GEAR TECHNOLOGY

JANUARY/FEBRUARY 2004
The Journal of Gear Manufacturing
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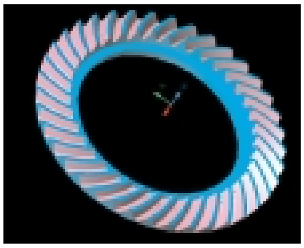
JANUARY/FEBRUARY 2004 *The Journal of Gear Manufacturing*

LUBRICATION

28

FEATURES



20

DEPARTMENTS

56

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BPA INTERNATIONAL

VOL. 21, NO. 1

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

Renaissance Man

I lost a good friend in October—one that many of you might know. Carlo Costi of Sogimex S.A.S. in Caponago (Milano), Italy, came out of the EMO show in Milan on October 28, caught a taxi and called his wife, Mariella, to tell her that he wasn't feeling well. He died—in the taxi—on the phone—talking to his wife. He was 60 years old.

Carlo was a gear machine tool merchant, widely known in the Italian gear manufacturing community and the worldwide Gleason and machine tool dealer communities. He will be missed by those who knew him. I will miss him not only because of our business relationship, but because, over the years, I got to know Carlo as a person.

He was a very unique man, who came from a unique background.

Carlo's father, Marco, was an Italian Jew who left Italy with the rise of Mussolini and went to Cairo, Egypt. There he met Carlo's mother, Maria, a Roman Catholic. Their 1941 marriage was blessed by the Catholic Church with the understanding that their first-born, who would be Carlo's brother, Enrico, was to be raised Roman Catholic. Carlo, like his father, practiced Judaism. I've always admired how comfortable each of these brothers was with the unusual religious makeup of their family. To each of them, it was always perfectly natural having a brother and a parent with a different religion, which is probably rare today.

Both Enrico and Carlo were born in Cairo, and after the war, the family moved back to Milan. In 1950, Carlo's father formed Sogimex—at first a trading company and later a machine tool merchant. Enrico joined his father in 1962 for a short period, left, and returned in 1970. My father had met Marco in the 1960s, and I met Marco and Enrico in the early 1970s.

Meanwhile, Carlo went to see the world. He came to America in the early 1960s, studying and then teaching philosophy in New York. While his brother and father were working in the machine tool business, he enjoyed the freedom of the hippie generation, studying, learning and teaching about a lot of the things that add richness to people's lives. We met in the early '80s.

My wife, Marsha, and I, shown in the photo with Carlo in 1995 in Estoril, Portugal, had the opportunity to spend quite a bit of time with Carlo, Enrico and their respective families, especially at the annual meetings of the European Association of Machine Tool Merchants (EAMTM), which are held in such places as Sorrento, Malta, Lanzarote, Barcelona, Sante Margherita and Cannes.

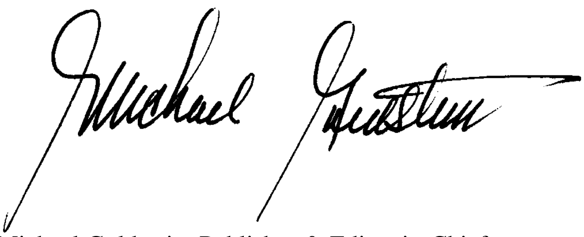
Our trips to those places were always more enjoyable because of Carlo. He was truly a Renaissance man. He easily and comfortably discussed the literature, architecture, history, wine and food of Italy and Europe. The depth of his knowledge, often first hand, was always quite surprising. We only had to mention that we were going to visit a particular area, and Carlo immediately would be able to tell us, in detail, of all the best places to visit, the best restaurants to try and the best foods to eat.

I talked to him often on my way to work, and I always enjoyed his excitement when watermelon or white figs, a memory of his childhood, were in season, and he always looked forward to Panettone at holiday time.

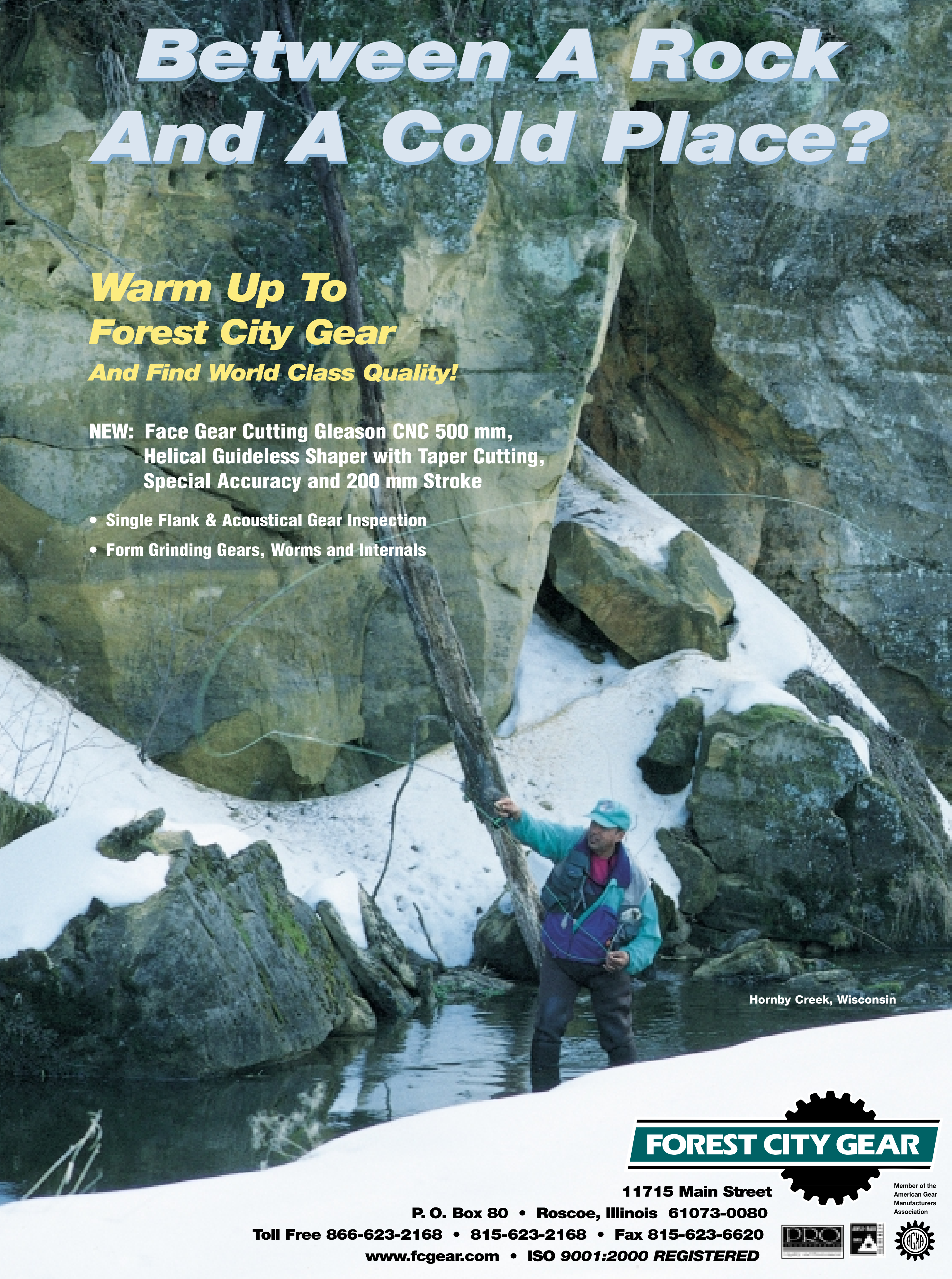
I also had the good fortune to spend time with his daughters, Micol, Miriam and Muriel, whom he adored. I have vivid memories of walking around Portofino with Micol and Miriam on each arm in animated conversation, with Carlo and Marsha behind us, deep into architectural discussions. When the EAMTM held its conference in Malta in 1998, Carlo brought Muriel, then 13. We all had such a good time together that we arranged for Muriel to come and stay with Marsha and me during the summer of 1999.

Carlo had a sweetness about him that is not often found and probably less often appreciated. He is already sorely missed, not only by his family, but also by others who knew him.

Arrivederci, Carlo. I'll have some Panettone for you this year.



Michael Goldstein, Publisher & Editor-in-Chief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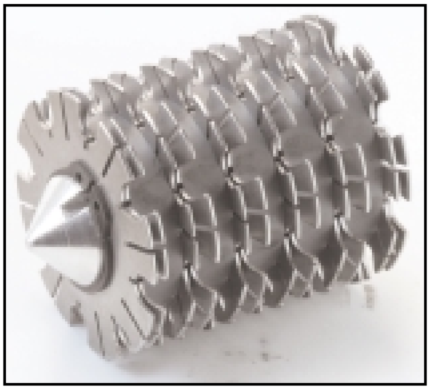
Magnetic Filtration

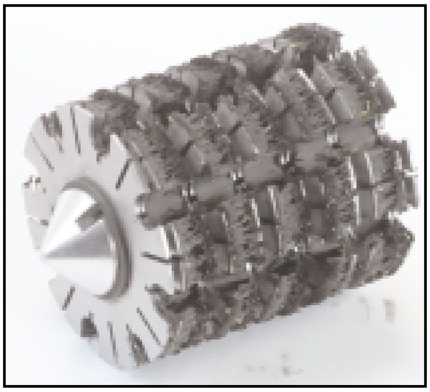
Fluid Conditioning Systems, of Warwick, U.K., has developed a simple device to remove ferrous contaminants from oil or transmission fluid with minimal reduction in fluid pressure.

The patented device, called the Magnom™, uses a magnetic field effect to remove particles as small as 0.07 microns from a variety of fluid types and viscosities. It was developed by a former Royal Air Force engineer who was working in the field of performance transmissions, according to Tom Hulme, CEO of FCS.

The engineer had been trying to solve the problem of scoring on pistons and gear teeth. He needed a better way to remove ferrous wear debris from the oil and transmission fluid. Conventional barrier filtration methods created too big a pressure drop, Hulme says. Another alternative, magnetic sump plugs, showed some promise, but they couldn't catch all the debris. In addition, Hulme says, large lumps of debris can sometimes wash off magnetic sump plugs and be reintroduced into the system, causing damage.



A Magnom core before use.



Debris is captured without reducing fluid flow.

The Magnom, however, is composed of simple annular steel plates, with flow channels sized so that fluid flow remains at or near 100%, no matter how much debris has been removed. In addition, Hulme says, contaminants are pulled laterally, and fluid flow causes refraction forces that compact the debris, preventing pieces from washing back into the flow.

Today, the Magnom is used by Lola Cars International for engine oil filtration. In a written statement, senior design engineer Duncan McRobbie said, "After four seasons of accumulating positive experience with a combination of fine mesh and Magnom filtration, we now have the confidence to use the Magnom unit, on selected projects, as the sole fine filtration media."

The Magnom was originally developed for performance motorsports, but Hulme says it has a wide variety of applications. Magnom filters have been manufactured in lengths ranging from 35 millimeters to 1 meter, and they've been used in gear transmissions, machine tools, and hydraulic equipment.

For example, Magnom filters have been used at electrical power generation plants to replace edge filtration for the removal of contaminants from the lubrication systems of coal mill gearboxes. They've also been used in the lubrication systems of print roller drive transmissions by a major American newspaper.

"We've never installed into a transmission environment and failed," Hulme says. "The majority of customers who've built up experience with the Magnom are now using it as their only fine filtration."

Another application of the Magnom filters is in machine tool cutting fluids. Magnom filters have been fitted on a variety of machine tools, including metal cutting, injection molding and EDM machines. According to FCS literature, a major British automobile transmission manufacturer has replaced its conventional filters on machine coolant systems, resulting in savings of £80,000 (approximately $140,000) per year due to reduced disposal and maintenance costs.

***Welcome to* Revolutions*, the column that brings you the latest, most up-to-date and easy-to-read information about the people and technology of the gear industry.* Revolutions *welcomes your submissions. Please send them to* Gear Technology*, P.O. Box 1426, Elk Grove Village, IL 60009, fax (847) 437-6618 or send e-mail to* hazelton@geartechnology.com.**

The Magnom can be sized depending on requirements. In many cases, it's designed as a "fit to forget" solution, where the filter never has to be replaced. "It never blocks," Hulme says. But in other cases, the Magnom can be designed for regular maintenance because it's easily cleaned.

Although the Magnom is used mainly to remove submicron debris from fluid systems, it is also capable of catching much larger debris. For example, the company has seen chunks of gear teeth as big as 4 or 5 centimeters removed from larger Magnom filters, Hulme says.

The Magnom is designed not to reduce fluid pressure, no matter how much debris has been captured, so it is most often placed before the pump in a system—a place where conventional fine mesh filtration can't go. Because there's minimal loss in pressure with the Magnom, Hulme says, the filter can be placed where it will be most effective in protecting the pump without risk of cavitation.

In addition to capturing ferrous materials through magnetic attraction, the Magnom captures some nonferrous particulate material.

The Magnom also has environmental benefits, Hulme says. It reduces or eliminates the need to dispose of conventional filters, and it reduces the amount of lubricant normally discarded. Contaminants can be disposed of separately instead of with used filters and excess oil.

Despite the benefits, the cost of the Magnom is relatively small. The unit has no moving parts, and the magnets and plates which make up the core are relatively inexpensive. Most of the cost of the unit is in the housing, Hulme says. Prices might range from $80 up to $7,000 for larger industrial systems.

"Like all good ideas, the cleverness is a function of the simplicity," Hulme says.

Better Blanking from Bar Stock

If you manufacture your own gear blanks from barstock or outsource your requirements, Watkins Manufacturing of Cincinnati, OH, wants to talk to you.

The company's SAW-Lutions™ rotary saw cutting attachment can be added to single- and multi-spindle automatic screw machines and CNC turning machines to replace the traditional cutoff method using single-point tooling. The result is a much faster, more efficient process that produces less waste and requires less secondary work, says sales manager Dirk Greulich.

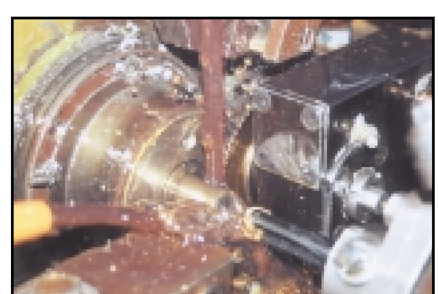
"Almost any job that runs through a screw machine, you're going to experience at least a 5–8% cost reduction on the total cost of manufacturing," Greulich says. "On parts such as gear blanks, or any part where the predominant operation is cutting off, the savings can be in excess of 30–50%."

The attachment was first developed in the 1960s. Known also as the Kerf Cutter™ system, it has been used extensively in the screw machine industry, according to Greulich. But recently, the company has begun exploring how the process can help the gear industry.

The attachment mounts to a host machine and replaces conventional tooling with a rotating saw. As the stock turns, so does the saw.

Watkins Manufacturing believes in the process so much that they have set up their own gear blanking operation to attract contract manufacturing work. If a gear manufacturer wants to install rotary sawing systems on his machines, Watkins will supply them. The company provides ongoing service and support, as well as on-site startup assistance with each system. But if you normally buy your gear blanks, Watkins believes it can manufacture the blanks more efficiently than companies that use other methods.

One of the benefits of the rotary saw cutoff method is that the cut is much thinner than methods that use single-point tooling, Greulich says. Because of the thinner cut, manufacturers can real-



The SAW-LUTIONS™ rotary saw attachment.

ize significant savings because less bar stock is wasted. At least 8–10% material savings is experienced and, in some cases, bar stock usage can be cut by 25–50% or more, Greulich says. Also, longer tool life and fewer tool changes contribute to long-term savings, he says.

Greulich adds that instead of long strings of sharp metal, the rotary saw produces very small, dustlike chips, that are much more disposable.

The process can become even more productive when multiple saws are run on the same arbor. With gear blanking, it's common to cut two or three blanks at a time, Greulich says. But the company has run as many as 10 saws on a single arbor.

Another advantage of the rotary saw process is that it can typically cut faster than conventional tooling. "This initial impact can drive cycle time down and productivity up substantially," Greulich says.

Also, irregular shapes, such as extruded bar stock or pinion stock, pose no special problems for rotary saw cutting, whereas traditional single-point tooling has a more difficult time with start-and-stop edges.

In many cases, secondary machining processes, such as double disk grinding, can be reduced or eliminated, because the rotary saw attachment produces parts with better squareness, flatness and surface finish than parts cut off with single-point tooling, Greulich says. The cut-off surface flatness and squareness, he adds, can be held to tolerances within 0.0003–0.002", depending on job characteristics.

The rotary saw attachment can be used on a multi-spindle machine, so additional machining operations can be performed at the same time. Those operations might include cutting blanks for shoulder gears, providing chamfers on the gear blank, drilling, reaming holes or OD work.

The process is ideal for volumes of more than 1,000 pieces, Greulich says. "But there really is no ramp-up. Eighty to ninety percent of the savings are from gear one." According to Greulich, there are even greater efficiency gains when a machine is producing the same part continuously over a period of a week or a month.

The Watkins rotary saw cutoff process has been used on bar stock up to 4" in diameter and up to 30 Rc in hardness, but the company is willing to "push the envelope," Greulich says, "especially when it's with materials we want to do R&D on."

Saws for the attachment can be made of high speed steel, tool steel or solid carbide, and a variety of coatings, including TiN, TiAlN and TiCN, are available to enhance performance.

In addition to gear blanks, the process can be used to make other high volume, precision turned parts, such as bearing races, spacers, rollers or bushings.

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Wenzel Group Expands to Gear Metrology Field

The Wenzel Group of Wiesthal, Germany, has founded a subsidiary, Wenzel GearTech GmbH, for the gear metrology market.

According to the company's press release, the company will start with 10 employees and will be managed by Hans-Helmut Rauth.

The new location will be used for design and development, sales and administration as well as a service base and demo center. Among the first products to be produced by the new subsidiary is a complete line of gear measuring machines with the required mechanical components produced in the mother plant.

New Account Manager at Inductoheat

Florie Schwartz was hired as account manager at Inductoheat of Madison Heights, MI.


Florie Schwartz

Schwartz has previously worked in the induction tube and pipe industry, according to the company's press release.

Inductoheat designs and manufactures induction-heating equipment.

Ipsen Selected as John Deere Supplier

Ipsen International was chosen as the supplier of an atmosphere batch furnace line for the John Deere Waterloo Works. The facility will use the fully-automated heat treat line for gear carburizing and agricultural equipment components.

According to Ipsen's press release, John Deere will utilize Ipsen's Iron Horse system to heat treat drivetrain gears and shafts distributed to manufacturing facilities worldwide.

The Iron Horse system includes the Carb-o-Prof real time carbon diffusing modeling and control package. The system also includes multiple gas-fired TQF-2 double-chamber batch straight through furnaces (size 17) with a rigid housing, positive motion transfer mechanism, and a low-NO_x combustion system using the company's Recon III burners.

Headquartered in Rockford, IL, Ipsen manufactures thermal processing technologies.

New Sales Representative at Philadelphia Gear

Michael Bashour joined Philadelphia Gear in the newly created position of southeast regional sales representative.

Bashour previously worked as district sales manager at Duff-Norton Co. and as a sales representative for Lufkin Industries.

Among his new responsibilities will be leveraging the company's technical expertise in the energy, mining, pulp and paper, and rubber industries.

Lay Machinery and Service Network Form Agreement

Service Network Inc. (SNI) has appointed Lay Machinery Systems as its exclusive representative for the state of Texas.

Among the products for Lay to bring to the market are the

SN400-I internal and the SN200-E external production grinders. Both are targeted to manufacturers of bearings, automotive, aerospace, industrial and heavy equipment components.

SNI offers service, parts and remanufacturing for all Heald grinders, which are available through Lay Machinery.

Lay Machinery of Dallas, TX, is involved in machine sales for numerous metalworking machine tool manufacturers.

Ajax Tocco Gets Japanese Contract

Ajax Tocco Magnethermic of Warren, OH, and ATM JAMCO of Tokyo, Japan, have been awarded a contract from Gohsyu of Tokyo, Japan, to supply a 2,000 kW induction billet heating system.

A key feature of the system is ATM's enhanced hold circuit, which can hold billets at a temperature during press while problems are corrected, according to Ajax Tocco Magnethermic's press release.

The heater will be sent to Japan for installation and start-up in the second quarter of 2004.

mG miniGears and EPSCO Sign Contract

mG miniGears reached an agreement with EPSCO Inc. for representation in the automotive industry.

According to mG miniGears' press release, their recent TS16949 certification played a large part in the decision to join forces with EPSCO.

mG miniGears designs and manufactures custom engineered gears and gearboxes for automotive, industrial and power tool customers.

New Appointments at Timken

The Timken Co. of Canton, OH, announced several personnel changes effective in early 2004.

Frank C. Sullivan was elected president and CEO of RPM International, a division of The Timken Co. Sullivan has held the positions of COO, CFO and a variety of corporate development and sales positions within RPM since 1987.

Tim Timken Jr. was elected executive vice president and president of the steel group. He has worked for Timken since 1992 in a variety of positions. For the last three years, he has served as corporate vice president and as a member of the board of directors.

W.R. Timken Jr. announced his retirement from his position as Timken executive officer. He will continue to serve on the board of directors.

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Philly Gear: A Long Life, A New Direction

Joesph L. Hazelton

Large marine gearboxes. More than a year in production, each weighing 125,000 pounds, the gearboxes were for U.S. Navy amphibious ships, for combining the power of 10,000 hp diesel engines to drive propeller shafts.

They were also the last major gear products shipped from Philadelphia Gear Corp.'s King of Prussia factory.

A mecca of the gear industry was closing. For more than 40 years, the mammoth factory (625,000 square feet) was a symbol of Philly Gear. It was the embodiment of a company with a long, storied history.

In 1892, Philly Gear was founded by gear pioneer George B. Grant, builder of the first hobbing machine for cutting spur gears. In 1916, it was one of nine gear companies to found the American Gear Manufactuers Association. In World War II, it was manufacturing 14-foot ring gears for battleship rotating gun turrets, for America's "arsenal of democracy."

In 2001, though, Philly Gear was struggling to survive, and its blue-and-white factory no longer fit into its future.

But the closing was part of a plan. Started in 1998, the plan called for transforming then 106-year-old Philly Gear into a company fit for the new economic order.

A New Direction

In 1998, Philly Gear faced up to a growing problem. Foreign competition was reducing the profitability of the U.S. gear industry. Many products manufactured overseas were proving cheaper and equal or near equal to those manufactured in the United States. Jules DeBaecke, Philly Gear's vice president of engineering, summed up the situation: "Too many suppliers and not enough customers."

