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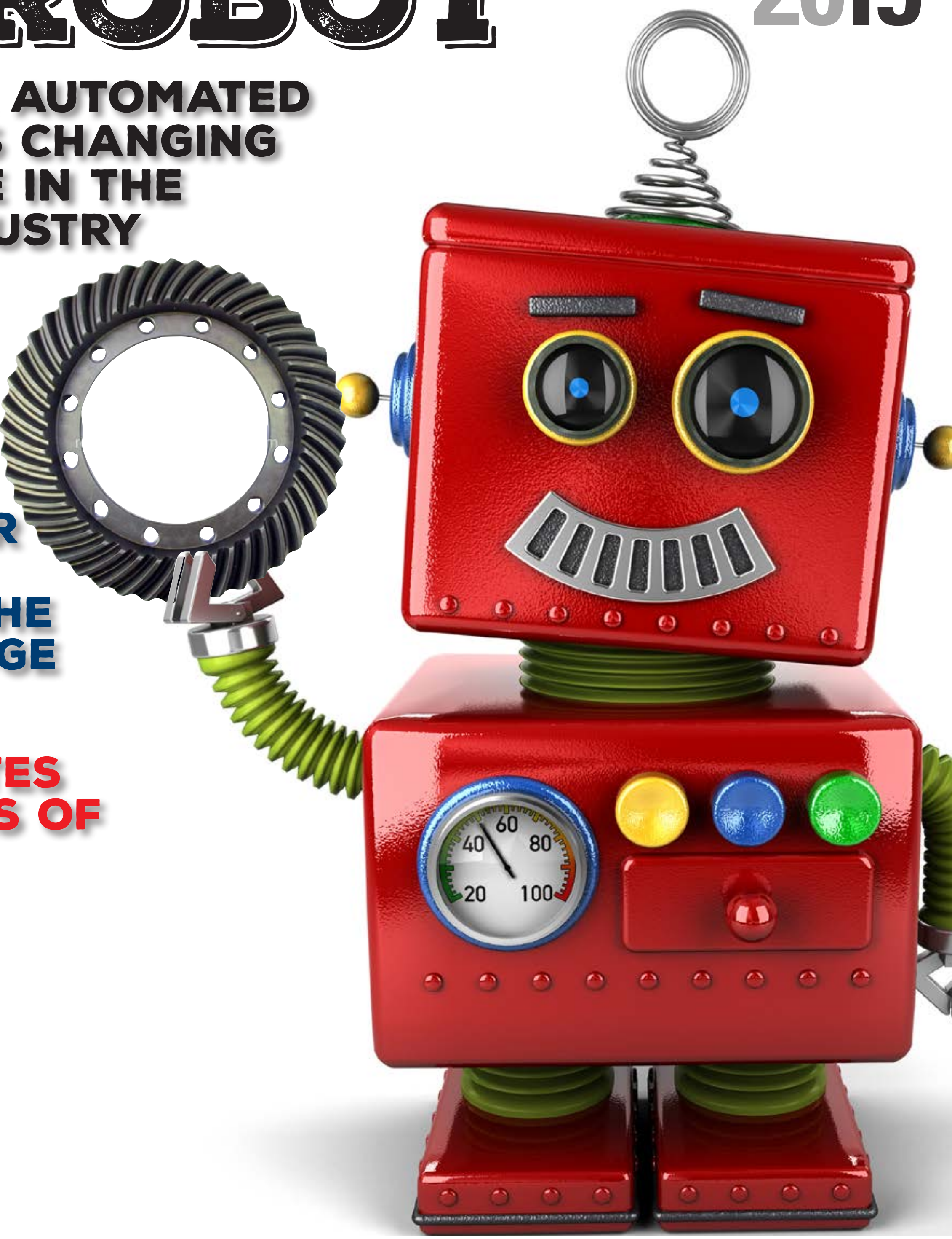
HI, ROBOT

MEET THE AUTOMATED MACHINES CHANGING THE GAME IN THE GEAR INDUSTRY



CIMCOOL, OELHELD AND BLASER SWISSLUBE WORK ON THE CUTTING EDGE

GLEASON CELEBRATES 150 YEARS OF SUCCESS

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THE JOURNAL OF GEAR MANUFACTURING

