissions in Strasbourg Plant

GM announced that it will invest approximately €160 million in its Strasbourg plant to produce its new family of six-speed, rear-wheel-drive automatic transmissions. The investment includes facility renovation, new machinery and equipment and tooling to support new processes.

"We are committed to the six-speed transmission playing a greater role in the GM powertrain product portfolio," says Tom Stephens in the company's press release.

The GM Powertrain transmission plant in Strasbourg, France, already produces the 5L40-E and the 5L50-E five-speed, rear-wheel-drive automotive transmission for luxury sedans, SUVs and performance cars.

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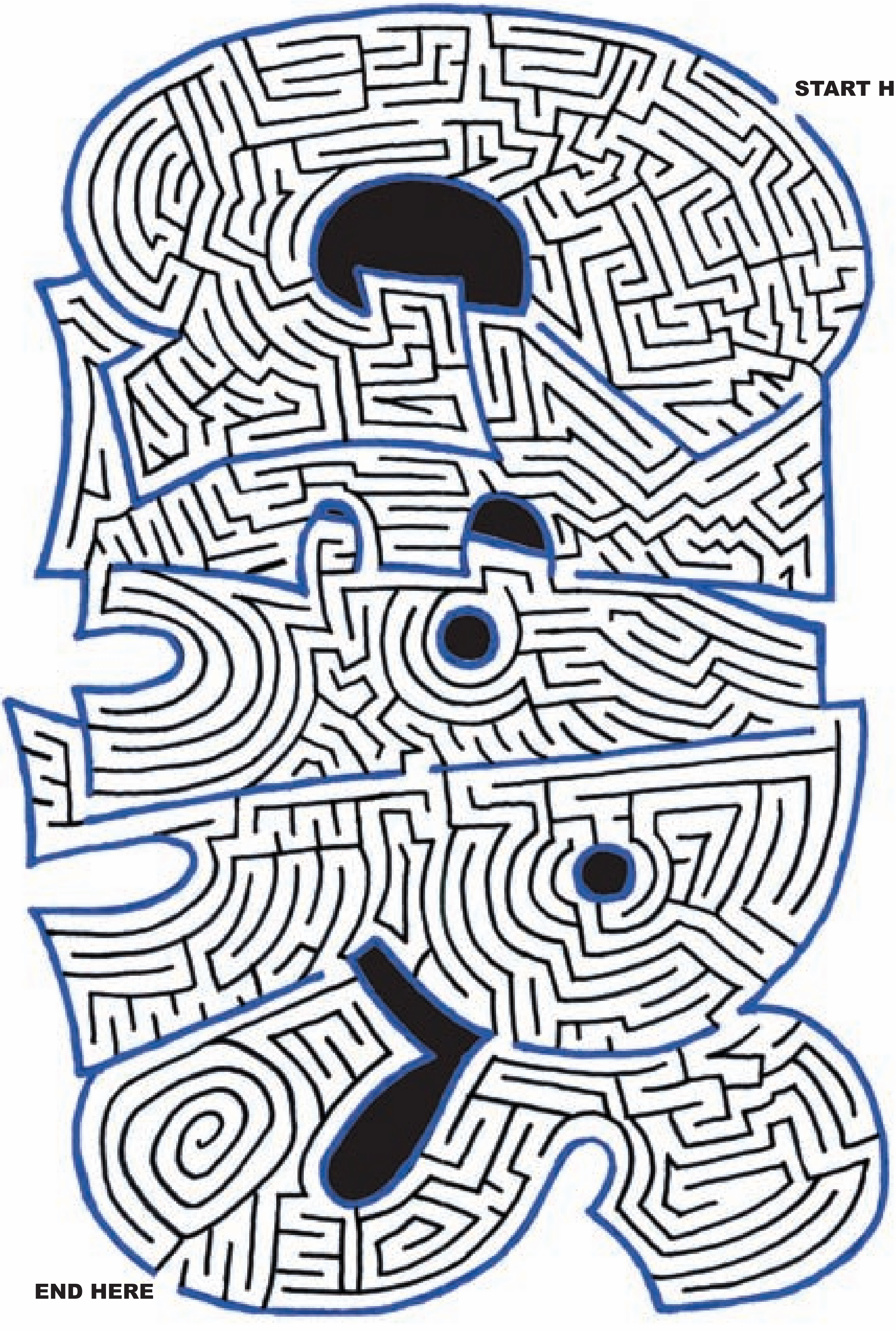
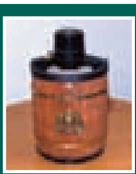
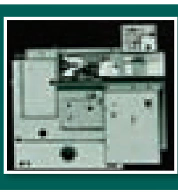



Chuck It... and... Check It

One of the little known product services within the **Star SU** enterprise includes workholding tooling for gear hobbers, shapers, and grinders and related equipment from a premier source—**Hainbuch**.

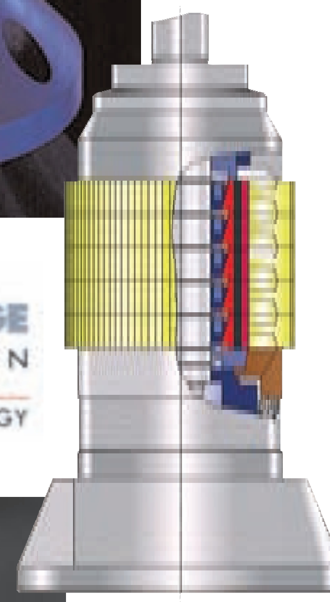
It also includes work centering inspection mandrels from a well-known manufacturer—**LeCount, Inc.**

Both give the most precise systems for clamping for cutting and clamping for inspection. Hainbuch manufactures a variety of bore and shaft clamping fixtures, either customized for a specific workpiece or as standardized tooling modules. Hainbuch makes fixturing for turning, milling, gear cutting and finishing.

LeCount manufactures expanding mandrels, multi jaw expanding spline mandrels, and customized mandrels for holding parts between centers for inspection, with an accuracy of 0.0001" (2,5 µm) TIR or better.

Whether chucking or checking, your local Star SU sales manager can help you find a solution to your clamping application, applicable to any machine tool in your facility. You can find Hainbuch Welge on the web at **www.hainbuchwelge.com** and you can find LeCount on the web at **www.lecount.com.**

Or just contact your Star SU salesman. We're closer to you than you may know.



HAINBUCH WELGE
CORPORATION
WORKHOLDING TECHNOLOGY

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