So the company decided on a new direction: serve the aftermarket. For Philly Gear, the aftermarket looked more profitable than manufacturing gears for new industrial operations.

Also, the company appeared well positioned to serve the aftermarket needs of the energy industry through its satellite sites in California, Delaware, Illinois and Texas. Russ Ball, chairman and CEO of Philly Gear's parent company, explains the sites were in areas populated with power plants. In the new strategy, the sites would be made into regional service and manufacturing centers.

Today, Philly Gear's top three industries are energy related: power generation, oil refining, and petrochemical.

As part of its new direction, Philly Gear changed its very

Philadelphia Gear Corp.

Established: 1892

No. of Employees: 150–200

Industries Served: Power Generation, Oil Refining, Petrochemical, Marine, Cement

Major Products: Gear Drives, Helical Gears, Planetary Gears, Spiral Bevel Gears, Straight Bevel Gears, Spur Gears

Quality Registrations: ISO 9001-2000

Website: *www.philagear.com*

Industry Affiliations

- American Bearing Manufacturers Association (ABMA)
- American Gear Manufacturers Association (AGMA)
- American National Standards Institute (ANSI)
- American Petroleum Institute
- ASM International
- ASME International
- Association of Iron and Steel Engineers
- ASTM International
- Heat Treating Society
- International Organization for Standardization (ISO)
- Society for Mining, Metallurgy, and Exploration
- Society of Naval and Marine Engineers

In 2001, a factory gave way to an office suite. While reorganizing itself, Philadelphia Gear Corp. moved its headquarters from its King of Prussia factory to a Norristown office building.

nature, from its physical structure to its employees' culture.

A New Structure

The first major changes in structure came in '01. In February, Philly Gear moved its executive and engineering staff from the King of Prussia factory to an office suite in nearby Norristown, another Pennsylvania city. In July, the last gearbox was shipped from King of Prussia.

Besides closing the factory, Philly Gear added a regional center in Alabama. Today, the five centers allow a national customer to deal with one company for all of its locations and allow a regional customer to use the center nearest its operations. Also, the California center provides specialized gear manufacturing.

Changes in structure involved changes in personnel, too. Philly Gear declines to provide exact numbers, but it employs about 10 percent fewer people today than it did in 2001.

Besides these changes, the company also brought its archive into the digital age.

A New Archive

Philly Gear wanted its employees to have quicker, more independent access to its records, to improve efficiency.

Previously, Philly Gear's archive was two iron mountains. Filing cabinets filling two warehouses contained the company's paperwork, including technical drawings, service records and sales information—some 600,000 paper documents. To access them, employees across the country faxed requests to the Norristown office.

If stored electronically, though, the archive could be accessed directly by employees via computer. So Philly Gear took its papers and converted them into digital images, a $1 million project.

Today, engineers and other employees, in Norristown and elsewhere, have access to the documents via a password-protected intranet.

Those records are useful to Philly Gear as an aftermarket supplier whenever it's called to service its brands of power transmission products.

But Philly Gear services more than its own products. The company expanded its repair and upgrade services to include more than 30 other brands of products.

According to DeBaecke, serving many brands of products increased Philly Gear's pool of possible customers.

Although focused on the aftermarket and the energy industry, the company still serves all industries on request and has both foreign and domestic customers. Industries still receiving new Philly Gear products include power generation, sugar processing, rubber, cement, pulp and paper, petrochemical and marine.

Aftermarket Services

"They have excellent repair services," Stephen Goodberry says.

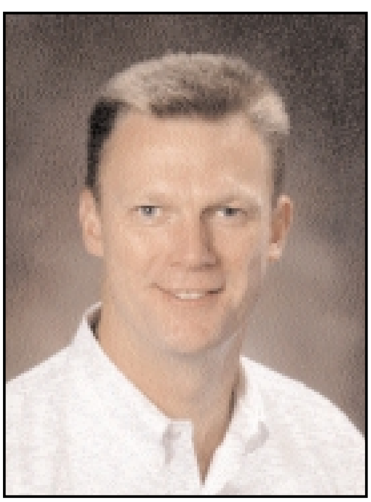
Goodberry is lycra® maintenance planner for Invista Inc. He plans all maintenance work for the fiber and chemical company's lycra-making machines, including their gearboxes. He also obtains the parts to keep the machines running.

In his job, he's worked directly with Philly Gear for 10-plus years. In the past, he's mainly used them as an OEM for new parts for new projects and for replacement parts. The last few years, though, he's also been using them as an aftermarket supplier, in part for repair services.

And why are those services excellent? Quick replies to calls, listening well, and expedited, quality repairs, Goodberry says.

"Once it's repaired," he adds, "it's fixed for good."

For example, three years ago, Goodberry learned of an impending problem with the gear reducers in his lycra spinning machines. Oil ferrography and vibration analysis showed excessive gear wear in the boxes.



President and CEO Carl Rapp stresses Philly Gear's new aftermarket, service strategy to employees, reminding them "what the scoreboard says and how the strategy's being executed."

The problem: Invista hadn't specified the boxes correctly; the oil pumps weren't the right size.

Goodberry contacted Philly Gear, and the companies got to work on the problem. They were looking at fixing 21 boxes in the lycra division, located in Maitland, Ontario, Canada.

The boxes were switched out three at a time, sent to Philly Gear, who quickly turned them around, and then put back in their machines. In

about a year, all the boxes were fixed.

"We were able to overhaul all 21 gearboxes before we sustained any downtime due to equipment failure," says Goodberry.

A New Culture

Philly Gear had long focused on engineering and quality and on OEMs, but Carl Rapp, president and CEO, says: "It wasn't as sensitive to customer service."

That culture may have been possible in the past, but times have changed.

"Customers do have other options out there," Rapp says.

In Rapp's opinion, Philly Gear had already taken a crucial step toward a new culture when he joined the company in September '01. Earlier that year, Philly Gear had closed its King of Prussia factory—in effect, severing ties with its past.

That closing and the opening of the Alabama regional center made clear: The new strategy wasn't empty talk, it was real change.

To improve service, the company increased its on-time delivery, communicated more with customers and improved its sales force through new hires and more in-house training.

Philly Gear also changed its culture through communication, communication and communication.

"We reinforce regularly what it is we're all about," Rapp says. "What the scoreboard says and how the strategy's being executed."

The reinforcement comes in newsletters and monthly and quarterly business updates. For the quarterly updates, Rapp visits each regional center and talks to every Philly Gear employee.

Rapp says changing the culture took more than 18 months. "It was bumpy," he adds. "I think we've come through the toughest part."

The Outlook

Philly Gear's new direction seems to be paying off. The company's aftermarket business has been growing annually.

And that performance is noticed by Russ Ball at American Manufacturing Corp., Philly Gear's parent company: "I am extremely bullish on the Philadelphia Gear strategy."

Transformed by the strategy, the company continues to manufacture power transmission products for customers, including the U.S. Navy. At its California center, Philly Gear is still manufacturing 125,000-pound gearboxes for Navy amphibious ships.

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SOFTWARE BITS

William R. Stott

Image courtesy of Professor Xiaodong Guo, Chongqing Institute of Technology.

GEAR AND GEARBOX DESIGN

KISSsoft is a software tool for the design of machine elements such as gears, shafts, bearings, bolts, splines and springs. The main features of *KISSsoft* were developed for gearbox design and analysis.

The software calculates most of the machine elements according to methods specified in the current versions of DIN, ISO and AGMA standards. If no standard is available, elements are calculated based on well recognized and accepted literature, says Stefan Beermann, marketing director for KISSsoft AG, located in Hombrechtikon, Switzerland.

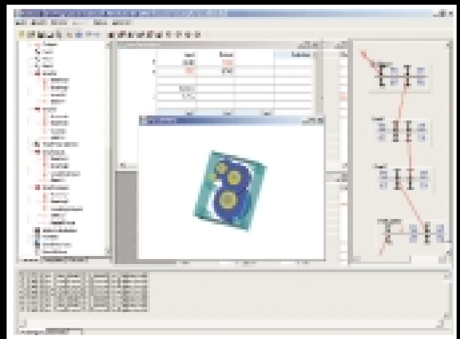
In addition to calculating geometry, the software performs load rating calculations against static and fatigue loads, and it includes a number of functions to help designers optimize the parts.

One of the most powerful functions, Beermann says, is the software's ability to iterate through a given set of parameters for spur or helical gears. This allows the software to determine the geometrically possible solutions and rate them according to strength, stiffness, noise, weight or other functions.

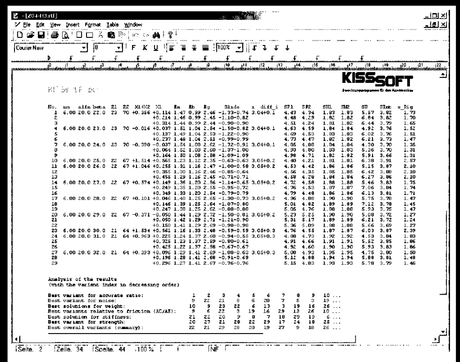
KISSsoft was originally developed by Kissling & Co. AG, a Swiss gearbox manufacturer, but development and sales are now being handled by KISSsoft AG, an independent engineering consultancy. "During the last 25 years, the software has been constantly improved, and more functionality is added every day," Beermann says.

Beermann adds that one of the strengths of *KISSsoft* is that it has been developed by trained and experienced mechanical engineers, helping "to ensure that the design engineer gets a practical tool for his daily work."

In addition to *KISSsoft*, the company offers an add-on package called *KISSsys*, which was developed for the definition of complete systems such as gearboxes or complete powertrains. With *KISSsys*, all parts—including gears, shafts, bearings and couplings—are linked, and the strength and life analyses are performed simultaneously for all elements.



***KISSsys* allows a whole system of machine elements to be presented, making it easier to size the elements to fit in a given housing.**



***KISSsoft* allows a designer to quickly see the results of changes in parameters. The example above shows how varying the helix angle affects criteria such as noise, weight and stiffness.**

KISSsys presents a 3-D graphic of the current state of the system. The graphic presentation shows the geometric influence of every change in parameter. "This approach greatly accelerates the design process and results in a much more balanced design," Beermann says.

For more information:

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The Gear Processor

HyGEARS version 2.0, "The Gear Processor"™ is a 3-D gear modeling program for the design and development of hypoid, spiral bevel, straight bevel, spur, helical and face gears, as well as involute splines.

HyGEARS allows the design, analysis and optimization of gear sets through functions such as tooth contact analysis (TCA) and loaded tooth contact analysis (LTCA). It supports the design and development of gears manufactured under Gleason's Face Hobbing™, Fixed Setting™, Duplex Helical™, Modified Roll™, Spread Blade™, Formate™ and Helixform™ cutting processes.

The software was developed by Dr. Claude Gosselin of Involute Simulation Softwares Inc., located in Sillery, Quebec. According to Gosselin, "The software has been extensively tested in industry."

Blank geometry, cutter blade shape and machine settings can be modified through the program's "Summary Editor," or those parameters can be optimized through more advanced user-guided functions.

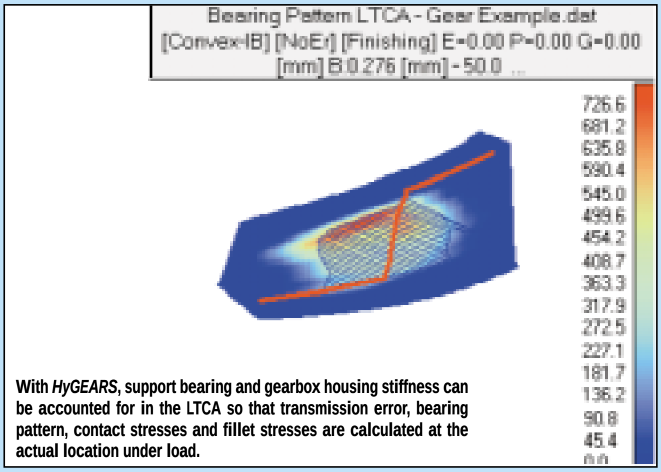
Transmission error, unloaded and loaded bearing pattern, torque transmitted by meshing teeth, bending and contact stresses, bearing reactions, thermal-EHD oil film thickness, temperature increase and scoring factors are all calculated in real time, Gosselin says.

Also, the axial and radial positions of meshing gears, their alignment and shaft angle can be modified to analyze worst-case conditions or to automatically produce grid-like projections of the unloaded and loaded behavior of a gear pair.

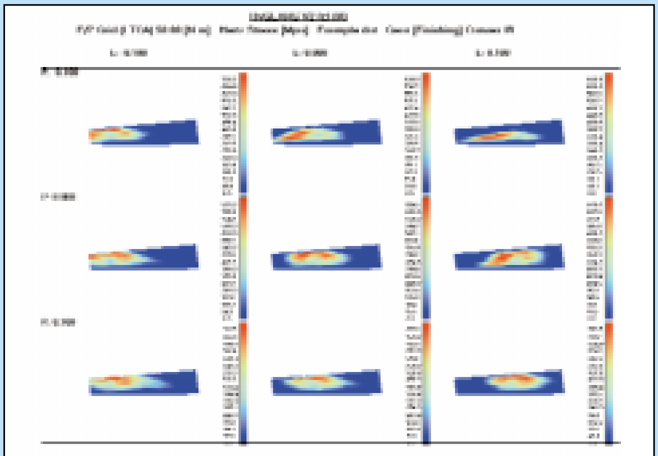
Some of the advanced functions offered by *HyGEARS* include finite element analysis pre-processing for meshing and load applications, as well as the analysis of gears under load using *HyGEARS'* proprietary finite strips, which Gosselin describes as "an ultra-fast subset of the finite element method." Also, the software's "Contact Element" module allows the evaluation of contact stresses at any point on the tooth surface.

The software can output target files for coordinate measuring machines, including Zeiss Ram/RFD, Gear Bevel or Höfler formats. *HyGEARS* can import CMM output files from the same types of machines as well as Klingelnberg inspection machines. This allows the software to calculate corrective machine settings or to reverse engineer existing gear teeth, Gosselin says.

"CMM results can also be used to estimate the TCA and LTCA behavior of a real gear pair," Gosselin adds, "and this allows troubleshooting problematic gear sets."



With *HyGEARS*, support bearing and gearbox housing stiffness can be accounted for in the LTCA so that transmission error, bearing pattern, contact stresses and fillet stresses are calculated at the actual location under load.



The axial and radial positions of meshing gears, their alignment and shaft angle can be modified to analyze "worst case" conditions, or to automatically produce grid-like projections of the unloaded and loaded behavior of a gear pair.

The software can be modified for customers in order to add specific functions or results, or to automate tasks, Gosselin says.

For more information:

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Simple and Easy to Use

The philosophy behind software at DR Gears, a gear consultancy based in Tunbridge Wells, England, is to keep it simple.

"In my 38 years in the gearing industry, I have used a lot of gear software. I have also worked with a lot of colleagues who are brilliant engineers but are scared of the gear field and consequently put up walls against this 'black art,'" says David Robinson, president of DR Gears. "I have tried through our software to bring a simple 1-2-3 method of use by offering simple, easy-to-use software that can be used for a single purpose."

Robinson offers a number of these simple programs through his website, *www.drgears.com*.

For example, *GeaRatio* allows the user to determine the number of teeth needed in each member of a gear set, based on entering a decimal ratio. It can be used to determine change gears for milling, hobbing, shaping or grinding machines. *Base Tangent* is used for calculating tooth size based on number of teeth, pitch, pressure angle, helix angle and profile shift. It will accept module, diametral pitch or circular pitch measurements. *Pin Diameter* calculates dimensions over or between pins for internal or external gears.

Each of those programs is available at the company's website for U.S. $50. The website also has a number of free utilities available for download.

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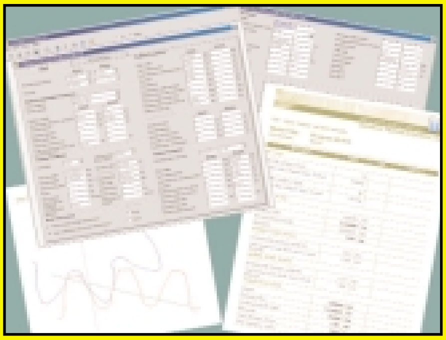
Integrated Gear Software from UTS

The gear design and manufacturing software of Universal Technical Systems Inc. has been widely used for nearly 20 years. Until now, that software was composed of individual modules. Now that system has been combined into a single, comprehensive environment.

UTS's *Integrated Gear Software* (*IGS*) brings together more than 70 modules of the UTS system—each representing a particular issue or stage in the gear design and manufacturing process—into one seamless knowledge environment that calculates, shares data, archives designs, does tolerance analyses and produces detailed reports.

IGS retains a modular structure, and the modules are grouped in six packages: Advanced Gear Design and Manufacturing, Basic Gear Design and Manufacturing for Metal Gears, Basic Gear Design and Manufacturing for Plastic Gears, Crossed Axis Gear Design, Epicyclic Gear Design, and Spline Design and Manufacturing. However, with *IGS*, all the modules are designed to work together and to pass data back and forth seamlessly.

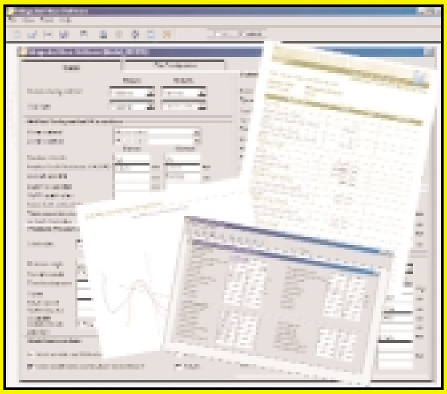
The metal gears basic package covers design and analysis, preliminary sizing, tooth thickness and coordinates, mesh geometry, profile shift coefficients, stress and life analysis, and measurement over pins. The plastic gear basic package covers all these and adds programs to cover such factors as temperature, moisture and mold design. The advanced package covers such issues as specific types of hobs and cutters, yield stress, involute geometry, scoring analysis, tip relief and minimum-weight gearbox.



Like the previous versions of UTS software, *IGS* is powered by *TK Solver*, UTS's mathematical and programming environment. One of the key advantages of using *TK Solver* is the software's ability to "backsolve." This allows designers to enter data in the fields they want, and the software solves for the other values.

The software also includes comprehensive project management features, so that designs can be grouped together by project and projects grouped together in packages. The project manager also allows designs from one project to be reused for another.

IGS comes with many standard reports, which can be printed or output to word processing files. The software also has the ability to prepare comparison reports so that values from different data runs can be shown side-by-side. Also, reports can be customized. The user can select which data should be shown, including inputs, outputs and plots, and these customized reports can be saved as templates and reused.



UTS gear software customers with a maintenance agreement can receive the upgrade to *IGS* automatically. Those with expired service agreements can renew them for a small start-up fee.

More complete details regarding the capabilities of *IGS* are available on the company's website, *www.uts.com*. UTS also offers an online demonstration of *IGS* through "Live Meeting," as well as on-site demonstrations.

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Forging Simulation

By simulating the forging process, engineers at ProSIM are able to reduce the design and development time for forged parts, including gears.

ProSim, based in Bangalore, India, is a consultancy specializing in process modeling for forged and other formed parts. The company uses finite element analysis software to develop what they call a "virtual gear forging shop."

Color bands show the strain distribution in warm forging a spur gear.

"Finite element analysis-based process modeling can be a useful tool for rapid design and development of the gear forging operation," says Dr. S. Shamasundar, director of ProSIM. "The costs involved in trial and error-based die tryouts can be reduced, and the lead time brought down."

The engineers at ProSIM use *DEFORM*, the commercial version of a nonlinear FEM code originally developed by Battelle Memorial Lab for the U.S. Air Force. *DEFORM* is produced by Scientific Forming Technologies Corp. of Columbus, OH.

Through the use of the software, ProSIM is able to predict defects such as laps, folds and underfills. ProSIM engineers can also estimate die load and the microstructure of forged parts, as well as predict tool and die wear and failure.

ProSIM uses the software to predict the flash geometry and volume produced by a forging process. Flash is excess material that has to be removed after forging. By optimizing the process, ProSIM engineers are able to reduce flash volume and decrease scrap.

"Gear forging process simulation means more development in less time," says Shamasundar.

For more information about *DEFORM* software:
Scientific Forming Technologies Corp., 5038 Reed Road, Columbus, OH 43220-2514
Phone: (614) 451-8330 • Fax: (614) 451-8325 • E-mail: *sales@deform.com* • Web: *www.deform.com*

For more information about ProSIM's services:
ProSIM, 326, III Stage, IV Block, Basaveshwara Nagar, Bangalore 560079, India
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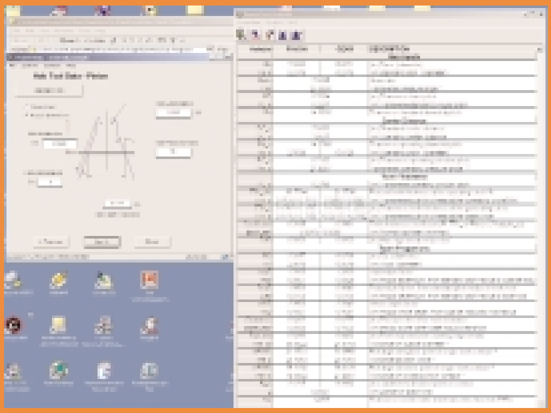

Parallel Axis Gear Analysis

PowerGear is a design and analysis tool for internal or external spur, single helical and double helical gears. The software was developed by Ray Drago and Remco deJong of Drive Systems Technology Inc., located in Glen Mills, PA.

The software uses a prompted input sequence that allows it to calculate gear tooth geometry, tool geometry, bending and contact stresses, flash temperature, strength and durability ratings in accordance with AGMA 2001-C95, EHD film thickness, frictional power loss, scoring hazard rating, tooth profile kinematics, subsurface shear stress/strength, required case depth for surface hardened gears, and other calculations. *PowerGear* also produces the manufacturing data needed to prepare an engineering drawing of a gear.

PowerGear can operate in conventional U.S. units or metric units, and it can switch between the two. Users can directly enter geometry parameters themselves or use the software's "parametric mode" to allow the program to calculate the geometry for them.

A complementary module, *DrawGear*, is included with *PowerGear*. *DrawGear* allows gear mesh action to be viewed dynamically on screen. The gears rotate so that a visual indication of mesh action can be observed.