The G 250 / G 450 can be easily equipped with various automation solutions

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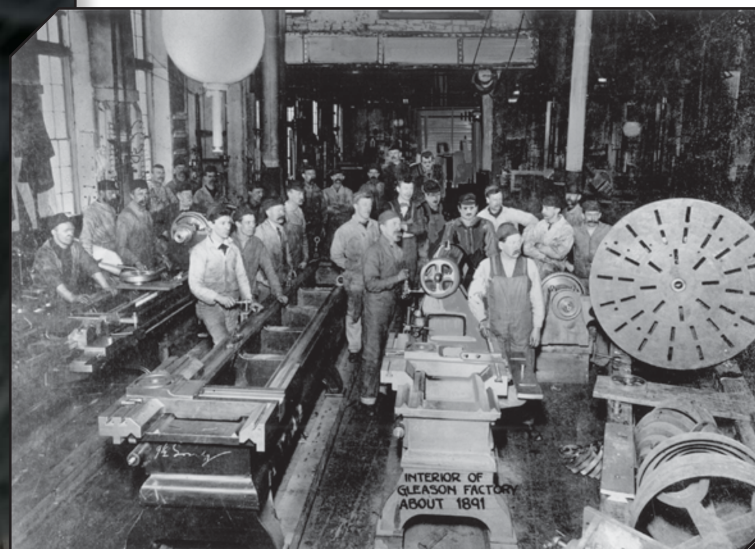

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departments

THE GEAR INDUSTRY'S INFORMATION SOURCE

www.geartechnology.com

DETECT GRINDING BURN

Learn how to detect grinding burn and other metallurgical defects in this video from Stresstech, which demonstrates the use of the GearScan 500 for inspecting gears. Visit *www.geartechnology.com* to watch the video.

Microgeometry

"Much of my design work involves math modeling gearsets to determine the lowest-cost components which will meet the requirements. Over the years, a designer develops his or her own set of guidelines for what geometry is acceptable and what is objectionable. A group of gear experts may agree on eighty percent of a design and argue for hours over the remaining twenty percent. This is particularly so in the area of microgeometry—lead and involute modifications that help improve performance at the extremes of loading."

Read more of Chuck Schultz's blog at *www.geartechnology.com/blog*

Buyers Guide: Recently Added

The following companies have recently upgraded to premium listings on *geartechnology.com*. Now you can find out more about their products, and you can contact them quickly and easily, through the *Gear Technology* buyers guide:

NACHI
NACHI AMERICA INC.

REISHAUER
Gear Grinding Technology

YIEH CHEN

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The other day I went to Starbuck's and ordered my usual four shots of espresso, straight up. I know what you're thinking: that's a lot of caffeine, especially for someone as naturally energetic as I am. But after years and years, I may have built up a tolerance to the caffeine. I picked up the espresso habit as a much younger man, when I worked for Daldi & Matteucci (DEMM) in Italy back in the '70s. And I've stuck with it ever since.

Anyway, when I received my cup from the barista, it felt a little bit light. I held it up and swished it around, asking, "Are you sure this is a quad?" The barista confirmed that it was, indeed, four shots, but told me that the company had recently recalibrated its machines to use less water.

I asked if I was going to be charged less because I was getting less coffee. The answer was no: the price remained unchanged. The barista explained that most people wouldn't notice, because they order espresso as part of a much larger drink. When you're ordering a 16-ounce caramel brulee latte, topped with whipped cream and caramelized sugar, a minor change in the amount of espresso probably doesn't affect the taste much. And you're still getting a 16-ounce drink. For me, though, the difference was obvious.

Initially, I felt cheated. I was paying the same price, but getting less. I thought it was a little underhanded what Starbucks was doing. If they had just raised the price, the change would have been obvious. In effect, they were raising the price, but in a way that seemed sneaky to me.

So I started thinking about ethics, competition and how you treat your customers.

Of course, this was just prior to the Super Bowl, and the sports news of the day revolved around deflated footballs and whether the New England Patriots cheated by deliberately deflating the game balls used in the AFC championship game against the Indianapolis Colts. Now I'm not saying whether they cheated or didn't. The NFL investigation is still ongoing at the time of this writing, but they've been caught before. And whether their infractions have had a direct result on games or not, the Patriots are Super Bowl Champions. Again. The consensus among most fans I've talked to is that they probably stretched the rules a little bit.

Does this mean that—in the NFL, at least—bending the rules is OK? Is cheating the new best practice? More importantly, do Americans believe cheating is an acceptable means of achieving competitive advantage? In the case of the Patriots, the reward seems to outweigh the risk.

Perhaps the same is true in the case of Starbucks. After all, most people wouldn't notice the change in formula. Maybe saving a little money where most people won't notice is just good business.

But swallowing that pill leaves a bitter taste in my mouth.

Here at *Gear Technology* we believe in giving our customers more, not less. For our advertisers, that means we've worked hard to increase the reach of our magazine by adding circulation, expanding our online offerings and tapping into new and better ways of putting *Gear Technology* into the hands of more and more readers in more and more places. This year we've increased our electronic distribution by 5,000 recipients, thanks to our expansion of *Gear Technology India*. And yet, we haven't raised our ad rates in more than five years.

For you, our readers, it means continuing to give you as much content as possible, every issue, and ensuring that it is as useful as possible. Our technical articles are still reviewed by industry experts to ensure their technical accuracy, relevance and significance. We write as many feature articles as possible, interviewing industry experts to bring you the insights you need to understand the trends and technologies in gear manufacturing.

Here at *Gear Technology*, you'll never get deflated balls, and we'll always give you the full cup of coffee.

Gleason

ANNOUNCES 175GMS ANALYTICAL GEAR INSPECTION SYSTEM

Gleason Corporation recently announced the introduction of the 175GMS Analytical Gear Inspection System, with faster complete inspection of automotive, aerospace and other smaller gears, as well as gear cutting tools and non-gear parts.

The latest addition to the GMS Series (with models available for gears up to 3,000 mm in diameter), the 175GMS completes the development of the GMS series and replaces the 175GMM. The 175GMS includes features such as surface finish measurement and prismatic feature measurement, an intuitive user interface and input screen for programming of work pieces and cutting tool data, built-in tutorial information for gear features with text, pictures and videos that are user editable, and an easy setup, remote I/O controls system and improved movement optimization to reduce the cycle times required for the complete inspection of almost any gear or gear tool.

The 175GMS Analytical Gear Inspection System is the first GMS system to feature the new Windows 7-based Gleason GAMA 3.0 applications software suite. It features a new-generation Renishaw 3D scanning probe head to provide accuracy and flexibility for the inspection of gears and gear-cutting tools and, in particular, finer pitch gears, and a new mounted operator workstation and an Advanced Operator Interface (optional) — both designed to improve the operator's effectiveness at every stage of the inspection process.

The Advanced Operator Interface puts a number of tools right at the operator's fingertips, including an environmental monitoring station to record temperature and humidity as well as video telephony, note pad and voice mail messaging capability, Gleason Connect for remote diagnostic support, creation of standard work instructions, online training tools, multi-lingual communication and more.

For more information:
Gleason Corporation
Phone: (585) 473-1000
www.gleason.com

KISSsoft

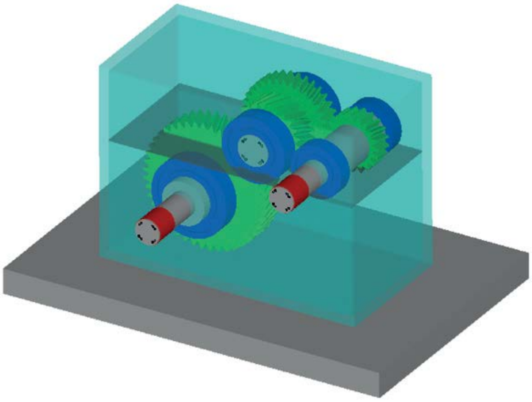
ADDS KISSSYS THERMAL MODELING

KISSsys is a system add-on to *KISSsoft*, where complete transmissions and drive trains can be modeled (SYS module). The gearbox package GPK Calculation, which is based on *KISSsys*, provides the user with 17 basic models of gearboxes as templates (GPK module).

With the "Efficiency Template" available for *KISSsys*, the efficiency calculation and thermal analysis in accordance with ISO/TR 14179 are carried out for all types of transmissions and drive trains. In addition, the template now includes a large number of new functionalities, which meet the requirements of the industry.

With the integrated programming language in *KISSsys*, a user's own modifications of the calculation code can be made. Improvements of the gear design and the required cooler power are therefore more purposefully and easily definable by the user.

For more information:
KISSsoft AG
Phone: +41 55 254 20 50
www.KISSsoft.AG

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EMCO Maier

INTRODUCES HYPERTURN 65 POWERMILL

The Hyperturn 65 Powermill offers a large spindle clearance of 1,300 mm, a powerful counter spindle which also allows 4-axis machining, a B-axis with a direct drive for 5-axis simultaneous milling operations, and an additional Y-axis for the lower turret.

Turning, drilling, milling and gear cutting operations can be completed in one setup. Additional handling and part storage is eliminated and workpiece precision is improved. Total production time, fixture and personnel costs, as well as floor space requirements, can be reduced with the Hyperturn.

With 29 kW and 250 Nm, the counter spindle has enough power to machine the workpiece simultaneously with two tools, enabling 4-axis machining.

The milling spindle, with 29 kW, 79 Nm torque and speeds to 12,000 rpm, promotes productivity in the complete machining of complex workpieces. The B-axis direct drive gives the Hyperturn 65 PM good dynamics and contour capabilities with 5-axis simultaneous machining, along with shorter tool change times. The additional Y-axis on the lower turret makes milling work possible at the same time as machining with the milling spindle.