The full professional version of *PowerGear* costs $695. A 30-day demo version can be downloaded at *www.gear-doc.com*. Also, a limited-capability student version of *PowerGear* is included in the cost of the "Applications in Parallel Axis Gear Design" seminars presented by Ray Drago at the University of Wisconsin-Milwaukee (visit *www.uwm.edu/dept/ccee* for information about the seminars).

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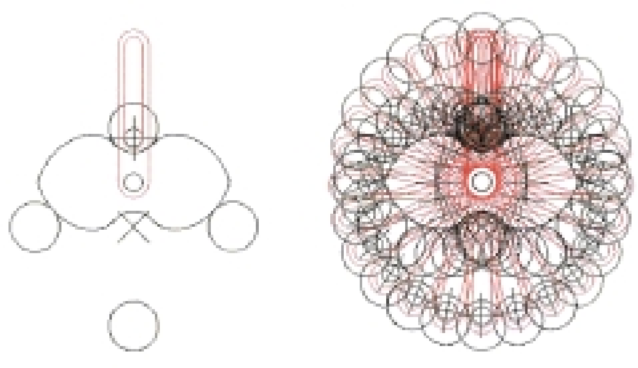

Trogetec's *ACADS* software can produce animations and motion profiles for unusual gear configurations, such as the one-station cardioid indexing device shown here.

Animated CAD Solutions from Trogetec

A newly released software package from Trogetec Inc. of Riverton, WY, was developed "to help gear designers obtain theoretically perfect solutions for realizing specific objectives in designing gears," says president Sandor J. Baranyi. Trogetec specializes in the design, engineering and manufacturing of trochoidal and involute gear systems.

The software, called *ACADS*, provides animated images of gear systems to allow designers to visualize and understand how complex mechanisms work. The software also can provide "composite-flash" images, which are static representations of a gear system's motion.

In addition, the software allows quantitative evaluation of various engineering conditions based on corresponding numerical data files or CAD images. Examples include studies on initiating or terminating gear tooth engagements, avoidance of involute profile undercutting and fouling. Applications for involute and trochoid (cycloid) gearing include: determining gear mesh efficiency; proving studies for CNC machining; convex/concave profile enveloping for internal or external spur, helical or spherical gear meshes; and special kinematic studies of mechanism operation.

According to Baranyi, the software can be useful in researching and developing competitive new mechanisms.

Trogetec also provides the following software titles: *EZGearplot*, for designing, manufacturing and quality control engineering tasks related to involute and cycloidal gears, speed reducers, roller chain sprockets, cams, compressors and vacuum pumps; *INVOGEAR*, a companion to *EZGearplot* that expands that software's capability to include nonstandard involute spur and helical gears; and *MODOPT*, which produces high-speed motion profiles for cams, motion servos and other mechanisms.

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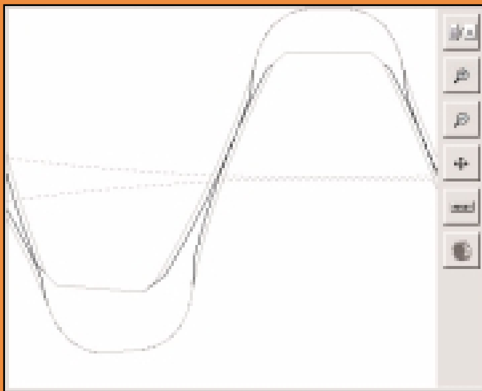

GearDesignPro from Dontyne Systems

GearDesignPro is a new program for designing spur and helical gears, published by Dontyne Systems of Newark, England. The software, which rates gears for contact and bending strength according to ISO 6336, is intended for both novice and advanced users.

Features of *GearDesignPro* include flash temperature calculations, center distance optimization, tolerancing based on ISO 1328, measurement over balls, and partial DXF output.

The center distance optimization routine allows the designer to determine the minimum center distance that still allows all safety factors to be above 1.0. The calculation is based on the input of helix angle, material properties and other geometry constraints.

One of the advanced features of the software is a "Design Workspace Search," which allows the user to generate thousands of gear designs and analyze and compare them in minutes. Various parameters can be plotted against each other, enabling the designer to select the optimum design for his or her requirements.

GearDesignPro comes in three different versions: Basic, Standard and Advanced. The Advanced version costs £1,200 (about $2,080) and includes all features and functions described above. The Standard version costs £800 (about $1,390) and excludes the "Design Workspace Search." The Basic version costs £200 (about $350) and excludes the "Design Workspace Search" and the center distance optimization routine.

For more information:

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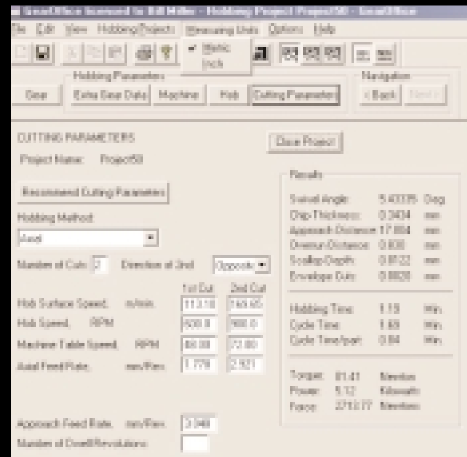


GearOffice© calculates hobbing parameters, including feed rates, cutting speed and number of cuts.

Software for Gear Hobbing

GearOffice© is a Windows-based computer program for calculating hobbing machine settings and for organizing gear setups, hobs, machines and hobbing projects.

The software was developed and written by GearOffice Inc. in consultation with Yefim Kotlyar of Bodine Electric in Chicago, IL. *GearOffice* is available for sale through GearHelp LLC of Cincinnati, OH.

The program is capable of calculating hobbing parameters, such as cycle time, chip thickness, approach and overrun distances, hob setting angle, feed scallop depth, depth of enveloping cuts, force, power and torque. The program provides recommendations for feed rate, cutting speed and number of cuts. Also, it can recommend an appropriate cutter from the *GearOffice* database or automatically design a new hob.

GearOffice provides various gear calculations as well, including the relationship between tooth thickness, dimension-over-pins and span measurement; hobbing machine adjustments based on over-pins or over-span measurements; geometry and gear inspection parameters; and tolerances according to AGMA, DIN or ISO standards.

"One of the unique features of *GearOffice* is its powerful organizer that provides means to create, maintain and sort gears, machines and hobs," Kotlyar says. All data is stored in an MS-Access database. A gear, machine and hob can be combined into a hobbing project to determine or specify cutting parameters. The same gear, hob or machine may be selected in multiple hobbing projects.

"*GearOffice* can be a useful tool for manufacturing engineers and managers, hobbing estimators, hobbing machine operators, hob inventory control personnel and gear inspection personnel," Kotlyar says.

GearOffice costs $650, and a 30-day trial version is available.

For more information:

GEARHELP LLC
903 Baccarat Drive, Cincinnati, OH 45245
Phone: (513) 947-8327
Fax: (513) 947-8328
E-mail: *Bill@GearHelp.net*

ProXpt Expands *GearCAD*'s Capabilities

ProXpt is a new software package from Gearsoft Design of Lane Cove, Australia. *ProXpt* is an advanced gear profile manipulation and enhancement tool designed to be used in conjunction with *GearCAD*, Gearsoft's gear design software.

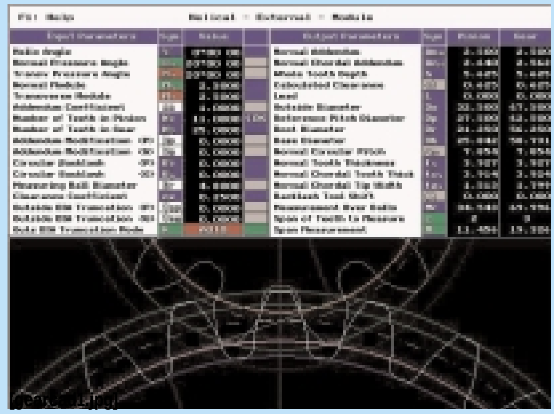
GearCAD performs geometry calculations for internal and external spur, helical and planetary gear sets using module, diametral pitch or Fellows stub tooth formats. Features of *GearCAD* include addendum modification, non-standard center distance, selectable backlash, tooth sizing and load checking. It also includes sub-windows for cutter selection, center distance calculation, permissible load approximation and other calculations.

"The visual design concept makes the program an ideal tool for the novice gear designer as well as an expert," says Gearsoft manager Stan Koch.

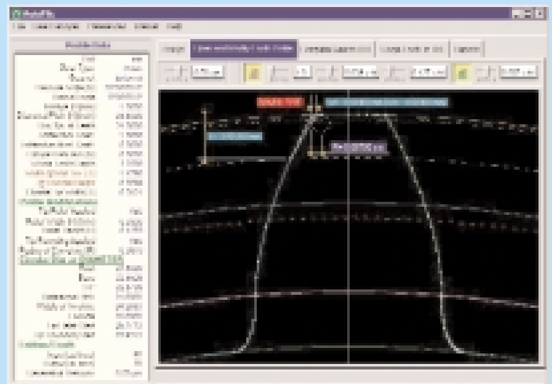
ProXpt takes the gear design a step farther, Koch says. "It is especially suited for designing profiles for plastic gears, sintered gears or high performance gears."

With *ProXpt*, the gear profile can be visually or numerically modified by applying tip relief and tooth rounding. The values can be exported as DXF files, which can be used as input for NC programs or CAD programs. *ProXpt* also converts DXF line output to arc output to reduce the size of the DXF files, Koch says.

GearCAD costs U.S. $895, and *ProXpt* costs U.S. $345. Demo versions of each are available at the company's website.



***GearCAD* is used for calculating internal and external spur, helical and planetary gears.**



***ProXpt* allows the user to modify the tooth profile of gears designed in *GearCAD*.**

For more information:
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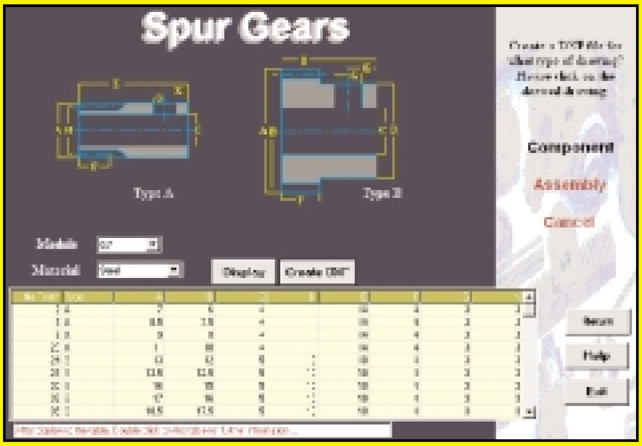
Gears and the Internet

The Mechanical Design and Concurrent Engineering Research Laboratory at The Nottingham Trent University in Nottingham, England, has been working on a number of projects aimed at bringing the gear industry into the Internet age.

"Application of Web-enabled technology into gear design and manufacture is one of our major research interests," says Professor Daizhong Su, head of the research group.

One of the projects the group has worked on is the development of a Java-enabled database that can create DXF drawings of gears on the fly. This prototype database would be used on a gear manufacturer's website. Instead of storing DXF drawings for each variation of a part, the team's software would create the drawings for users at the click of a button.

Another project at the research group is the development of a gear design optimization routine created to run over the Internet without downloading any software. The group is also working in other areas of Web-enabled collaborative design, Su says.



Researchers at The Nottingham Trent University have developed an interactive database that will generate DXF drawings of gears on the fly.

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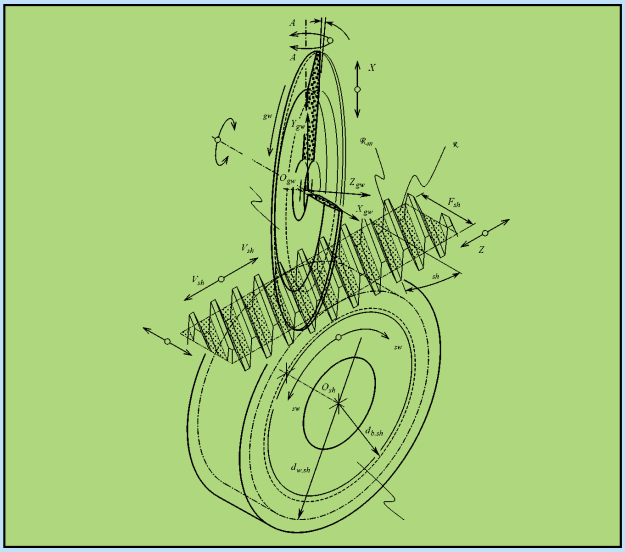
Web: *www.facct.ntu.ac.uk/research/groups/mechdes*



Modified Shaving Cutters for Low Noise

Dr. Stephen P. Radzevich, a former professor of mechanical engineering and consultant to New Venture Gear in Syracuse, NY, has developed software for reducing noise in automobile transmissions that use pinions finished by gear shaving.

The software, called *SHAVER*, was developed for use with the Mitsubishi ZA30CNC shaving cutter grinder. The main function of the software is to modify the tooth surfaces of shaving cutters in order to provide modified tooth surfaces of pinions manufactured by them. Those modified pinion tooth surfaces help to create quieter transmissions.

"Application of topologically modified pinions allows the reduction of transmission error up to two times," Radzevich says.

SHAVER allows computation of the desirable shaving cutter tooth surface, the grinding wheel axial profile and the actual shaving cutter tooth surface that will result. The software also computes the actual pinion tooth surface that will result from using the cutter, as well as predicted deviations between the actual pinion tooth surface and the desirable pinion tooth surface.

According to Radzevich, the software could be expanded to allow for optimization of parameters such as grinding wheel diameter, grinding wheel axis tilt angle, and worktable acceleration/deceleration. Radzevich is also working on versions of the software to be used with cutter grinding machines from Kapp and other manufacturers.

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Transmission Analysis

The *TYCON* software package from AVL List GmbH is a specialized tool for the analysis of valve trains, timing drives and transmissions. *TYCON* can help engineers calculate the dynamic behavior of gears and shafts in transmissions or gear units. Those calculations can be useful in assessing contact behavior and forces and investigating noise mechanisms, such as gear rattle or whine.

TYCON determines tooth contact forces in gear meshes as well as changes in flank contacts. The software can also calculate forces in belts or chains, as well as torques in shafts. The displacement, velocity and acceleration components of gears, pulleys, sprockets and shafts are also calculated.

Gear elements are represented by mass and moment of inertia. They're modeled with up to six degrees of freedom. Variable gear mesh parameters include backlash, stiffness, damping and geometry. Friction forces can be defined as constant or dependent on friction and velocity. Contact geometry, meshing stiffness and damping can be calculated in a pre-processing module.

The software also includes a variety of related elements in its modeling analysis. Those elements include shafts, bearings, belts, chains, sprockets, pulleys and guide elements.

TYCON has an interface to another AVL software package, *EXCITE*, which is used for acoustic analysis of engines and transmissions.

AVL, founded in 1948, is a privately owned, independent company specializing in the development of powertrain systems for internal combustion engines as well as instrumentation and test systems.

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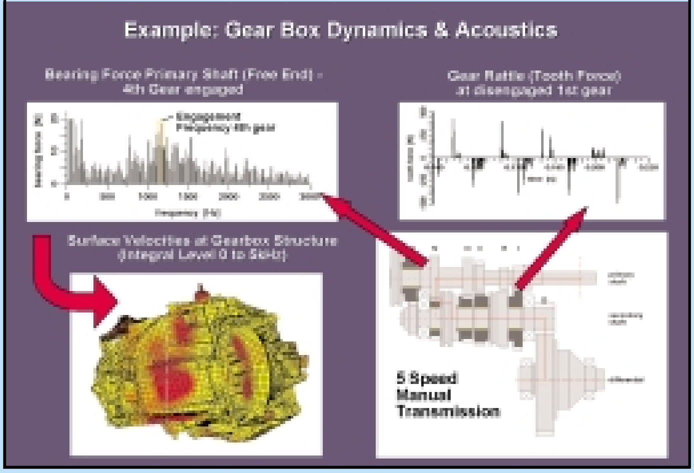
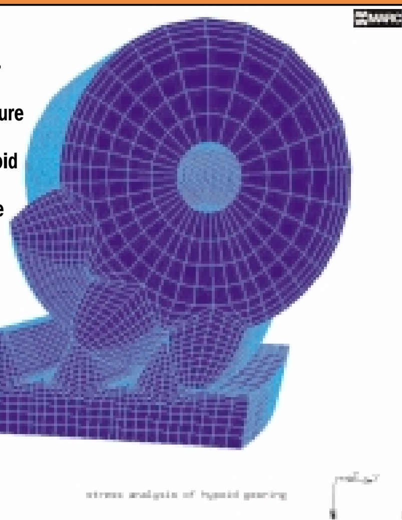
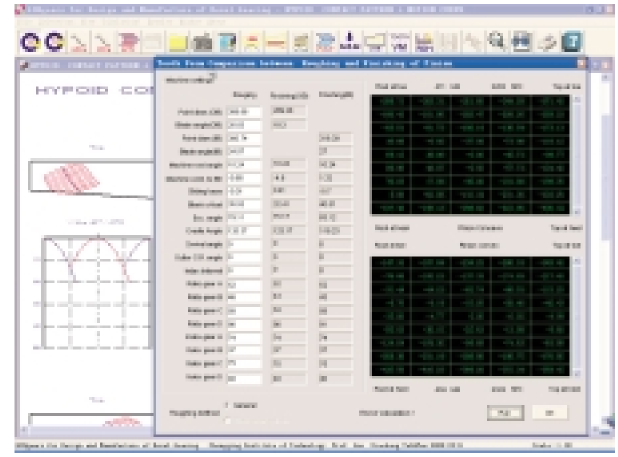




GSHgears **is comprehensive software for the design, manufacture and development of spiral bevel and hypoid gears. It includes the ability to export finite element models.**



GSHgears **can export data for the creation of 3-D solid models through the simulation of the cutting process.**

Spiral Bevel Design, Manufacturing and Analysis

GSHgears, developed by a research group at Chongqing Institute of Technology in China, is commercial software for the design, manufacture and analysis of spiral bevel and hypoid gears of the Gleason tooth system.

According to associate professor Xiaodong Guo, who led the group that developed the software, *GSHgears* can help engineers determine blank dimensions, cutter specifications and machine settings. The software can calculate stock distribution for pinion finishing, and the user can modify the roughing setting to optimize stock distribution.

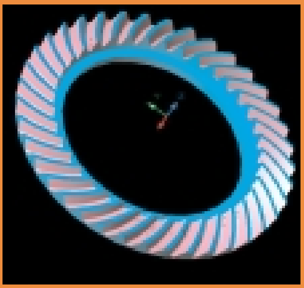
Also *GSHgears* includes tooth contact analysis for optimizing contact patterns and reducing transmission error.

The software provides an interface to 3-D gear analyzers from M&M Precision Systems Corp. The software's output data can be used to initiate the M&M gear analyzer, which simplifies the operation of measuring a bevel gear, according to Guo. Also, the inspection machine interface allows measured data to be imported into the software. After a gear's actual tooth surface is measured on the 3-D gear checker, *GSHgears* can calculate machine modifications using its own optimization algorithm designed to achieve the ideal tooth form.

In addition, the software includes a finite element pre-processing module, which allows the user to create a multi-tooth finite element model for *MARC, ABAQUS* or *I-DEAS* finite element analysis software. The FEA model is based on the designed gear parameters, such as blank geometry and actual cutter specifications and machine settings.

Cutting process simulation is achieved through an *AutoCAD 2000* model, which imports data from *GSHgears*, creates the cutter and gear 3-D solid models, simulates the cutting settings and creates a 3-D toothed gear solid model.

So far, Guo says, the software has been installed in more than 40 factories in China and one in Turkey.



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Free Gear Design Software

If you're looking for proven gear design software but don't have the budget for an expensive system, Fairfield Mfg. Co. Inc. of Lafayette, IN, has a solution for you.

Since 1985, Fairfield has sold the DOS version of the company's software through the AGMA, but now the software, including a beta Windows version, is available for free via *www.fairfieldmfg.com*.

Fairfield's gear design software calculates geometry, rating, stress and life values for spur, helical, planetary, bevel and spiral bevel gears. Calculations are based on AGMA 2001-B88 and publications of The Gleason Works.

In addition, Fairfield has provided a beta version of a dimensional analysis program to aid in performing and keeping track of assembly stackups during the design phase of a project.

For more information:
FAIRFIELD MFG. CO. INC.
US 52 South • P.O. Box 7940 • Lafayette, IN 47903-7940
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Understanding Fluid Flow to Improve Lubrication Efficiency

Haruo Houjoh, Shun-ichi Ohshima, Shigeki Matsumura, Yasuhiro Yumita, Keiji Itoh

Abstract

Excess lubricant supply in gearing contributes to power loss due to churning as well as the requirements of the lubrication system itself. Normally, a much larger amount of oil than required is used for cooling because so much of it is thrown away by centrifugal force. To lower the amount of lubricant required and reduce those losses, it is necessary to discover the ideal location of the supplying nozzle. The authors have measured the pressure variation during the mesh process, which will give us an idea of how we can deliver the lubricant with minimal but efficient cooling. Pressure measurement was done for several pairs of helical gears that have gages installed at the bottom of the root space. A sucking action is found to distribute lubricant along the tooth mesh, especially at the recess side of meshing. Although there is a global axial flow due to the helix angle, which is directed from the leading side towards the trailing side, the opposite flow exists partially at the trailing side.

Table 1—Dimensions of tested gears.

Gear ID		S	H1	H2	H3	H4
Helix angle (deg.)	*b*	0	13	16	21	30
Number of teeth	*z*	76	74	73	71	66
Normal module	m_n	4				
Pressure angle (deg)	α_n	20				
Face width (mm)	*b*	100				
Center distance (mm)	*a*	304				
Outer diameter (mm)	d_a	312				
Contact ratio		1.82	3.44	3.77	4.28	5.09

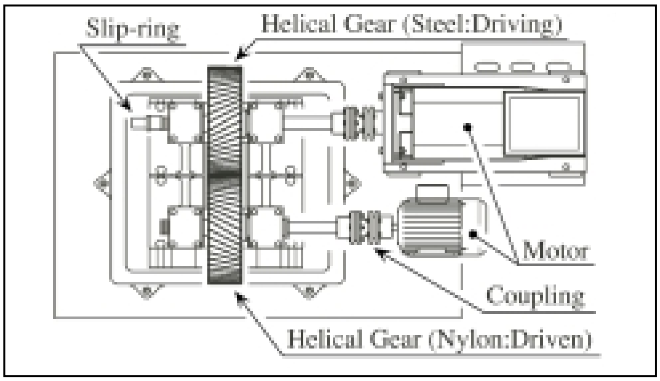

Figure 1—Gear arrangement for pressure measurement.

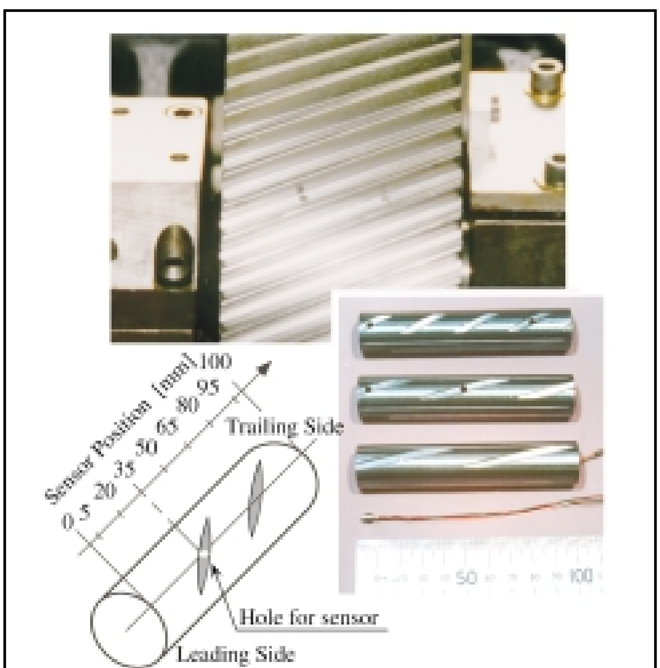

Figure 2—Appearance of rods and gear with rods at the bottom of teeth.

Introduction

Social requirements for energy saving are forcing various efforts to reduce excess power losses of mechanical elements. For a gear reducer, auxiliary consumption may be due to lubrication systems, windage, etc. Several solutions have been proposed by gear manufacturers. Renk AG is now utilizing a vacuum chamber to reduce windage loss (Ref. 1) while D.D. Winfree describes a method of decreasing windage loss by applying a baffle close to the tooth tip (Ref. 2). Since there are quite a few kinds of gear reducers, the solution must not be unique to just one kind.

Although the lubricant is expected to cool the tooth surface just after meshing, most of it does not work as expected because the lubricant is cast or thrown away by a strong centrifugal force before tooth engagement occurs. If one feeds the oil from the mesh entrance, most of it will get out before the mesh action. It is only vaguely known whether feeding the oil from the mesh exit works for both lubrication and cooling. These arguments have existed since the early stages in gear technology. However, the optimal way to avoid energy loss by reducing the amount of oil is still uncertain.

With a main focus on cooling the tooth, it is necessary to observe the behavior of the medium around the mesh region and find a way to deliver the oil to the appropriate position. This depends on the pitch line velocity, but the authors have found some strong pumping and suction effects, even at operating speeds of less than 50 m/sec. Accordingly, the present work will provide a database of dynamic air behavior, which closely correlates the oil delivery. The behavior at the mesh end region is mainly observed since it is important to feed enough oil there to cool the tooth surface.

The authors have already presented the behavior for a pair of spur gears (Ref. 3). Although the result was quite interesting, it seemed difficult to utilize the results for practical gearing since the air gets into the tooth space from both ends as a one-dimensional flow and collides at the middle of the tooth width. On the contrary, observation of a helical gear pair seems quite valuable since axial pumping action is expected to assist delivery of oil to the full surface.

Experimental Condition

Tested Gears. Four gear pairs were prepared to measure the pressure fluctuation at the tooth space bottom with different helix angles as shown in Table 1. Gears were assembled as shown in Figure 1 for pressure measurement. Each pair consists of a steel gear as a driver for pressure measurement and a nylon gear as a follower for dry operation. Every steel gear has left-hand helix angles, while the nylon gears have right-hand helix angles. For pressure measurement, cylindrical rods were embedded into a steel gear body aligned parallel to the axis so that a part of its skin conforms to part of the tooth space bottom.

Pressure Measurement Rod. For this purpose, rods were inserted to pre-bored holes before hobbing the gear blanks. Then, teeth were fabricated by hobbing, along with tangential shifts, to have narrower tooth thicknesses so that the bottom of a tooth space has sufficient width for exposing the pressure gage surface properly. Afterwards, the rods were removed and machined to attach the pressure gage so that the sensing surface was in the same plane as the bottom surface. Four or five rods were embedded in one gear body in such a position that the measurement could be done at desired places distributed width-wise over the length of the tooth space.

As shown in Figure 2, the measurement positions of the sensors were designed to be approximately b = 5, 20, 35 and 50 mm axially distant from the leading edge of the tooth space. Because of symmetry in the rotating direction, b can also equal 95, 80, 65 and 50 mm respectively under reverse rotation. Semiconductor press gages with a 3 mm diameter were used and embedded in the rod. Then the sensor surface becomes part of the bottom of the space and measures gage pressure. The sensor could measure transient behavior with resonance frequencies higher than 50 kHz.

Measurement

A schematic measurement system is presented in Figure 3. The pressure signal was fed through a slip ring at the end of a shaft to an FFT analyzer, and it averaged the signal synchronously to a once-per-revolution trigger signal. The number of averaging was determined 256 times to eliminate variation and system noise.

Measured pressure fluctuation can be presented in terms of two kinds of angular positions of a gear—the first is the angular position of individual pressure sensors that demonstrate behavior in accordance with the rotation of tooth space on the traverse cross-section, including the sensor. The other presents the behavior against the gear body, which corresponds to the dependence on time and medium motion. In this paper, the latter expression is used and represented by the angular sensor position of b = 5 mm. Figure 4 indicates the angular movement graphically to assist in better understanding the geometry.

Experimental Results

Figure 5 shows gage pressure vs. angular movement of a driving gear for the case where the helix angle is $\beta = 13°$ at the speed of 3,780 rpm (about 60 m/sec) of pitch line velocity. The

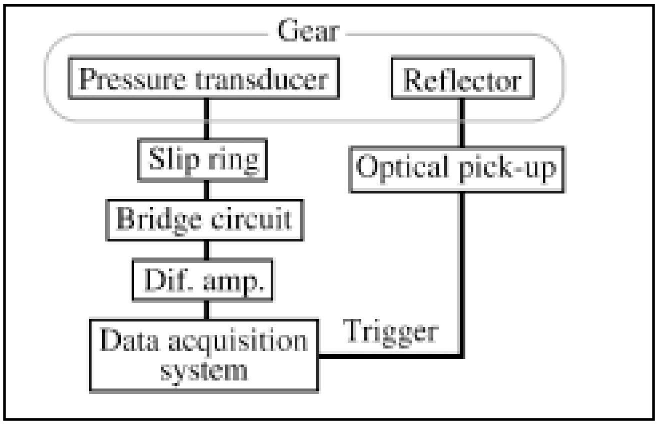

Figure 3—Schematic diagram of measurement procedure.

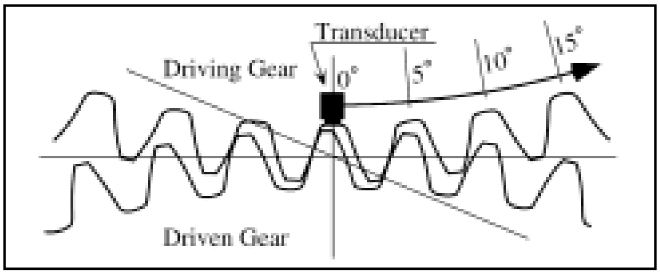

Figure 4—Geometry of pressure sensor installation from axial view.

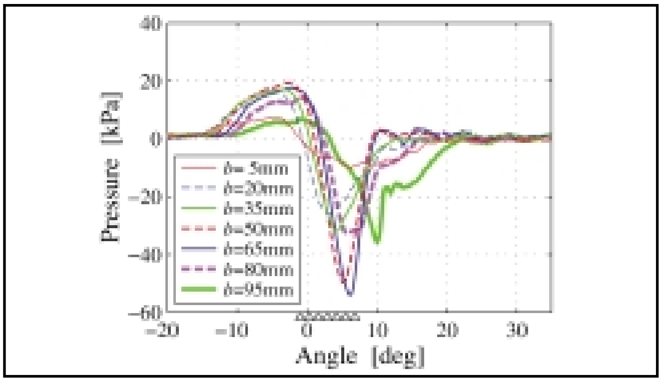

Figure 5—Time dependence of pressure at tooth space for a helical gear pair (β = 13°); Triangles at the bottom of abscissa show the position of the minimal cross-sectional area of individual pressure measurement.

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Shun-ichi Ohshima *has been an assistant professor at the Tokyo Institute of Technology since 1994. His area of expertise is in acoustic measurement technology with a 2-D microphone array and experimental visualization.*

Dr. Shigeki Matsumura *is an associate professor at Tokyo Institute of Technology. He is credited with developing a dynamic simulator for a pair of helical gears under partial load conditions.*

Yasuhiro Yumita *is a project engineer at East Japan Railway Co. His area of focus is in pressure measurement.*

Keiji Itoh *is an engineer at Mitsubishi Heavy Industries Ltd. Itoh specializes in the visualization of oil delivery by using an oil droplet shot via a custom-made electric gun.*

horizontal axis indicates the angular position of a sensor placed at b = 5 mm. The small triangles on the horizontal axis mark the points where the center of backlash of each transverse cross section passes across the pitch point height.

Pressure rise begins at the leading end of the tooth space b = 5 mm, and it is followed by consequential pressure rise point-by-point to the trailing end. The pressure fluctuation is not

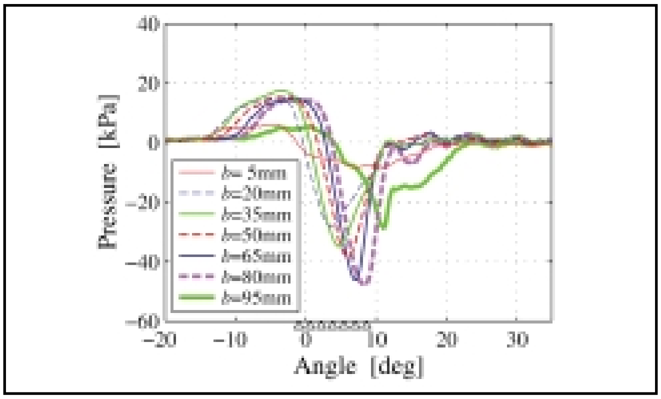

Figure 6—Time dependence of pressure at tooth space for a helical gear pair (β = 16°). Triangles at the bottom of abscissa show the position of the minimal cross-sectional area of individual pressure measurement.

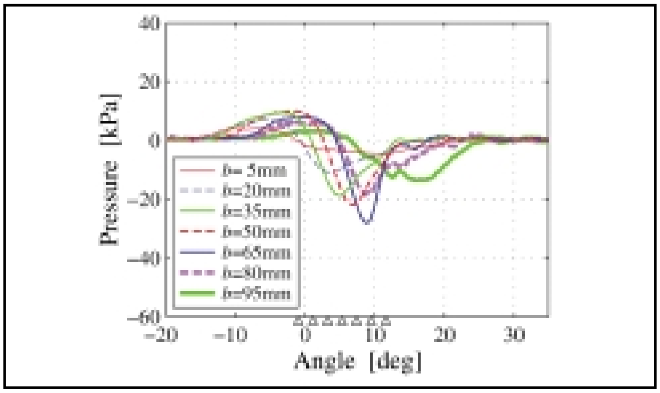

Figure 7—Time dependence of pressure at tooth space for a helical gear pair (β = 21°). Triangles at the bottom of abscissa show the position of the minimal cross-sectional area of individual pressure measurement.

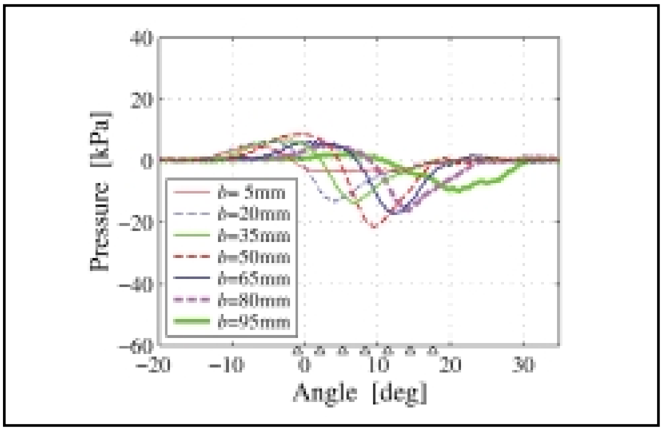

Figure 8—Time dependence of pressure at tooth space for a helical gear pair (β = 30°); Triangles at the bottom of abscissa show the position of the minimal cross-sectional area of individual pressure measurement.

strong at the leading end, and the trailing end's fluctuation is different from others. This weakness must be due to the boundary effect of tooth ends. Pressure curves at the inner locations have phase lag that corresponds to the helix angle. Basically, individual pressure increases gradually as the space goes through meshing and becomes higher at one pitch before the sensor passes through the pitch point height. The maximum is hereafter called "positive peak."

The maximum pressure seems independent of sensor position except at both ends. After reaching the maximum pressure, it then switches from positive to negative when the center of the backlash cross section passes along the pitch point height. Negative pressure becomes lower when the sensor passes across the pitch point. This is called the "negative peak," which occurs when the backlash space passes along the pitch point height. Both representative points slightly differ from each other with respect to peak magnitude and timing, both of which are dependent on sensor position.

The negative pressure is remarkably strong when compared to positive pressure. It is exceptionally strong at the points of both b = 50 and 65 mm. The pressure fluctuation resembles the results of spur gear tests presented by the authors from the aspect of global view. In addition, there is a specific pressure fluctuation at the trailing end b = 95, where the negative peak position is hardly found because it lasts for a certain period, which seems independent of the formerly described peak.

The results of other gears are shown in Figures 6–8. The basic shape of pressure variations is almost the same except for the magnitude. As the helix angle increases, the pressure becomes smaller and spacing of traces become wider due to larger lag times between adjacent sensing sections.

Discussions

Dependence of pressure on speed. From Figures 5–8, positive and negative peak pressures were read from the temporal traces and plotted on Figure 9 for two types of gears β = 13° and 30°. It is obvious that the peak pressure (absolute value) is proportional to the square of speed for both positive and negative. This quadratic tendency is naturally understood from the viewpoint of compressible fluid dynamics. Previous studies for a spur gear indicated this same tendency.

Dependence of pressure on helix angle. It is also clear that the peak pressure decreases as the helix angle increases. The negative peak pressure is much stronger than the positive one. It is supposed that the positive peak pressure at the entrance of engagement will refuse the oil delivery. On the contrary, negative pressure at the end of the engagement will help the oil delivery reach the tooth surface after meshing. This will be available only for effective cooling on the surface, not for friction reduction, because the oil must be thrown away by the centrifugal force.

Temporal and spatial behavior of pressure fluctuation. The pressure variation at the bottom of the tooth space indicates nothing but the pressure. Then, it is necessary to grasp the pressure fluctuation versus time in a 3-D space and imagine the motion of the medium.

Figure 10 shows the results compiled from the pressure measurement in Figure 6, β = 13°, 3,780 rpm. Each plot indicates the instantaneous pressure distribution along the tooth space. Angles presented at the left side indicate the angular movement of the gear in terms of the position of the pressure sensor placed at 5 mm interior from the leading end face of the gear. The negative angles indicate the region where the space is approaching the mesh, and therefore the angular position of –1° means that the tooth space of the driving gear at b = 5 mm is at the position before passing the pitch point height.

Oblique lines are the timing of backlash space passage at individual transverse cross sections where, as shown in Figure 11, mating (driven) tooth tips just enter the tooth space or invade the tip circle; preceding working tooth surfaces of the tooth space finish engagement; working surface of the tooth space enters mesh and the backlash space is isolated from the adjacent space; the sole backlash space is at its minimum; the preceding working surface finishes engagement; working surface of the tooth space finishes engagement; and mating tooth tips leave the tooth space boundary (tip circle of driving gear).

Negative pitch pressures occur just before the space bottom passes through the pitch point height. It travels from the leading end toward the opposite end with negatively growing pressure. However, the negative peak position follows the axial travel of tooth contact with a small lag, depending on the sensor location. It is assumed that the suction travels continuously by drawing the air from the leading area. Pressure becomes maximum at b = 65 mm. Then the peak pressure disappears before reaching the end of the face width. Instead, another negative peak grows at the trailing end and it does not move, but the magnitude does vary.

For the gear with helix angle β = 30°, as shown in Figure 12, the negative pressure region travels uni-directionally from the leading to the trailing end. The result indicates that, if the oil is fed so it has an axial velocity component or oblique incident, then it can be properly delivered with the aid of suction produced by the gear itself.

These phenomena suggest that there are two features: One is similar to a spur gear pair, in which air comes into the tooth space from both ends of tooth width. The other is specific for a helical gear, in which air travels uni-directionally due to axial movement of instantaneous tooth-to-tooth contact area.

The result indicates that if the oil is fed from the recess side, it is first sucked into the tooth space. Since the negative peak travels along the tooth space, oil will get deep into the tooth space in the actual direction. Therefore, it should be fed with axial velocity from the leading edge toward the trailing end. The reason is, axial movement of medium is mainly dependent on phase difference of mesh geometry between the leading end and the trailing end of helical gears, or on overlap ratio. This means if the helix angle is small but the face width is wide, the gear pair may be classified as "helical-like" rather than "spur-like." Therefore, movements of the helical gear pair can be utilized to assist lub delivery.

Visualization of Oil Delivery

To visualize the oil delivery, two kinds of experiments were conducted for the gear pair of β = 21°. One is shown in Figure 13 via a hand sketch after operating the gear pair for a certain length of time. The lubricant oil was manually fed with an oil

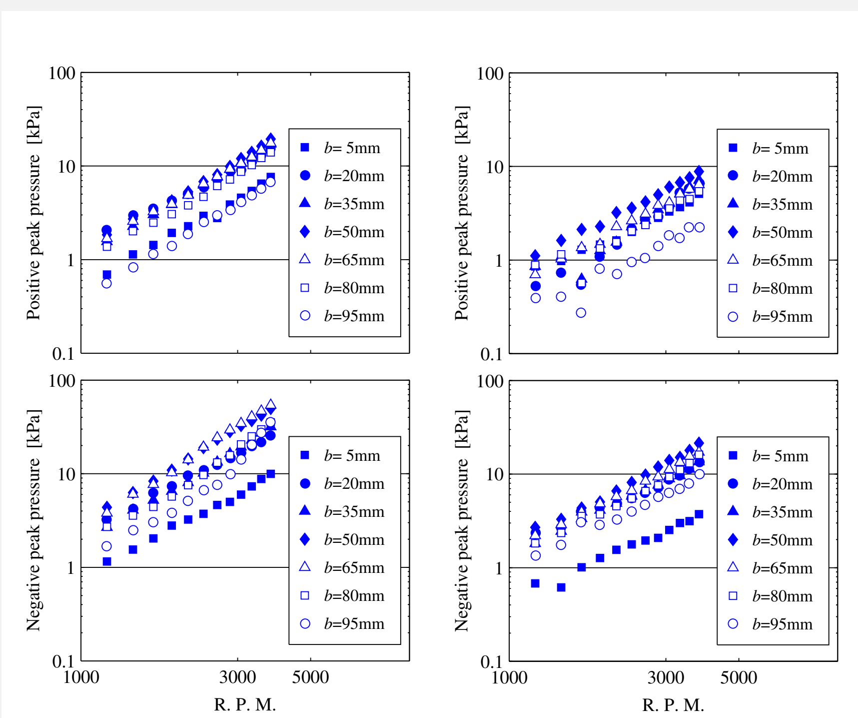

Figure 9—Dependence of representative pressure on gear speed (absolute peak value at both compression and sucking side); Left β = 13°, Right β = 30°.

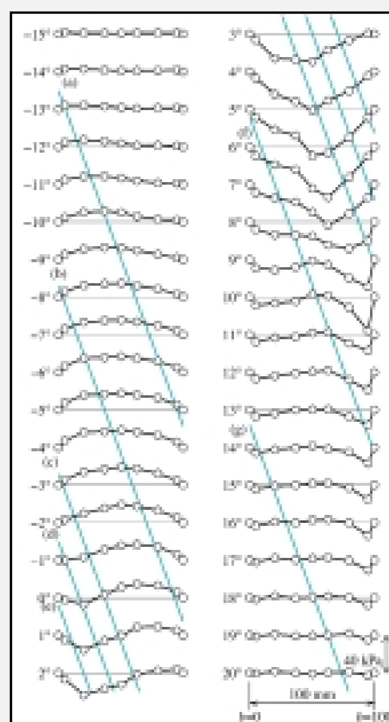

Figure 10—Pressure distribution along the tooth space vs. gear rotation (β = 13°).

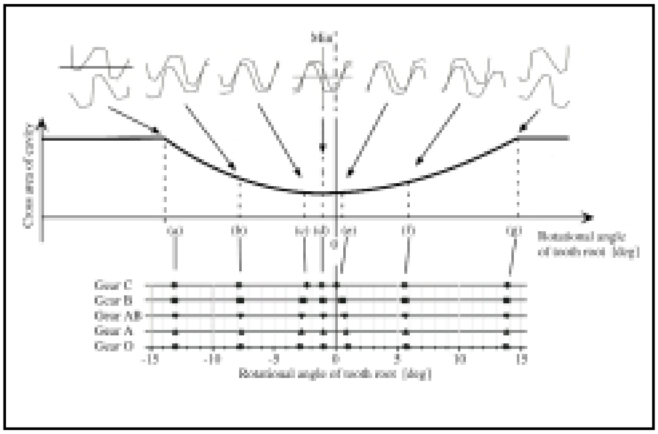

Figure 11—Angular movement of gear and geometry of mating teeth and space.

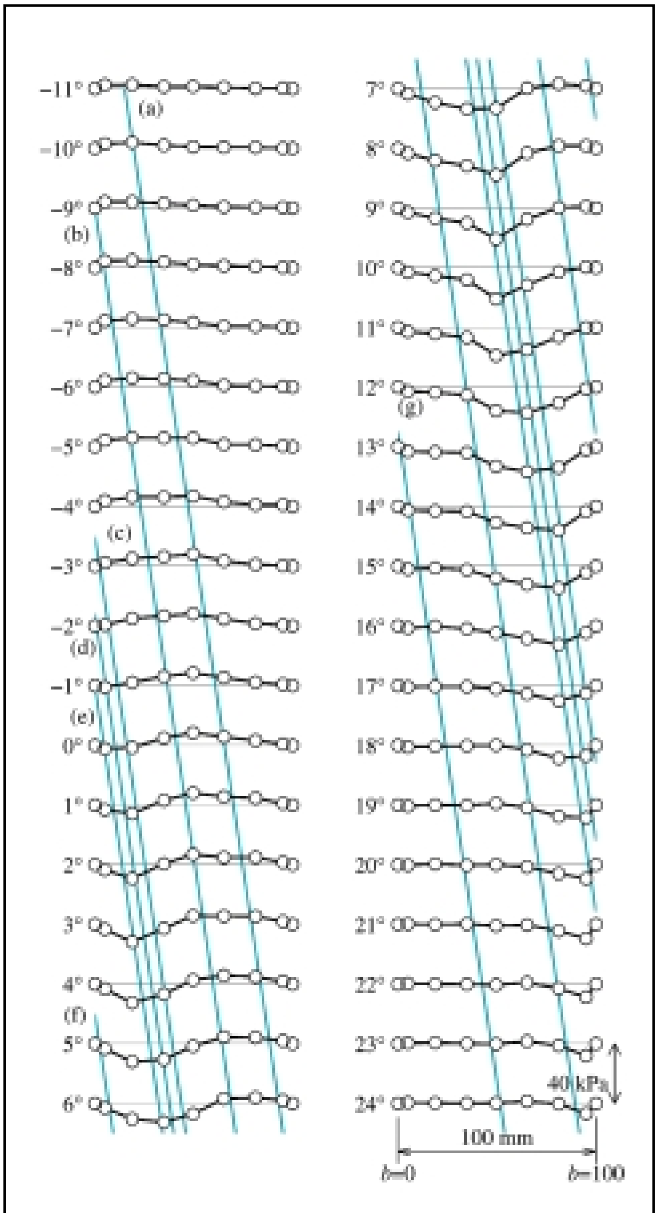

Figure 12—Pressure distribution along the tooth space vs. gear rotation (β = 30°).

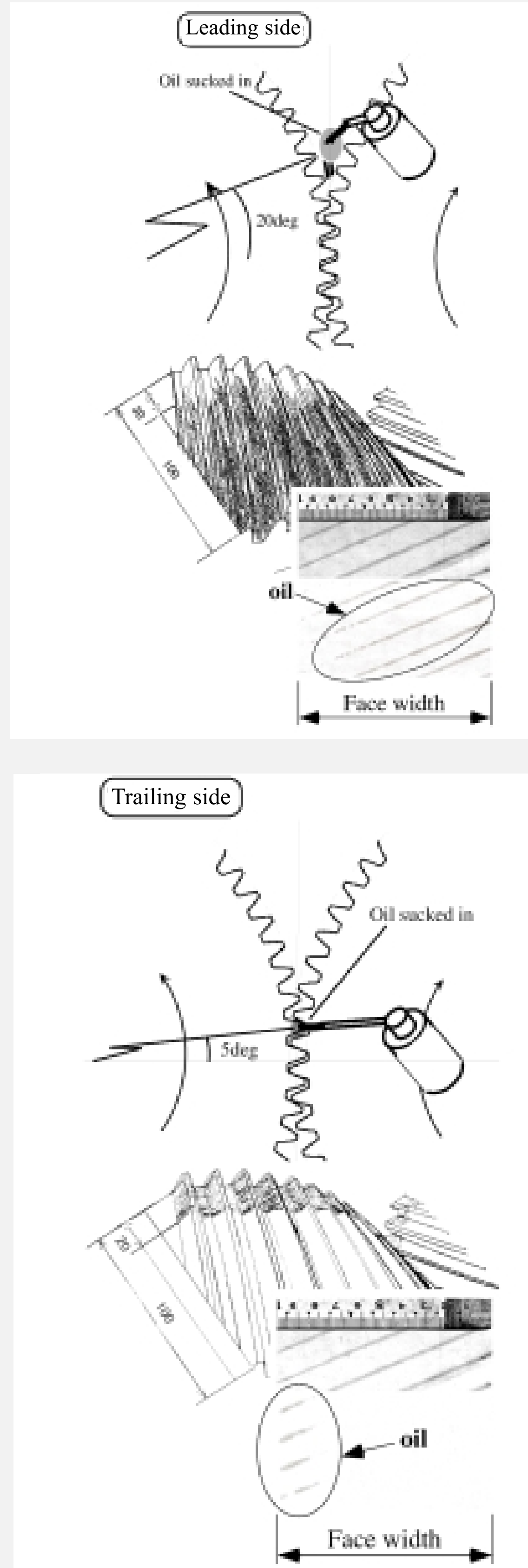

Figure 13—Hand sketch of oil supplied from both ends of the tooth space and the observed result of oil delivery; Top: fed from leading side, Bottom: fed from trailing side.

feeder as presented in the figure. At the exit of a nozzle, the oil had slightly more velocity when compared to the gear speed. Oil delivery was visually checked and then verified by printing the oily top of the teeth over paper. As seen in the figure, if an oil feed is at the recess region, oil reaches a certain longitudinal depth. However, it is clear that oil did not go across the whole face width. Instead, if the oil is fed from the trailing end, it reaches a depth where the oil did not make it from the opposite end.

Another experiment was done using an oil droplet, which was shot by an electric solenoid as drawn in Figure 14. The oil nozzle was designed such that a small amount of oil could be shot by the impacting action of the solenoid. The oil droplet was horizontally shot in an axial direction from the leading end of engagement and behind the intersection of tooth tip circles.

Figure 15 shows a result taken by printing the oily tooth tip land where the droplet was attached during the travel. The figure is presented by the contrast of the full width tooth stamp. The left-side figure is the result for a smaller amount of oil or higher initial speed velocity. The right-hand figure is the result for larger droplets, which means the initial velocity is slower. These results indicate that the oil droplet is flying over the intersecting line of two circumferential cylinders in the axial direction. There are two features recognized—a radial sucking action even though the tooth space has centrifugal action and an axial acceleration of the droplet since the right-hand figure shows the parabolic trace. It is unusual that, even at the recessing region, there is a strong force keeping the oil close to the gear.

Validity for Other Dimensions

It is difficult to experiment for various configurations such as different modules, different face widths, etc. Therefore, it is desirable to estimate the phenomena in a non-dimensional form. From the experience of acoustic measurement done by one of the authors for pumping action (Ref. 4), it is supposed that the dynamic behavior of the medium follows a parameter of b/λ where λ is the sound wavelength of tooth frequency.

This means the sound emission follows a similar law governed by the tooth face width and the size of a tooth or module. Module is implicitly included within the parameter λ, which is inversely proportional to mesh frequency. If one designs a gear pair with a fixed center distance or under the condition where the number of teeth times the module is constant, then mesh frequency is proportional to the number of teeth times revolution speed. This leads to the parameter $b*z*N/m$, which will determine the pressure in which the variation rate of space area is taken into consideration. Peak pressure will decrease as the helix angle increases.

The other estimate is spur- or helical-like characteristics of axial movement. For this argument, the authors think the parameter should include module and face width in addition to tooth angle. This is because the mating tooth affects movement of the medium. Therefore, if the helix angle is small but the face width is wide, the gear may be classified as "helical-like" rather than "spur-like."

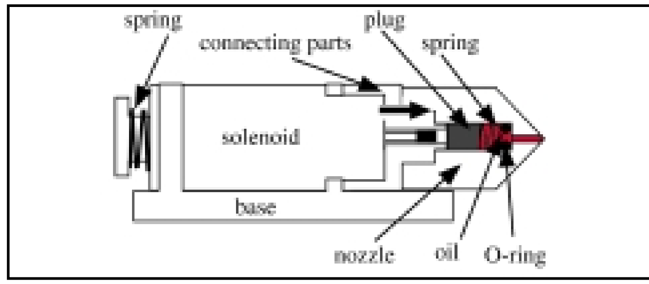

Figure 14—Schematic of the oil shooter.

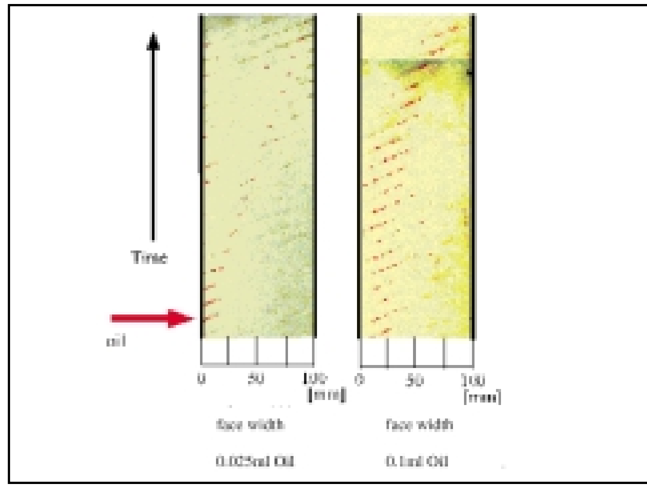

Figure 15—Stamp (red parts) of oil droplet shot from the leading end at the height of about 40 mm from the pitch point. Left: Initial speed is about 13.5 m/s. Right: Initial speed of about 7.5 m/s.

Conclusions

For the purpose of realizing lubrication efficiency improvements, behavior of the medium at the exit of mesh is measured and discussed. The results of this study show that there is an axial travel of strong negative pressures as the meshing proceeds. Also, there is sucking action in the axial direction as well as the concentric direction at the end region of engagement. ✪

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This paper was originally published by the American Society of Mechanical Engineers at the DET '03 ASME Design Engineering Technical and Computers and Information in Engineering Conference. It can be purchased at the ASME digital store online at *www.asme.org*.

Service Behavior of PVD-Coated Gearing Lubricated with Biodegradable Synthetic Ester Oils

Manfred Weck, Oliver Hurasky-Schönwerth and Christoph Bugiel

Abstract

The following article is concerned with the analysis of the wear-reducing effect of PVD-coatings in gearings. Standardized test methods are used, which under near-real conditions enable statements to be made about the different forms of damage and wear (micropitting, macropitting, scuffing).

The basic aim of the analyses is to transfer the functions of individual lubricant additives to the surface of the material via the application of wear-protection coatings in order to be able to reduce the additive content in gear lubricants. The report shows that the use of metal-carbon layers enables the omission of surfactant additives.

Introduction

Alongside performance capability and fulfillment of required specifications, the environmental compatibility of technical products is increasingly at the forefront of public interest. This trend is caused on the one hand by a general increase in environmental awareness and on the other by the increasing scarcity of non-renewable raw materials that are used as the starting materials for the commercial production of many goods.

Gearboxes are lubricated with mineral oil or synthetic-based lubricants for reasons of wear protection and for drawing off heat. These lubricants are alloyed with additives to achieve the required characteristics. The additives cause the lubricants to become potentially environmentally toxic and thereby conflict with the trend for producing environmentally sustainable products.

A first step for the improvement of environmental compatibility is the use of easily biodegradable lubricants, which nevertheless contain additives for the purposes of lubricant performance. A further step is the avoidance or reduction of additives without diminishing load-bearing capacity, wear behavior, lifetime and reliability of the gearing operated with additive-free or low-additive lubricants. Hard material, physical vapor deposition (PVD) coatings can compensate for the missing additive functions and are able to perform the functions of additives.

The first phase of the analyses on this subject was carried out at the Laboratory for Machine Tools and Production Engineering, located at Aachen University, in Aachen, Germany. In the first phase, tests were carried out on a rolling test rig to simulate the tooth flank contact with PVD-coated rollers using rapidly biodegradable synthetic esters (Refs. 1–3). Of the hard material PVD coatings used in the test—CrAlN, TiAlN, WC/C and ZrC—the amorphous metal carbon coating WC/C proved particularly effective. In the second phase, this coating system is being examined in single-stage gearing with regard to its wear protection characteristics.

Test Structure, Coating and Lubricants Used

There is a series of standardized test procedures for the analysis of the operational behavior of lubricants which are carried out on FZG back-to-back test rigs with an axle distance of a = 91.5

Table 1—Characteristics of the WC/C coating (Balzers Verschleißschutz GmbH).

Characteristics	Value
Microhardness (HV 0.05)	1,000
Friction value against steel (dry)	0.15–0.20
Coating thickness (µm)	1–4
Internal stress of coating (GPa)	–1.0
Max. application temperature (°C)	300
Coating color	black–gray
Coating structure	laminate

Table 2—Laboratory values for the test oils in the fresh state.

Specification	Reference oil CLPE 100	Basic oil COE 100
Viscosity at 40°C (mm^2/s)	98	92
NZ figure (mgKOH/G)	1.4	1.3
Viscosity index (–)	180	169
Water content (%)	< 0.1	< 0.1

mm (Ref. 4). As purely lubricant tests, these procedures are generally carried out with uncoated standard gearing. By using coated gear sets, it is possible to expand test procedure statements on the behavior of coating systems to their use in real gear tooth flank contact situations. In the test procedures, the scuffing test (Ref. 5), the micropitting test (Ref. 6) and the macropitting test (Ref. 7) are seen as fundamental in the evaluation of performance and the behavior in operation of a lubricant.

The WC/C coating employed is a commercially available carbon layer with a metal content, applied by means of a PVD-sputter process. The characteristics of this coating are given in Table 1.

Table 2 contains the basic specification data for the rapidly biodegradable synthetic ester, which is used both with additives (reference oil, CLPE 100) and without additives (basic oil, C0E 100).

Analysis in Accordance with FZG Scuffing Test Method

So-called FZG-A gearing, which displays a distinct one-sided profile displacement, is used in the scuffing test in accordance with DIN 51 354 Part 2 (Ref. 5). The result is a high sliding speed on the tooth flanks and consequently a particular sensitivity to scuffing.

Two sets of gears, one uncoated and one WC/C-coated, were provided for the analyses. Each one was tested in combination with the reference oil and the basic oil. Figure 1 gives the mass loss figures for the uncoated test gears relative to the respective load levels applied.

With the reference oil, there was no significant increase of mass loss during the test period. The reference oil can therefore be certified as achieving a damage load level > 12, according to the test method specified in DIN 51 354 Part 2. On the contrary, during the scuffing test with the basic oil, traces of scuffing were detected on the pinion and gear from load level 8 onwards. In order to compare the development of the scuffing damage with that of the coated gearing, the scuffing test was continued up until load level 12, although the damage criterion had already been achieved after load level 8. The scuffing on the pinion leads to progressive mass loss, which after load level 10 amounts to $\Delta m = 60$ mg and after load level 12 $\Delta m = 169$ mg.

Figure 2 shows photographs of the uncoated pinion at the end of the test. The bottom photo shows slight scratches running in the direction of the profile on the flanks of the pinion teeth which

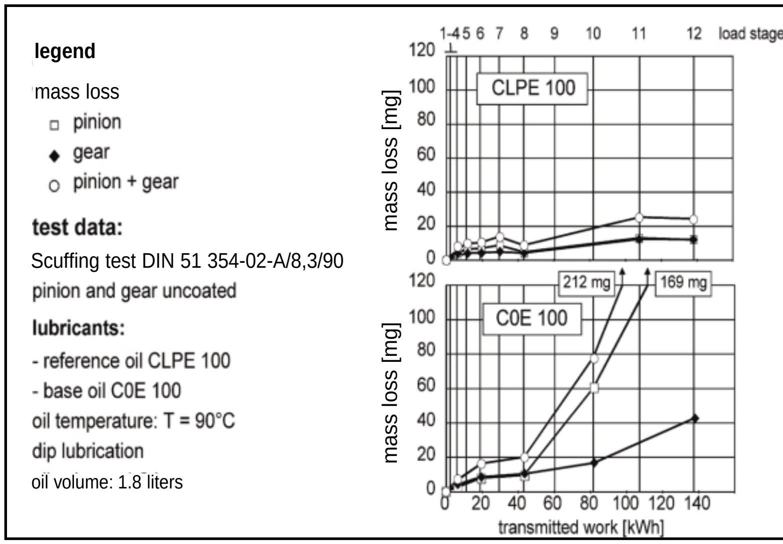

Figure 1—Mass loss of uncoated gear sets in the scuffing test with reference and basic oils.

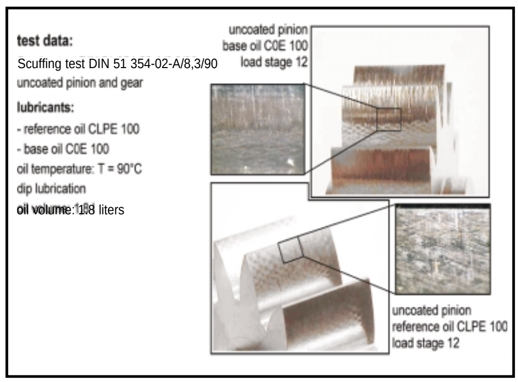

Figure 2—Photographs of the uncoated pinion at the end of the test (after load stage 12).

were lubricated with the reference oil. The surface structure produced by the Maag crossgrinding, however, is observed to be practically unaltered after the conclusion of the analyses. The pinion tooth flanks lubricated with the basic oil, though, reveal distinct scuffing in the area above the rolling circle. That scuffing has led to a complete destruction of the top surface of the tooth flank.

Scuffing tests with the reference and basic oils were also carried out under identical test conditions on WC/C-coated gear sets. The mass loss of the pinion and gear determined after each load level is shown in the diagrams in Figure 3.

In the scuffing test with the reference oil, the WC/C-coated gear set displays a linear progression of mass loss over the test period. This mass loss results from the continuous abrasion of the WC/C coating, which is increasingly evened out due to its laminate structure.

In this case, mass loss is observed on the test gear. The abraded particles of the coating settle at the bottom of the oil sump in the test gears in the

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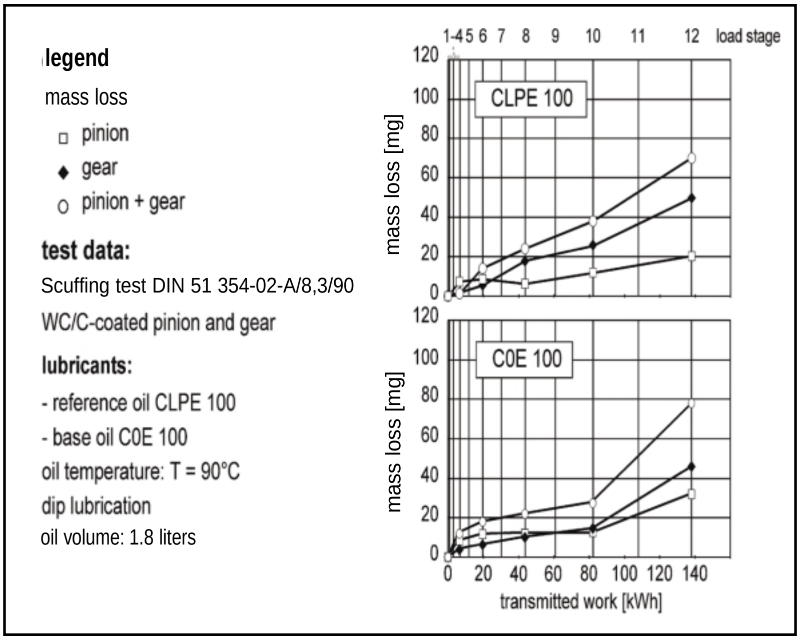

Figure 3—Mass loss of WC/C-coated gear sets in the scuffing test with reference and base oils.

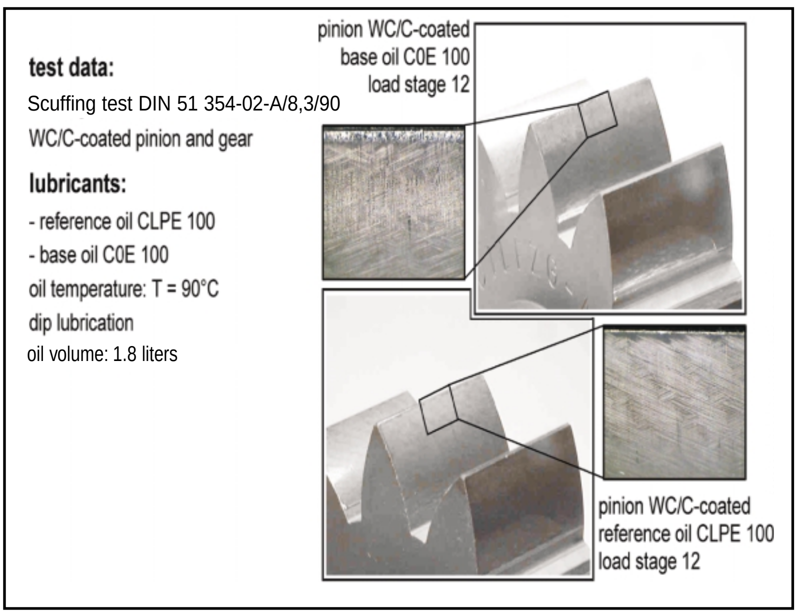

Figure 4—Photographs of the WC/C-coated pinion at the end of the test (after load stage 12).

form of black sludge. Direct contact of the metallic surface of the tooth flanks can be ruled out because examination under a light-optical microscope after the end of the test revealed no exposed flank areas either on the pinion or on the gear.

The scuffing test with the WC/C-coated gear set in combination with the basic oil shows the wear-protecting effect of the WC/C-coating.

After completion of the test to load level 12, the total mass loss recorded with the basic oil is practically identical to the total mass loss of the tooth flanks lubricated with the reference oil with additives within the bounds of measurement reproducibility when determining mass loss.

Photographs of the WC/C-coated tooth flanks of the pinion are shown in Figure 4. Under the light-optical microscope, small areas of wear can be seen in the WC/C coating after load level 12 on the tip of the pinion and at the root of the gear, giving rise to direct contact with the metallic surface. The coating must be improved in this respect.

In conclusion, comparing the scuffing tests of the uncoated and WC/C-coated gear sets with the synthetic ester's basic oil, we can determine that the WC/C coating under the specified test conditions leads to significantly less wear of the tooth flanks of the coated gear set. The reduced wear is expressed in an approximately 2.5-fold less mass loss of the coated pinion and gear compared with the uncoated pinion and gear.

Furthermore, the comparison of the two scuffing tests with WC/C-coated gearing shows that the wear-reducing effect of the WC/C coating is evidently not dependent on the lubricant's additives. In accordance with the current stage in the analyses, the wear protection effect of the reference oil additives appear to exercise no effect on the coated surface and is largely assumed by the coating.

Since the wear-reducing effect of the WC/C coating is temporally limited due to the abrasion, ultimately the scuffing resistance of the combination of the uncoated gear set and the reference oil with additives must be estimated to be greater than the combination of WC/C-coated gearing and basic oil.

Consequently, there is a need for further research and development in order to be able to make improvements to the behavior in operation and the wear resistance in particular of the coating and to match the coating to the requirements.

Analysis in Accordance with the FZG Micropitting Test Method

The influence of lubricants and their additives on the development of micropitting are quantitatively defined with the aid of a micropitting test (Ref. 6). The micropitting test is in two parts and encompasses a load stage test and a subsequent endurance test. In the load stage test, the micropitting resistance of the tribological system gear lubricant is determined in the form of a damage load level in given operating conditions. The endurance test gives information about the progression of damage over greater load cycles.

The standard test gearing used in the micropitting test is the unmodified FZG-C test gearing. As shown in previous analyses carried out by the authors (Ref. 8), the entry impact of these gear teeth caused by the absence of tip relief leads to damage of any coating applied, thereby impeding any wear-reducing effect. For this analysis, therefore, modified test gearing is used, with crowning and tip relief on the pinion and gear.

In these analyses, micropitting tests were carried out with two sets of gears, one uncoated and one PVD-coated, and the rapidly biodegradable synthetic ester with additives (reference oil CLPE 100). The mean pinion profile form deviation measured in these tests is shown in Figure 5. The results of micropitting tests with the unmodified FZG-C test gearing variant are also shown (Ref. 8).

In Figure 6, the profiles of the unmodified and modified test pinions are documented. If we look at the mean profile form deviation of the unmodified pinion variants, we observe an almost continuous increase in both instances. This is largely affected by the cratering caused by the entry impact in the root region of the gear tooth. Micropitting was also detected over the entire width of the tooth of the uncoated pinion in the initial meshing contact area (see Fig. 7).

Under the same test conditions for the WC/C-coated pinion, no micropitting was recorded. Nevertheless, very small pits had developed in the initial meshing contact area.

If we look at the mean profile form deviations measured on the corrected uncoated test pinion in Figure 6, it is clear that the entry impact is sufficiently reduced by the tip relief to prevent cratering in the tooth engagement area, while a practically constant profile form deviation of $f_{fm} = 3.5$ µm is measured over the entire test period. The WC/C-coated corrected test gearing displays a practically identical progression of measured profile form deviations.

Analyses in Accordance with the FZG Macropitting Test Method

The so-called FZG macropitting test is a short test to determine the macropitting resistance of a gear set (Ref. 7). It is a repeated single-stage test of deep fatigue strength. This test procedure is also carried out on the FZG back-to-back test rig (Ref. 4). The test gearing has the same gearing data as the test gearing for the micropitting test, but with less roughness (R_a = 0.2 . . . 0.4 µm).

One uncoated and one WC/C-coated variant of the modified FZG-C gearing is analyzed in conjunction with the reference and basic oils. The stress cycle limit in the standardized FZG macropitting test (Ref. 7) is specified as $40 \cdot 10^6$ stress cycles on the driving pinion. For improved differentiation of the test results, within the context of

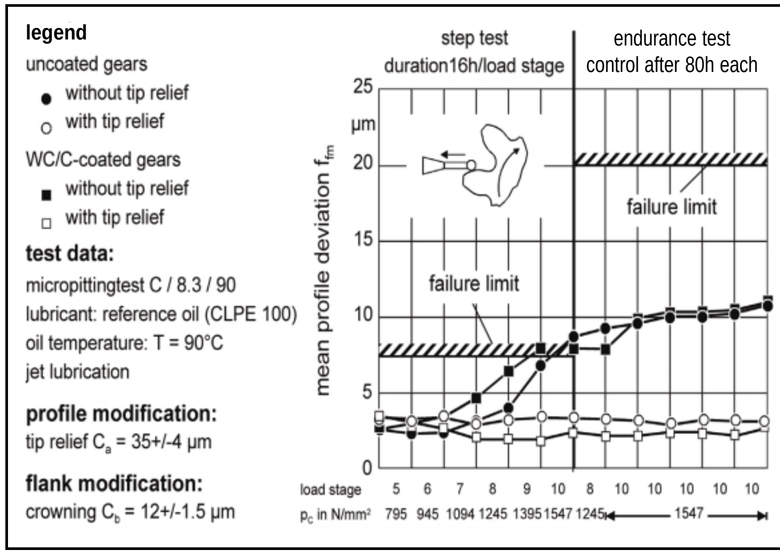

Figure 5—Mean profile form deviation measured at the unmodified and modified test pinions in the micropitting test.

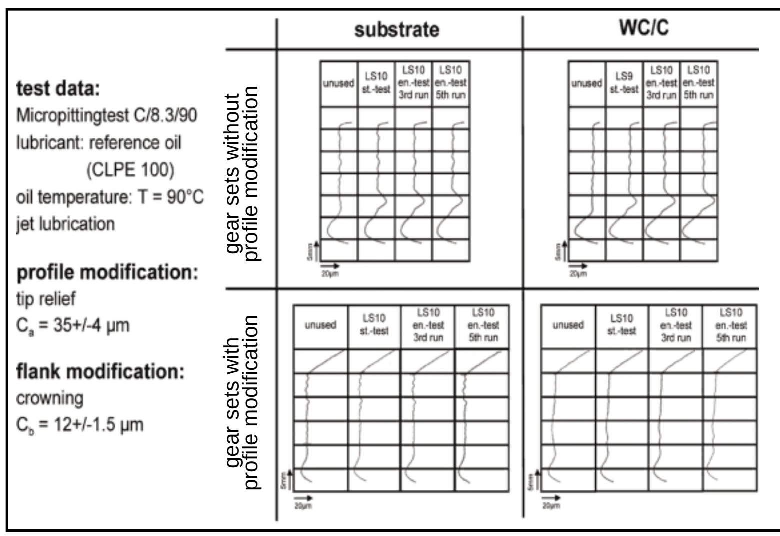

Figure 6—Profile measurement on unmodified and modified test pinions in the micropitting test.

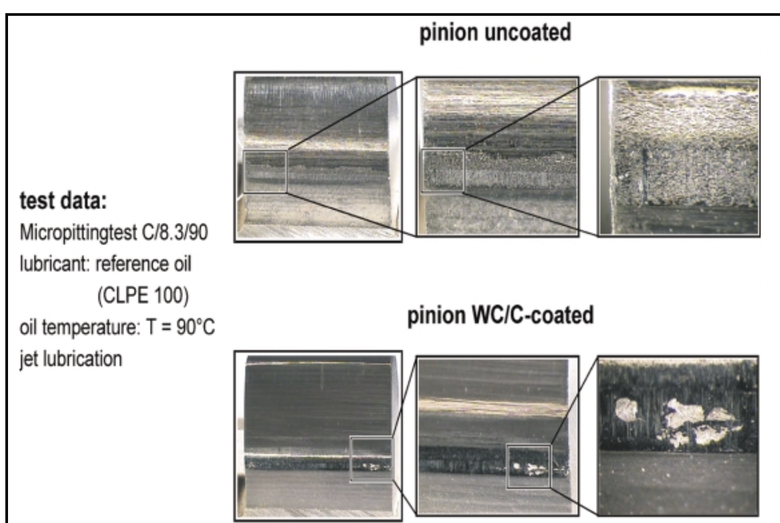

Figure 7—Photographs of the uncoated and WC/C-coated tooth flanks of the unmodified pinion after the end of the micropitting tests.

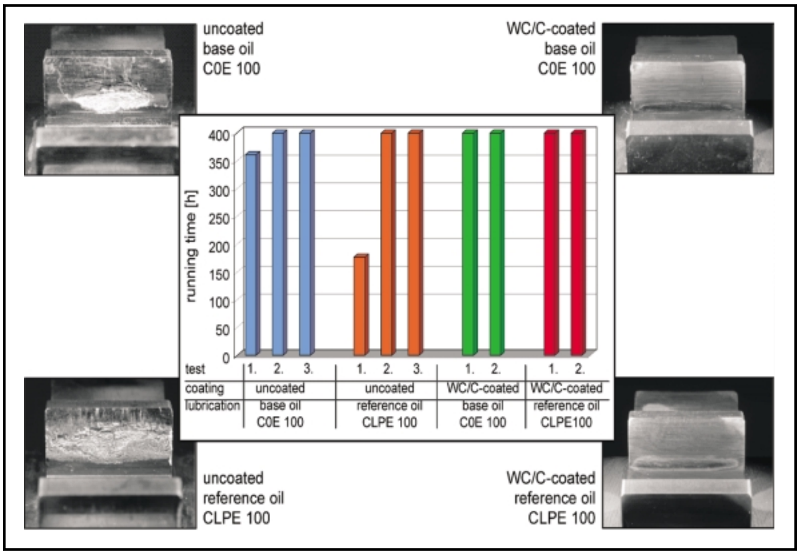

Figure 8—Run times in the macropitting test.

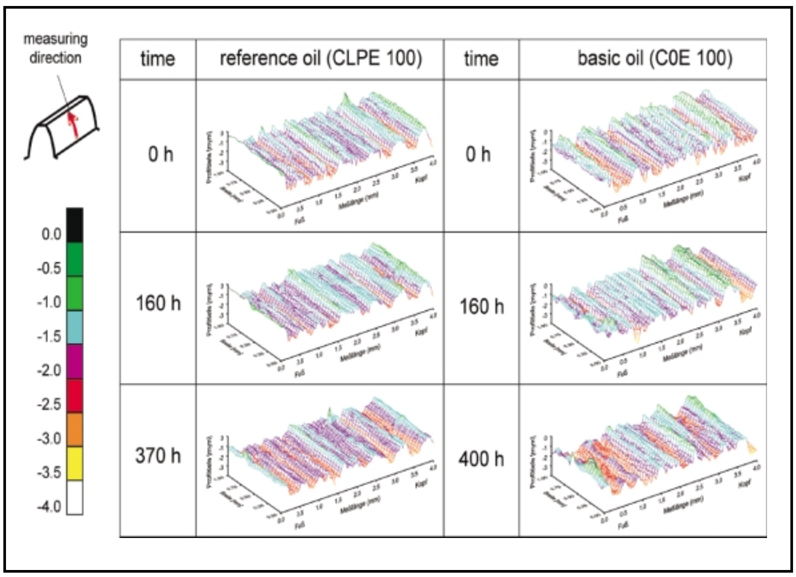

Figure 9—Surface structure of the uncoated pinions.

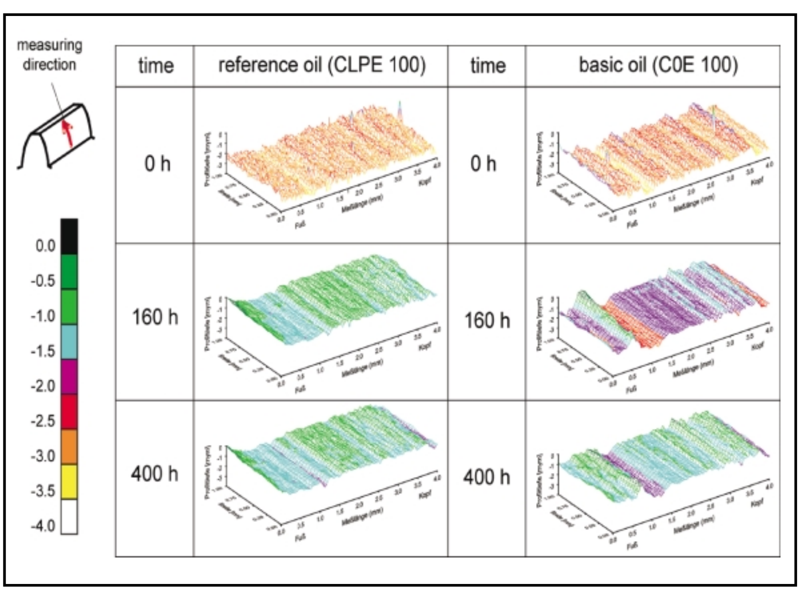

Figure 10—Surface structure of the WC/C-coated pinions.

this analysis, a stress cycle limit of $54 \cdot 10^6$ (test duration 400 hr.) is set. The results of the macropitting tests carried out on the test gearing are documented in Figure 8 on the basis of the run times achieved and in the form of photographs of tooth flanks at the end of the test.

It is essentially possible to determine that the natural macropitting resistance of the basic oil without additives is already so high that the test gearing in two out of three tests endured $50 \cdot 10^6$ stress cycles without macropitting damage. Taking into account the stress cycle limit of $40 \cdot 10^6$ stipulated in the test specification, all three test gear sets would be evaluated as fatigue-tested without damage.

The macropitting tests with the rapidly biodegradable synthetic ester with additives also produced two fatigue-tested specimens without damage in three tests. The flank photos in Figure 8 nevertheless also document that massive macropitting damage occurred in one each of the test sequences of the uncoated variants.

The results of the macropitting tests with WC/C-coated test gear sets are also shown in Figure 8. In this case, two tests were carried out respectively with the reference oil and with the basic oil. In those tests, the stress cycle limit without damage of $54 \cdot 10^6$ was achieved. This result therefore implies a positive influence of the WC/C coating on the tooth flank resistance and/or on the stress cycles endurable without damage.

In order to obtain additional information about the condition of the tooth flanks, as well as visually inspecting the tooth flanks of the test pinion, individual specimens were examined after preset run times with the aid of a contact stylus instrument and a device for measuring the 3-D surface roughness. Figures 9 and 10 show 3-D contact stylus measurements of uncoated and WC/C-coated pinions, respectively.

The measurements were carried out before the start of the macropitting test, after 160 hours of run-time and at the end of the test. The measurement process was designed to enable measurements to be carried out in the same area of the tooth flank in each case.

If we look at the surface structures of the uncoated pinions shown in Figure 9, we can observe grinding marks running in the direction of the tooth width resulting from the hard fine machining with Maag finish grinding. The initial roughness of the tooth flanks in the direction of the profile is approximately R_z = 2.4 µm. No obvious alteration of the surface structure of the

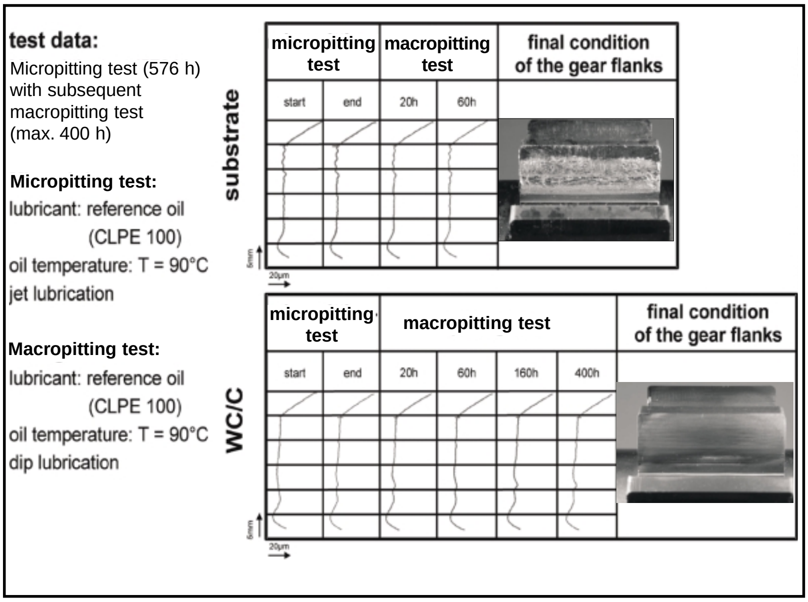

Figure 11—Profile tracings and flank photos of the pinions in the random test.

tooth flanks during the test period can be observed on the gearing lubricated with reference oil nor on the uncoated test gearing lubricated with basic oil.

The measurements of the WC/C-coated pinions in Figure 10 show that the tooth flanks after coating—that is, before running—display an isotropic surface structure in which the grinding marks are no longer clearly discernible, although all test gear sets (uncoated and WC/C-coated) come from the same production batch. The cause is the microblasting treatment of the gearing. This treatment was carried out as standard by the coater before the coating.

As the run-time of the macropitting tests is increased, the WC/C-coated pinions display an evening of the surface roughness in the form of a significant reduction of the roughness peaks and troughs. This evening out of the surface roughness, which can also be observed in analyses of WC/C-coated rollers not shown here (Refs. 1–3 and 8), leads to an increase in the supporting area of the tooth flanks in comparison with their uncoated states and thereby to a reduction of the local loading on the tooth flank edge zone. This behavior of the coating, in combination with the low friction value of the coating, may be the cause of a positive influence on the macropitting resistance.

Random Tests on the Load-Bearing Capacity with Increased Run Time

In order to be able to gain a more precise indication of the macropitting resistance of WC/C-coated gearing in comparison to uncoated gearing, two random tests with increased run-time were carried out. The results are given below. One uncoated gear set and one WC/C-coated gear set were chosen for each random test. Both gear sets had been previously used in a micropitting test. These two gear sets had each undergone a full micropitting test with a run-time of 576 hours with identical load sequences and using the reference oil. In this initial state, both gear sets were subjected to a trial run under Hertzian compression at the pitch point normally used in the macropitting test of p_C = 1,659 N/mm^2.

Figure 11 shows the profile measurement recordings for the pinions at the start and the end of the first performed micropitting test. It is possible to see that only a minimal profile form deviation occurred during the progress of the micropitting test. The test gear sets were inspected at regular intervals throughout the macropitting test and after defined run times on a gear measurement rig.

In the case of the uncoated set of gears, massive macropitting damage occurred in the macropitting test after a run-time of 60 hours. Scuffing was also detected at the tip of the pinion tooth which had resulted, however, from meshing interference as a result of the large area of macropitting damage. A photo of a tooth flank is shown at the top of Figure 11. In comparison, the WC/C-coated test gearing was free from damage at the end of the macropitting test after 400 hours, as documented at the bottom of the figure on the basis of the recorded profile measurements and the flank photographs.

The result of this random test further clarifies the positive influence of a WC/C coating on macropitting resistance and endurable stress cycles.

Summary

This report documents the results of analyses of the amorphous metal-carbon coating WC/C applied by means of the PVD process in the tribological system of tooth flank contact. It presents test-bed analyses in which the use in operation of uncoated and WC/C-coated gear wheels were tested in combination with a rapidly biodegradable synthetic ester and its basic oil. As well as determining the load-bearing capacity of WC/C-coated gearing, investigations were also carried out to the extent that the wear protection functions of the surfactants contained in lubricants can be assumed by the coating.

The analyses with uncoated and WC/C-coated gear wheels in combination with synthetic ester and basic oil revealed a significant difference, particularly in the scuffing test, with regard to wear on the tooth flanks. Under the specified test conditions, approximately 2.5-fold less mass loss of pinion and gear was recorded in the case of the WC/C coating using base oil in comparison with the uncoated gears.

In the micropitting test, it was determined that there is no sign of the recognized damage form of micropitting in the case of the WC/C coating. At the same time, it is evident that comparable profile form deviations of uncoated and WC/C-coated test pinions occurs with unmodified test gearing.

In the macropitting tests, a clear increase in the stress cycles endured without damage was observed on the part of the WC/C-coated test gearing as opposed to the uncoated gearing. This resulted in particular from a significant evening out of the tooth flanks and from the low friction value of the coating. As a result, the supporting area of the tooth flank increases and the local load is lowered.

Acknowledgments

This work was financed by the Deutsche Forschungsgemeinschaft (DFG) for the Collaborative Research Center's project 442, "Environmentally compatible tribological systems." The authors would like to thank the company Balzers Verschleißschutz GmbH (Balzers Wear Protection), located in Bingen, Germany, for coating of the test gears. ⚙

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, in VDI report 1665. It is republished here with VDI Verlag's permission.

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TECHNICAL CALENDAR

January 13–15—14th Annual International Colloquium on Tribology & Lubrication Engineering. Technische Akademie Esslingen, Stuttgart/Ostfildern, Germany. Topics include testing of lubricant properties, gear lubrication, friction and wear in extreme environments, coolants and basics of friction. English and German are the official languages of the show. 650€ or $748. For more information, contact the sponsors by telephone at (49) 711-340-0823 or by e-mail at *anmeldung@tae.de*.

February 9–10—Introduction to ANSI/AGMA/AWEA 6006-A03, Standard for the Design and Specification of Gearboxes for Wind Turbines. National Wind Technology Center, Golden, CO. Sponsored jointly by AGMA and the National Renewable Energy Lab, this program will include presentations on the technical requirement of AGMA's 6006 standard from different perspectives and introduce the new global wind turbine standard. In addition, attendees can take a tour of the NWTC dynamometer and NWTC test facilities. $320. For more information, contact the AGMA by telephone at (703) 838-0052 or on the Internet at *www.agma.org*.

February 23–25—National Design Engineering Show & Conference. McCormick Place Convention Center, Chicago, IL. Featuring the latest in the CAD/CAM, rapid prototyping and contract manufacturing industries. Registration is free before January 26. For more information, contact Reed Exhibitions on the Internet at *www.reedexhibitions.com.*

February 26–29—BI-MU Mediterranea. Fiera Del Levante, Bari, Italy. For individuals in the machine tool, robotics and automation industries. The main focus will be on systems based on modular design, which can be adapted to production variables. The fee is 260€ or $299 to attend and 55€ or $64 for exhibitors. For more information, visit the event's website at *www.bimu-mediterranea.it.*

March 16—Heat Treating & Hardening of Gears. Holiday Inn City Center, Chicago, IL. Sponsored by the Society of Manufacturing Engineers, topics include specific microstructures and mechanical results, performance successes, quality control methodologies, and guidelines for preferred procedures. $495 for SME members, $695 for non-members. For more information, contact the SME by telephone at (313) 425-3098 or on the Internet at *www.sme.org*.

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New Potentials in Carbide Hobbing

Fritz Klocke and Oliver Winkel

Abstract

To meet the future goals of higher productivity and lower production costs, the cutting speeds and feeds in modern gear hobbing applications have to increase further. In several cases, coated carbide tools have replaced the commonly used high speed steel (HSS) tools. Because this leads to production processes working on the upper limit of their performance capabilities, the tolerances for deviations from the optimum process settings are getting smaller. To deal with this situation, especially in carbide hobbing, all factors that have an influence on the hobbing process—like the workpiece geometry, the process parameters and especially the tool design—have to be taken into account if a high level of process performance is desired.

This essay will present a case study based on two industrial gearings. The investigations include the influence of coating, substrate, layout and edge preparation on tool performance.

In detail, fundamental baseline trials using "fly-cutter hobbing" will be presented. Besides several coating and substrate combinations, different tool layouts have also been tested. To verify the results, real hobbing trials under industrial production conditions have been carried out as well. Finally, the potential of modern simulation and calculation programs to optimize hobbing processes will be shown.

The report aims to give new impulses to the tool design of carbide hobs and to an optimized process setting.

Nomenclature

ρ_s	cutting edge roundness (µm)
l_{zn}	total resharpening stock (mm)
$\gamma_{0\,max}$	maximum hob lead angle (°)
$\delta_{x\,max}$	maximum scallop depth (µm)
t_h	machining time (min.)
φ_{as}	tip clearance angle (°)
ST	semi-topping
P	protuberance

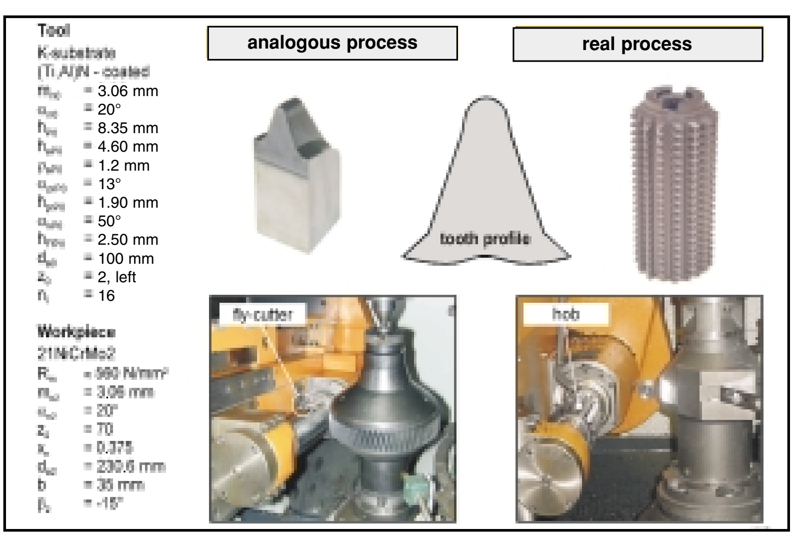

Figure 1—Analogous and real hobbing processes.

Introduction

To be competitive on the global market, gear manufacturers would like to increase their productivity and reduce their production costs. Therefore, cutting speeds and feed rates have increased significantly over the last years. Additionally, new substrate materials like carbide have been established in many hobbing applications to meet these demands.

Since the price for carbide tools is usually two to three times higher than the price of an HSS tool (Refs. 1–3), the cycle times have to be much smaller to realize economically efficient manufacturing processes. Furthermore, the consequently higher cutting parameters—in combination with the usually desired dry cutting conditions—increase the necessity of an optimized setting for the hobbing process (Ref. 4).

To assure a high level of productivity and reliable process performance, a total understanding of the gear cutting process and its complex structures becomes more and more important. Especially for carbide hobbing applications, all factors that have an influence on the process—like the machine, the workpiece geometry, the process strategy and particularly the tool design (Ref. 5)—have to be taken into account if a high level of optimization is desired.

In order to achieve widespread use of carbide hobs for dry gear cutting and to compete with the more commonly used HSS tools (Ref. 6), some further potentials for the optimization of the performance of the carbide hobs have to be used. Besides the continuous improvement of sintering and grinding technology, new developments in the fields of coatings and substrate materials, edge preparation (Ref. 7), decoating (Ref. 8) and simulation software (Ref. 9) might offer new possibilities.

In this paper, the potential of a modern tool design concerning coating, substrate, edge preparation and tool layout for carbide tools in dry hobbing applications will be presented. Additionally, the uses of new software tools for tool layout and process analysis will be shown.

An Analogous Process

To do more work and be cost effective, fundamental investigations have been carried out using an analogous process, "fly-cutter hobbing," to simulate the gear hobbing process. In this analogous process, the hob is replaced by just one tooth (see Fig. 1).

The figure shows the comparison of the tools and the set-ups for the analogous and the real hobbing trials. The interior of the machine with the fly-cutter collet and the workpiece clamping system for the analogous process can be seen on the left side. The hob and the machine setting for the real hobbing process are shown on the right. To assure the best possible comparability between the two kinds of trials, the design and the profile of the fly-cutter tooth and the hob teeth are identical.

To simulate the wear behavior of a shifted hob, the fly cutter is moved continuously through all generating positions of the corresponding hob. After each pass, the axial position of the fly cutter is increased by the amount of the axial feed of the simulated hobbing process. With this strategy, it is possible to create the same chip geometries as in real hobbing and to generate an identical gear.

Since the real hob is reduced to just one tooth, the tool costs are much lower and a smaller number of workpieces is needed to create the desired wear on the fly cutter. Furthermore, the analogous tools are easier to handle, and therefore a more detailed analysis of the wear phenomena is possible.

To prove the applicability of the tendencies discovered in the analogous trials, real hobbing trials under industrial production conditions have been carried out.

In this report, the investigations are based on two industrial gearings. The first one is a gear from a car gearbox, with a module of m_n = 2.5 mm, 38 teeth and a face width of 14 mm. The second one is a gear from a truck gearbox with a module of m_n = 3.06 mm, 70 teeth and a face width of 35 mm.

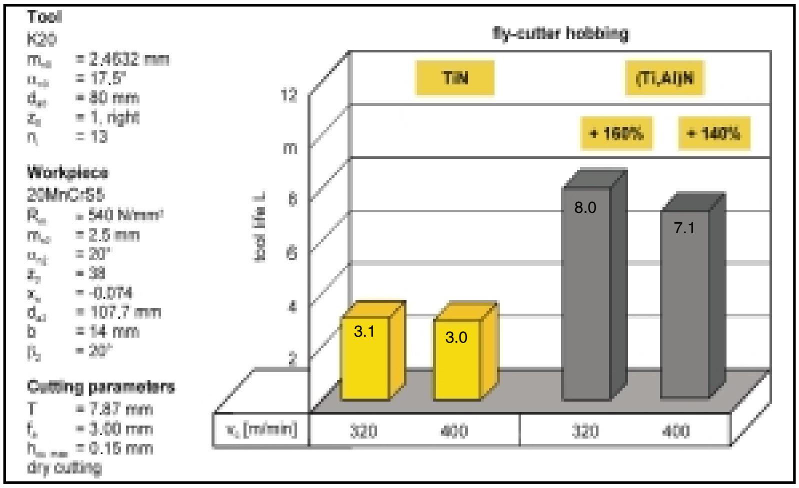

Figure 2—Advantages of (Ti,Al)N coatings in dry hobbing.

Optimization of the Coating System

Since dry cutting requires more tool performance than wet cutting concerning mechanical, thermal and chemical wear resistance, the choice of a suitable coating system is an important factor. Furthermore, the coating system, together with a suitable edge preparation, could be the component of the tool that is the easiest to change if all steps carried out previously, e.g. the grinding, are best adapted.

The TiN coating is still commonly used because of its relatively low price compared to its performance, especially in wet cutting operations. Figure 2 shows that these performance abilities will very quickly reach their limit if a dry cutting operation is desired.

During the investigations shown in the figure, the tool life of the TiN-coated tools was only about L = 3 meters. (A hob's tool life is often measured in meters per shifted hob tooth. The length is the total length of workpiece teeth cut by a hob tooth. In the analogous process, the fly-cutter hob has only one hob tooth, so its life is measured as simply 3 meters, for example.)

With the (Ti, Al)N-coated tools, up to L = 8 meters of tool life could be achieved. This means an improvement of the tool performance by a factor of 2–2.5. The reason for this significant difference is, on the one hand, the higher hardness of the (Ti,Al)N coating. While the TiN coating has a hardness of about 2,700 HV, the hardness of the (Ti,Al)N coating is about 3,600 HV (Ref. 10).

On the other hand, the higher thermal wear resistance is the most dominant factor. The maximum application temperature for the (Ti,Al)N coating is about 850°C, whereas this temperature for the TiN coating is only 450°C (Ref. 10). Therefore, the absence of the cooling lubricant in dry cutting leads to temperatures which the TiN

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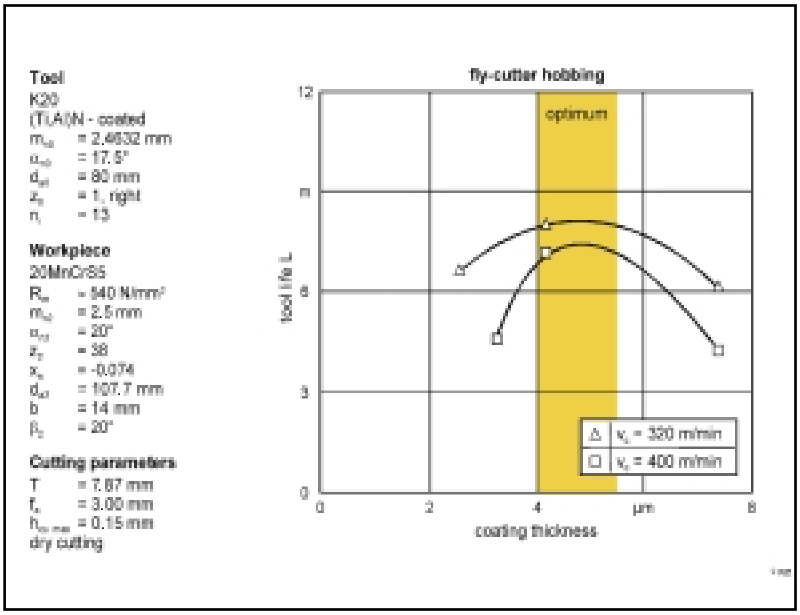


Figure 3—Tool life depending on the coating thickness.

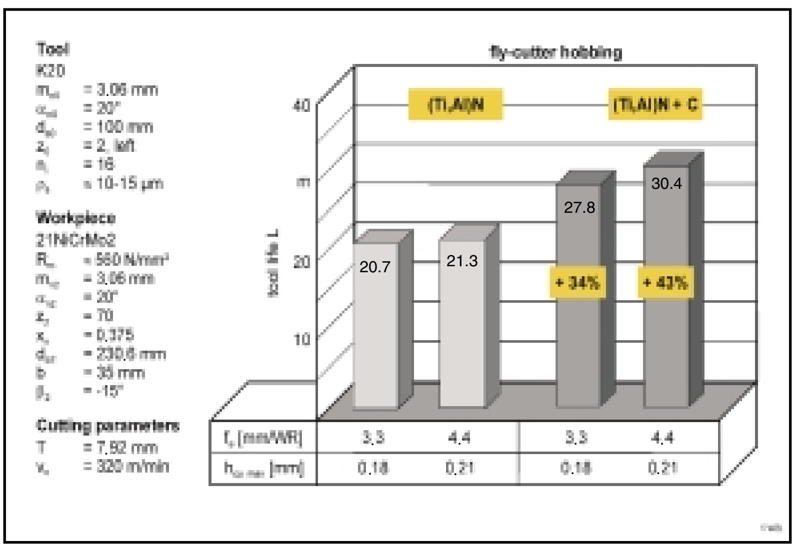


Figure 4—Influence of a lubricious top layer on the tool life.

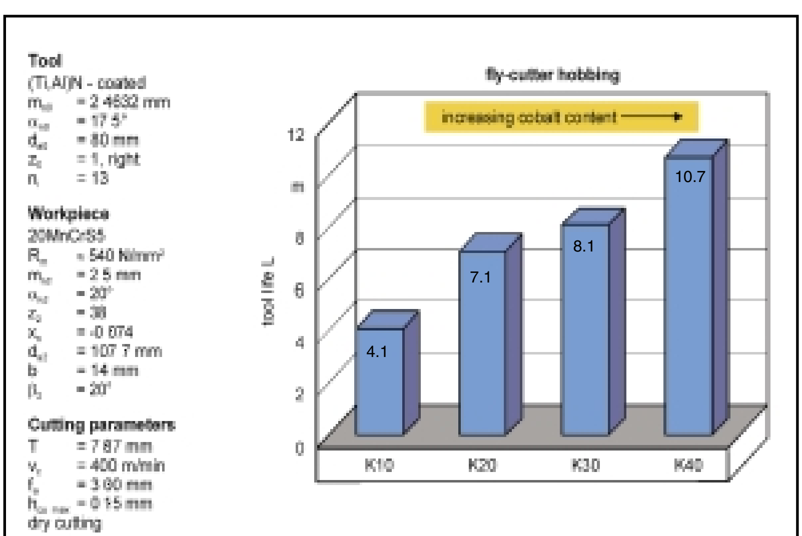


Figure 5—Tool life depending on the choice of the substrate.

coating is not able to resist. Here, (Ti,Al)N-based coating systems are the best solution.

Besides the type of coating, the coating thickness is of high importance. Figure 3 shows that optimum values for the coating thickness have been identified at 4–5 µm for carbide tools.

If a coating thickness of 5.5–6 µm is exceeded, the tool life decreases significantly. This can be explained by the fact that, on the one hand, a higher coating thickness will increase the abrasive wear resistance as well as the thermal isolation of the substrate. But, on the other hand, too much coating thickness will lead to a chipping of the coating because of increasing internal stresses.

Because of these results, this (Ti,Al)N-monolayer coating with a coating thickness of about 4 µm has been chosen as the standard coating system for all the following analogous and real hobbing trials.

As was stated before, it can also be seen that an increase of the cutting speed makes the tool life more sensitive to deviations from the optimum coating thickness. While the difference in the tool life for both cutting speeds is quite small in the area of the optimum thickness, the tool performance at higher or lower coating thicknesses is much worse.

To investigate the potential of coating combinations, a coating system based on the standard (Ti,Al)N-monolayer coating in combination with an additional lubricious top layer of amorphous carbon was tested. The hardness of the top layer is only about 800 HV (Ref. 10) and its thickness was about 1 µm. Because of the low hardness, the idea of this top layer is to reduce the friction and consequently the forces at the cutting edge (Ref. 11). Thus, the initial wear should be minimized and the progress of wear of the tool should be reduced. Both should lead to higher tool life.

Figure 4 shows a comparison between the tool life for the standard (Ti,Al)N coating and the coating with the additional top layer.

For the two different cutting parameters in both cases, the lubricious top layer leads to increases in the tool life of more than 30% and more than 40%. Therefore, the investigations prove that the hard/soft concept for coating systems can improve the tool performance not only in conventional cutting applications (Ref. 11) but also in hobbing applications.

As a conclusion, TiN coatings should be substituted with (Ti,Al)N-based coatings in dry hobbing applications. Because of the higher thermal stability of the (Ti,Al)N coating, much higher tool life can be achieved. The optimum area for the coating thickness is about 4–5 µm. To further improve the tool performance, lubricious top layers, e.g. made of amorphous carbon, offer additional benefits.

Choice of Substrate

Besides the choice of a suitable coating system, the substrate material is of special importance. The substrate must combine a high resistance against abrasive wear and a sufficient toughness to match the loads in interrupted cutting processes.

Therefore, Figure 5 shows a comparison of the tool life for different carbide substrate materials under constant cutting conditions. These investigations focused on WC/Co substrates (K-grades) because they are the most commonly used carbide materials today. The cobalt content differs between 6% (K10) and 12% (K40). The increasing Co content thereby corresponds with a decreasing hardness and an increasing toughness of the substrate.

The figure shows that with increasing cobalt content, higher tool life can be achieved. The tool life for the K40 is more than 2.5 times the value for the K10. Therefore, the toughness of the substrate seems to be more important than the hardness in this application. It also can be concluded that "softer" carbide materials are able to match the demands in dry hobbing applications. Furthermore, the higher toughness should help to improve the process reliability concerning cutting edge chipping.

Edge Preparation

Besides the continuous improvement of the coating systems and the carbide substrates, the tool preparation, especially the cutting edge treatment, might offer new benefits. Although the positive influences on the tool performance are well known from conventional cutting processes, like turning and milling, this technology is not very commonly used for gear hobs.

An adequate edge roundness is supposed to lead to improved tool life behavior and to offer better process reliability. Although there are some recommendations for an optimum edge radius for hobbing tools (Refs. 12–17), this technology is not very commonly used. This may be related to the uncertainty about the optimum radius values, the manufacturing of the rounding and the tool performance during hobbing.

Starting with the improvement of the cutting edge preparation, some trials were carried out to optimize the cutting edge roundness of fly cutters. An optimal edge roundness should reduce the initial wear of the fly cutters and should lead to a better tool life. To create the desired cutting edge roundness, the tools have been blasted with aluminum oxide.

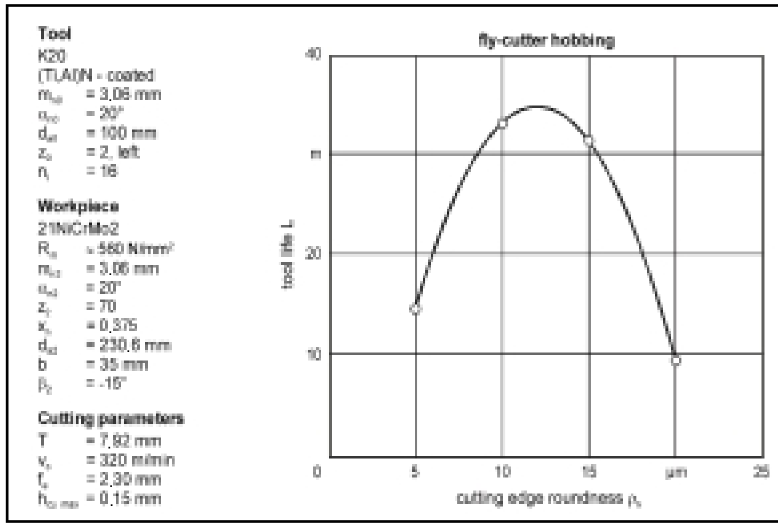


Figure 6—Tool life depending on the cutting edge roundness.

In some basic trials, the influence of different cutting edge radii on the tool life was investigated. Therefore, various edge radii in the range between 5 and 20 µm have been tested. All values for the radii are related to a measurement before coating. During these trials, the cutting speed and the axial feed with respect to the maximum head chip thickness have been kept constant.

The tool life depending on the cutting edge roundness is shown in Figure 6. It can be seen that the tool life can be improved significantly by an adequate rounding of the cutting edge.

For the investigated cutting conditions, the optimal cutting edge radius is in the range of $\rho_s \approx$ 10–15 µm. The increase in tool life compared to the almost untreated tool ($\rho_s \approx$ 5 µm) can be more than 120%. Therefore, there is a large potential benefit in the edge treatment for this application.

If the cutting edge radius exceeds values of $\rho_s \approx$ 15 µm, the tool life decreases drastically. It is assumed that the decrease of the tool life is related to the rise of the cutting forces that will increase the stresses in the substrate and the coating. The cutting edge is no longer sharp enough to cut the high number of relatively small chips that typically occur in hobbing processes.

Too small of a cutting edge radius leads to very sharp cutting edges that have to withstand much higher stresses during cutting than rounded ones (Ref. 18). In this case, the coating or the substrate can be overloaded and a chipping of the cutting edge occurs. For the fly cutters with an optimized

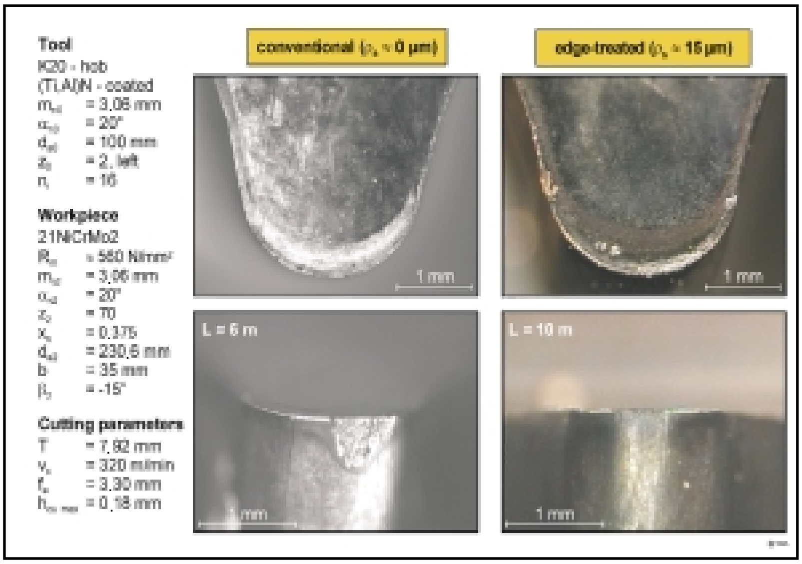


Figure 7—Wear behavior depending on the edge treatment.

edge preparation, the protective effect of the coating is greater for the substrate than it is if the cutting edge radius were too small (Ref. 19).

As a conclusion, an adequate cutting edge roundness will increase the tool life by protecting the cutting edge and coating against chipping. Through an optimized edge radius, the usually sharp cutting edge does not crack any more during the first cuts. Therefore, the coating fulfills its protective function on the cutting edge for a longer time. Additionally, the edge becomes more resistant to chipping. Since the coating protects the substrate material against abrasive and adhesive wear, this edge treatment should lead to better tool performance.

Based on these results, verification tests through real hobbing trials have been carried out under industrial production conditions on the same gearing. The test hobs have been used untreated (conventional) and prepared with a specific cutting edge roundness in the area of $\rho_s \approx 15\ \mu m$ (see Fig. 7).

In the first real hobbing trials, the hobs without a special edge treatment were used. The cutting edge roundness was in the area of $\rho_s \approx 0$–3 µm before coating. After 6 meters of tool life, chipping of the cutting edge on the tip of only some of the hob teeth could be found (see Fig. 7's left photographs). The chipping happened unexpectedly because after 5 meters, there was only initial wear. It is well known that for carbide hobs, the substrate tends to chip when it is overloaded because of lower toughness and less ductility compared with HSS (Ref. 20). Therefore, the process reliability which is very necessary for mass production was not achieved.

Based on the good results from the analogous trials, the next trials were carried out with edge treated hobs. Under the same cutting conditions as in the first real hobbing trials, the tool performance was significantly better. No chipping of the coating with respect to the substrate occurred at the tip of the hob teeth, and the tool life was much better, as shown in Figure 7's right photographs.

The trial was stopped after 10 meters of tool life because the maximum wear width exceeded $VB_{max} = 0.15$ mm. At that time, there was only a little wear on the tip, and a characteristic wear in the protuberance of the leading flank could be seen on all teeth in the shifting area. So not only the tool life, but also the process reliability was significantly improved. In this case (higher cutting parameters), the edge preparation has led to an improvement in tool life of about 60%. The differences in tool life between the analogous and the real hobbing trials can be explained by the ideal laboratory conditions and the lower dynamic effects because of the lower cutting forces in the analogous process.

As a conclusion, during the real hobbing trials, the transferability of the results from the analogous process to the real process concerning the wear phenomenon was quite good. Although the tool life in real hobbing was only about 30–40% of the tool life in the fly-cutter hobbing tests, the tendencies were comparable and the tool performance was still at a very high level.

Software Support

Besides the choice of an adequate coating system, substrate material or edge preparation, the tool design is one of the most important criteria to assure both satisfactory tool life and sufficient cost effectiveness. The tool design has to take into account the cycle time, the machining costs and the tool costs.

Especially in gear hobbing, the tool design is very difficult because of the high number of parameters. On the one hand, the workpiece geometry and the technical data of the machine are fixed conditions. On the other hand, the technological parameters—like cutting speed and axial feed with respect to maximum head chip thickness—have to be chosen correctly. Finally, maximum scallop depth or maximum cycle time are boundary conditions that have to be fulfilled by a proper tool design. Taking into account that the hob itself has a high number of degrees of freedom, e.g. outside diameter, number of gashes, number of threads, usable length, etc., the optimum hob design becomes a multi-dimensional problem.

Since this problem usually cannot be solved by hand, adequate software programs have to support the tool designer. This was the motivation for WZL to create its own software tool, *Hobbit*. The program is able to calculate by boundary iteration the optimum hob design out of a matrix of thousands of possible tool designs. Thus, the user only has to enter his boundary conditions concerning machine and workpiece data as well as desired cutting speeds and chip thickness. Then, the program calculates all possible tool designs that match the declared circumstances and assesses them.

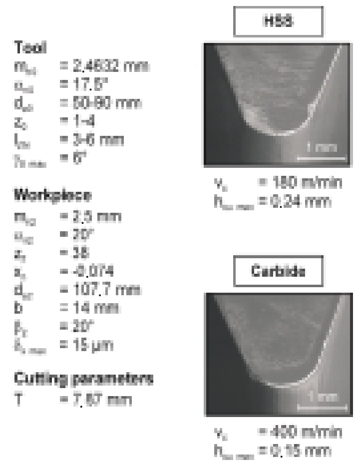
To illustrate the potential of such software systems, Figure 8 shows two calculations for an improved hob design. The first case is an HSS tool, the second one a carbide hob. Analogous trials have been carried out with both tool systems, so that the specified cutting parameters will result in approximately equal tool life for the two basic tool designs, which are shaded in gray. As shown in the figure, both hobs are not optimal designs for their cycle time.

Therefore, certain boundary conditions were declared which are documented on Figure 8's left side. Afterwards, the calculation was done, and the best results are presented in the chart on the right side of Figure 8. It can be seen that in both cases, the main times could be decreased significantly. On top of each chart, the fastest tool designs are shown. Furthermore, the best designs with relatively small outside diameter (lower tool cost) and the best designs with a higher number of starts are presented.

Figure 8 expresses two statements very clearly. The first is that, because of their totally different cutting parameters, HSS and carbide tools for the same gear must have a different geometry. While the HSS hob is usually used at medium cutting speeds and high chip thickness, the carbide hob is used at high cutting speeds and lower chip thickness. Therefore, the tool layout has to be different.

The second statement is that, although the carbide tool will be run at very high cutting speeds, the HSS tool will almost reach the same cycle time because of the higher achievable chip thickness. Since the carbide hob usually has to be faster than the HSS hob to be cost efficient, new developments have to provide new benefits to realize improved cutting speeds and also higher allowable chip thickness.

As a conclusion, software tools, like *Hobbit*, have to allow users to find the best tool design for their boundary conditions out of a huge number of possible layouts. Furthermore, the user is able to get quantitative information about which tool concept (HSS or carbide) might be the best for his application.



Favorable hob - design			
diameter d_{a0} [mm]	threads z_0	gashes n_i	mach. time t_h [min]
84	2	18	0.32
78	2	17	0.32
70	2	15	0.36
88	3	19	0.39
80	2	13	0.53

Favorable hob - design			
diameter d_{a0} [mm]	threads z_0	gashes n_i	mach. time t_h [min]
70	1	15	0.26
64	1	14	0.27
88	2	19	0.34
80	1	13	0.36

Figure 8—Example for a machining time-optimized hob.

Even if an optimized tool design has been identified, the hobbing process still is very complex and hard to understand. Because of the complicated generating kinematics in combination with a complex tool geometry, the chip geometries in hobbing processes are not easy to calculate. Since the chip geometry correlates with the loads during cutting and the wear of the tool, it is helpful to know the existing contact conditions. Therefore, WZL has developed another software program, named *Sparta*, which is able not only to simulate the hobbing process and calculate the chip geometries but also to calculate characteristic process values to quantify the process.

Starting with the different chip geometries, the program illustrates the complex shape of the undeformed chips, as can be seen in Figure 9. Here, a three-flank chip geometry typical for hobbing processes is shown.

The X-axis shows the position on the cutting edge, and the Y-axis represents the cutting direction. The chip thickness is illustrated by the height (Z-axis) of the diagram. It can be seen very clearly that every point of the cutting edge has to withstand a different type of load. This makes the hobbing process so difficult to optimize because one coating/substrate system has to match all these different demands.

However, several characteristic values—e.g. the distribution of the chip thickness or the contact length, the effective clearance angles, the chip volumes or the dynamic contact conditions

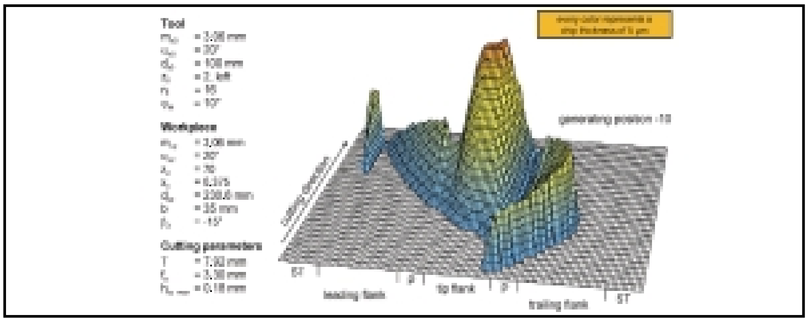


Figure 9—3-D illustration of a simulated chip's geometry.

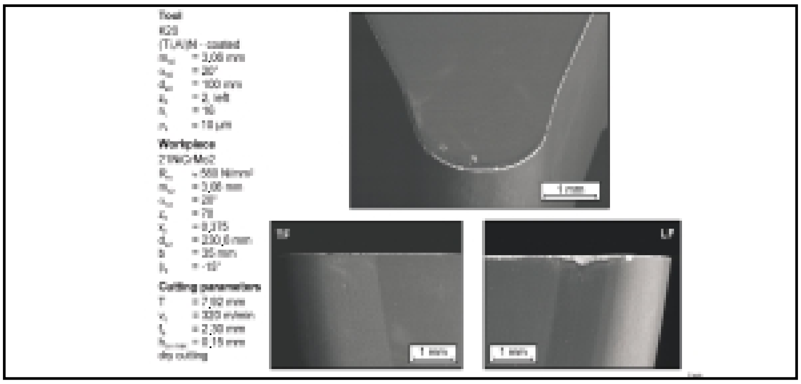


Figure 10—Typical wear on a fly cutter.

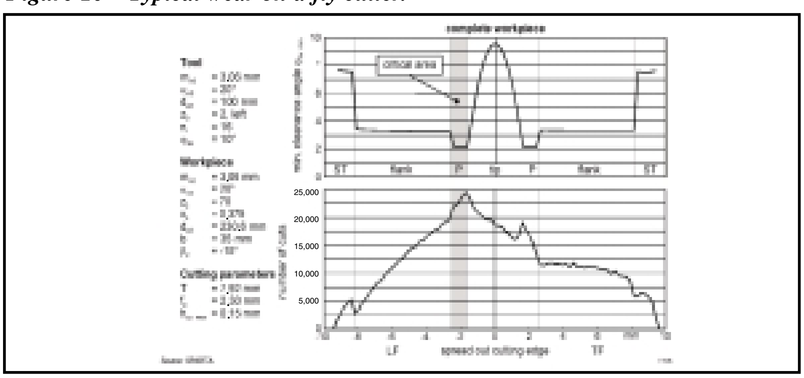


Figure 11—Analysis of two important parameters in hobbing.

between hob and workpiece—can be calculated out of these data for the chip geometries.

These characteristic values can help the user get a deeper insight into his process than just judging it by the maximum head chip thickness. This additional information can be used, on the one hand, to support a better process setting or tool design and, on the other hand, to analyze processes and tools which have not performed satisfactorily.

To give a practical example, Figure 10 shows the typical wear of a fly cutter for the considered gearing.

While the wear on the trailing flank is very small, the wear on the leading flank in the area of the protuberance is critical and sets the limit for the tool life. Since analysis of the chip geometries did not lead to concrete ideas about this phenomenon, additional calculations concerning the characteristic values have been carried out.

Two of those values are shown in Figure 11 along the cutting edge to give first hints to explain the observed wear.

Figure 11's upper part shows the minimal effective clearance angles, while its lower part shows the number of cuts. In this context, the number of cuts means the number of chips during the cutting of a whole workpiece in which the considered cutting edge section is involved. On the left side of each diagram, the leading flank is shown and the wear critical area of the protuberance is marked in gray.

It can be seen that wear was relatively small in the area of the protuberances with effective clearance angles about 2°. This is related to the lower pressure angle of only 13° compared to the pressure angle of 20° on the flanks. These low clearance angles lead to a bigger contact zone between the workpiece and the tool in this area. The bigger zone consequently results in higher friction and thus higher temperatures and abrasive wear.

Furthermore, the number of cuts is significantly higher on the leading flank than on the trailing flank, especially in the area of the protuberance. Therefore, the corresponding cutting edge section has to penetrate the workpiece more often. The combination of these two effects explains the wear phenomenon.

Improvements might be possible by increasing the effective clearance angles at this point, for example, by choosing a bigger tip clearance angle or, if possible, a profile modification with a higher pressure angle in the protuberance.

As a conclusion, both software systems can help the user in better designing, analyzing and understanding the challenging hobbing process. Such programs will give valuable support to create technologically and economically efficient processes, especially in the field of dry hobbing with coated carbide tools because of the smaller windows for optimal process settings.

Conclusions

There are still large potentials in the field of dry hobbing with coated carbide tools. This includes the further optimization of the coating system, the substrate material, defined edge preparation and tool design. The process reliability of the carbide hobs should especially be a key aspect because these tools are usually applied in mass production.

In this paper, the investigations were based on different (Ti,Al)N-based coating systems because TiN coatings are not suitable in dry hobbing applications. Concerning tool life, the coating thickness should not exceed 4–5 μm. Lubricious top layers, e.g. amorphous carbon, can lead to an increase in tool life by 30–40%.

The trials on different carbide materials proved that the requirements of a dry hobbing process with regard to substrate are concerned primarily with toughness, not hardness. Therefore, substrates with higher cobalt content showed better tool life.

Furthermore, investigations to determine a suitable range for cutting edge rounding and its potential concerning the tool life of carbide hobs were performed. The results show that a cutting edge roundness of $\rho_s \approx$ 10–15 μm improves the wear behavior of the carbide tools in fly-cutter hobbing significantly. The results from the analogous process were verified by real process trials carried out under conditions of industrial production. Although the tool life was much smaller in real hobbing, the better tool life and higher process reliability could be achieved.

Finally, software tools, like *Hobbit* and *Sparta*, have been presented to point out their ability to support the user in his efforts to determine optimal tool designs and process settings as well as to achieve a better process understanding. Additionally, the software tool *Sparta* should also help to analyze and give hints to improve insufficient tool or process performances. Especially in the field of dry hobbing with carbide tools, because of the smaller windows of the optimal process settings, such programs will give valuable support to create technologically and economically efficient processes.

Only with an optimized tool design with regard to substrate, coating and layout, one will have the chance to run carbide hobs with very high speeds and feeds.

Therefore, it can be summarized that carbide hobbing is still a challenge. But there are also new benefits to using the high potential of this substrate material, especially since HSS materials seem to have reached their performance limits.

Systematic research activities in combination with a consequent software development will be necessary to support the end user in his efforts to meet future demands.

Acknowledgments

The investigations in the present paper were conducted as a part of the Brite-EuRam project CAPCAT (project no. BE97-4739), which was financed by the European Commission.

The authors express their sincere appreciation to project partners CemeCon GmbH, Plansee Tizit GmbH, Samputensili S.p.A. and SVA AB for the supply of the tools. Furthermore, we wish to record our gratitude to Scania CV AB and Volvo Car Corp. for their support during the trials.

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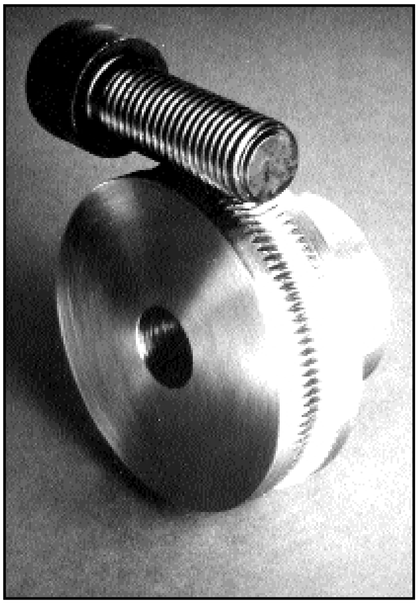
This paper was presented at the ASME/AGMA 2003 International Power Transmission and Gearing Conference, held Sept. 3–5, 2003, in Chicago, Illinois, U.S.A. It was presented under the title “Potential of Carbide Tools for High Performance Hobbing” and published under that title in *Proceedings of the 2003 ASME Design Engineering Technical Conferences & Computers and Information in Engineering Conference.* It is republished here with ASME’s permission.



Precision Gearing from Dynamic Automation

The precision gear from Dynamic Automation works with a standard machine screw or long-length threaded rods. It can adapt to rotary or linear motion applications.

According to the company's press release, this gear was used to solve one of the toughest engineering problems at McClellan Air Force Base in a minimum available space. The gear has been used to drive sample carriers 100" deep under water at a speed of 10" per minute.

The precision gear is available in a variety of standard sizes and can be custom ordered. In addition, it is capable of fine adjustment and positive positioning.

For more information, contact Dynamic Automation of Chicago, IL, by telephone at (312) 782-8555 or on the Internet at *www.dynamicgear.com.*

New Gear Tester from Wenzel

The new gear tester from Wenzel is equipped with a scanning probe system, an integrated rotary table and air bearings for high precision spur, helical and bevel gear measurement.

The GearStar 400 operates on workpieces with min./max. diameters of 5–400 mm, a module range of 1–20, and operates on four axes.

The GearStar 800 has a diameter of 5–800 mm and a module range of 1–20, with four axes as well.

For more information, contact Wenzel GearTech of Karlsruhe, Germany by telephone at (49) 172-698-2349 or by visiting their website at *www.wenzel-geartec.com.*

New Fine Gear Cutting Machine from Wahli

The Wahli 100 CNC is a fine gear cutting machine that's fully controlled by CNC and designed for the microtechniques industry.

According to the company's press release, the machine is a synthesis of a high level simplified mechanical part and modern electronics. Its three-point

Corrections • Corrections • Corrections

A number was omitted from one of the equations in "Application of Statistical Stability and Capability for Gear Cutting Machine Acceptance Criteria." The article was written by Thomas J. "Buzz" Maiuri and was published in *Gear Technology*'s November/December 2003 issue. The omission occurred on page 38, in the equation about the lower capability index (CPL).

The CPL equation should have included a 3 in the denominator, like the denominator for the upper capability index (CPU). So the CPL equation should have read:

$$CPL = \frac{(\bar{\bar{X}} - LSL)}{3\hat{\sigma}_{Tot,s}}$$

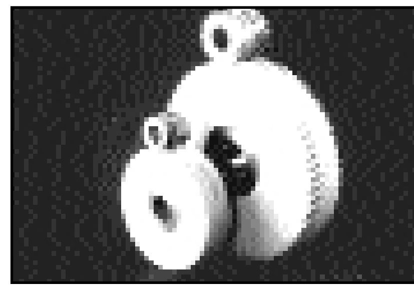
Also, in the industry news section of the November/December 2003 issue of *Gear Technology*, on page 18, we reported that Applied Process specializes in austempering *non-ferrous* materials. The company's correct specialty is austempering, a high performance heat treating process for *ferrous* materials.

We apologize for any inconvenience.

—The Editors

structure is welded and isostatic. There is a numerical interpolation for each feed axis. The high rapid traversing speed is rated at 4 meters per minute, and the spindle operates at a speed of 15,000 RPM.

For more information, contact Wahli Ltd. of Safnern, Switzerland, by telephone at (41) 32-356-0273 or the Internet at *www.lambert-wahli.ch.*



Gear Material from Intech

Intech Power-Core is a hybrid composite gear material that wraps around a sturdy metal core.

According to the company's press release, the hybrid gear design features a sturdy material that is gravity-cast directly onto a rugged, knurled metal core. The gear material is engineered to offer high performance tensile and flexural properties over a range of operating conditions. Gear teeth are hobbed into the outer plastic portion of the gear material.

A bore directly machined into the metal core secures the shaft connection that enables the designer to attach the composite gear using traditional metal gear methods.

A gear blank is mounted directly onto an arbor of the hobbing machine and enables the cut of a precision bore into the metal, serving as a reference point for the gear's critical dimensions.

For more information, contact Intech Corp. of Closter, NJ, by telephone at (201) 767-8066 or on the Internet at *www.intechpower.com.*

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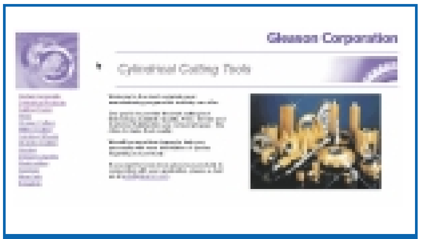

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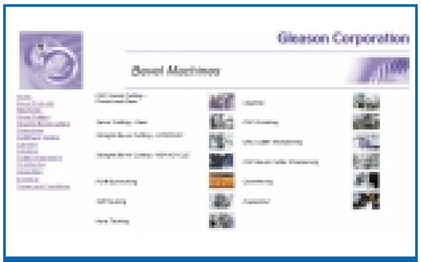

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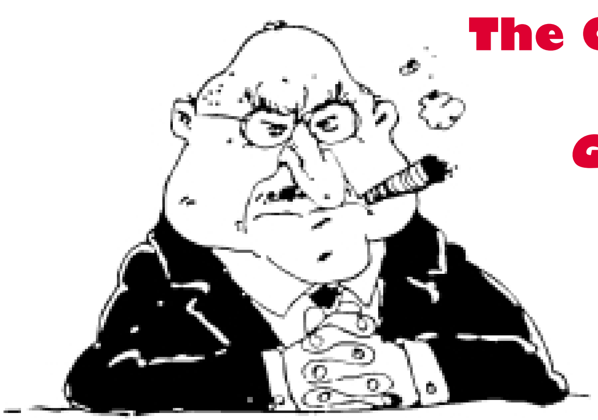

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UNSOLVED GEAR MYSTERIES

If there is such a thing as a gear fairy, then it's possible he makes surprise visits to various colleges to deposit gears under the pillows of deserving professers.

Ohio State's Department of Mechanical Engineering has been housing two large collections of gears for over 100 years. Nobody knows exactly how the earlier ones got there. According to Professor Don Houser, the first set was either purchased or donated at the turn of the century, and the second was bought from the Illinois Gear & Machine Co. in 1954.

"The later set, which is more conventional, we're sure we bought from Illinois Gear for about $9,000 in 1950s dollars. The non-circular gears, which are gold in color, are the ones we're open to hearing any ideas from someone who's more aware where they came from," says Houser.

A popular theory is that these came from Germany by way of a gear pioneer named Peter Koch. There are some tags on several of the gears, but they're hard to decipher. Houser spent about a week tracing the ancestry of the various bevel gears, worm gearboxes, etc. with no luck.

It wasn't until about 10 years ago that another faculty member, Professor Gary Kinzel, took it upon himself to clean and paint the gears. He showcased them in a display area that had been sitting vacant for years. Now, visitors at the Department of Mechanical Engineering can be stimulated by 30 feet of gearing for their viewing pleasure.

Even though the gear collection doesn't have as loyal of a following as the school's football team, it can provide a few minutes of entertainment if you're in the right frame of mind. Red and black are eye-catching visuals for the displays, and the geared mechanisms look very modern under this color scheme. The older of the two collections, called the Illinois Tool Demonstration Gear Collection, has a more antique appearance with golden gears supported by wooden frames.

Curiosity-seekers who don't have business on the second floor of Ohio State's Robinson Library can see the exhibit virtually at *www.gearlab.org.*

A variable pitch gear pair meshes compatibility.

A chic red and black non-circular gear pair.

Cornell University's mechanical and aerospace engineering department is in the midst of a project that involves electronically coordinating their models of machine mechanisms with those at Ohio State and at various museums and universities in Europe.

Currently online at *kmoddl.library.cornell.edu* and housed in a hallway in the department's facilities, this collection of about 250 models contains about 25–30 gears, some of which also came from Illinois Gear.

Others date back centuries, including the collection of Franz Reuleaux of Belgium. Cornell purchased the collection in 1882 for $8,000. Among the notable pieces are models that show the difference between epicycloids and involute gears, the subject of fiery debate in the 19th century.

Unlike the situation at Ohio State, the professors at Cornell know the details about the older collection but are clueless on where the Illinois Gear models originated. Professor Francis Moon speculates that they are from the 1950s or '60s, but isn't sure.

"Engineers aren't always the greatest at keeping their history," he admits.

If you own something that resembles any of these gears and it's just taking up space in your office, the Gear Lab would be happy to take them off your hands. In addition to these, Houser also keeps a private stash of more mainstream gears in his office that he's always adding to.

Either of the two schools' engineering staffs would appreciate any information about the background of their mystery gears—unfortunately they're not prepared to offer a cash reward.

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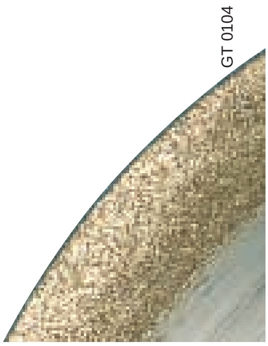

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