The milling spindle with HSK-T63 tool interface can be used for both turning and drilling/milling work. It can be continuously swiveled within a range of ±120° and clamped at any point. With a Y-travel of +120/-100 mm, most machining work can be carried out. This includes gear-cutting operations, turning/milling work for crankpins, 5-axis machining, and more. The tools can be prepared according to the customer's requirements with a 20-piece pick-up magazine, or a 40 or 80-piece chain magazine.

The Y-axis is accomplished by two interpolating axes, resulting in a distribution of the cutting force in two levels and adds stability to heavy-duty turning and milling. This means the lower turret with integrated milling drive can also be used for complex milling operations at all 12 positions, combined with a Y-axis with ±50 mm travel.

Twenty, 40 or 80-piece tool magazines with HSK-T63 give the user more possibilities for complete machining operations of workpieces, with simultaneously low set-up times for individual parts manufacturing and high-stability for turning and milling works.

As an alternative to the VDI30 or VDI40 12-position tool turret, EMCO offers a new generation turret with a BMT interface and direct drive. Higher stability and precision, and performance data similar to a milling machine, enable the complete machining of turning/milling workpieces.

The machine versions with a milling spindle and turret including milling drive (SMBY/SMBY2) have a cross slide underneath with a 12-position radial turret for 12 driven tools working up to speeds of 5,000 rpm.

The automatic bar machining and/or delivery of unit loads via a robot solution or the EMCO gantry loader offer increased efficiency in automation.

For more information:

EMCO Maier Corporation
Phone: (248) 313-2700
www.emco-world.us

Jergens

EXPANDS RANGE OF PALLET SOLUTIONS

Jergens, Inc.'s range of pallet solutions has been expanded to include two more styles, a 4-Pin pallet and a manual version of the company's ZPS (Zero Point System). Announced in September at IMTS 2014, the new pallet solutions offer users several key features.

The new 4-Pin pallet mounts directly to the machine table and uses a single hex actuator for quick fixture exchanges with precise, secure location for reduced setup time. Locating studs can be mounted directly to existing fixtures to convert them for quick change-overs. A machinable blank fixture plate is also available as an option.

The new ZPS features a manual, single-hex actuator to release and secure fixtures for a range of applications large and small. The manual actuation eliminates the need for air or hydraulic connections required with current ZPS systems. The new manual ZPS modules are available in two sizes, K10 and K20 and offer timing slots for 90-degree part indexing.

"The two additions complement our range of pallets that includes the Drop & Lock pallet changers that integrate with our Fixture-Pro line of multi-axis tooling and our QCB series allowing customers to choose the system that matches their specific need," said Paul Kieta, national sales manager for Jergens Workholding Solutions.

The Drop & Lock range of pallet changers is available in round and square configurations, two platform sizes, 130 mm and 250 mm, and in inch or metric mounting patterns. The QCB pallet series is available in two sizes, can interface with the Fixture-Pro mounting system, and provides for direct mounting of Jergens 5-axis (multi-axis) vises for raising parts above the machine table for 5 axis machining access.

For more information:
Jergens, Inc.
Phone: (877) 486-1454
www.jergensinc.com

SKF

INTRODUCES NEW MACHINE TOOL OBSERVER

The new SKF Machine Tool Observer MTx serves as a single device connecting all operating-parameter sensors to actively monitor, observe and log the performance history of machine tool spindles, grinding machines, or other rotating equipment.

This solution collects information about the accumulated condition levels of a machine tool via the connected sensors to monitor with continuous recording and long-term storage of critical operating data. The MTx can be used as a stand-alone unit or integrated into a control system, whether for OEM or end-user applications. The technology ultimately supports preventive maintenance objectives by helping to detect operating abnormalities before they can escalate.

The system consists of a microcontroller-based electronics assembly with internal memory for data storage in real time. The electronics assembly can be connected to up to six different sensor types for monitoring vibration, speed, temperature, humidity, eddy probes, and oil streak, among other parameters. It supports a wide range of different types of sensors, where a maximum of 14 of these sensor types can be connected at the same time. The system compiles detailed documentation of machine tool history and working conditions and enables traceability of incidents by accurately logging their duration, date and time.

For parameterization and data presentation, a server/client software package has been developed for standard Ethernet (LAN) interface with DHCP/IP protocol. The software package allows users to manage and run multiple units installed on a PC, network or over the Internet. Each connected sensor can be monitored online for ongoing accessibility and shared evaluation.

The MTx requires minimal wiring. In addition, two relay outputs can be configured for alarm or emergency stops and email alerts can be generated, based on predetermined sensor limits.

For more information:
SKF United States
(847) 742-7841
www.skf.com

Seco Tools

ADDS NEW HELICAL TOOL TO SQUARE T4-08 LINE

Seco Tools, LLC recently added a new helical tool to its Square T4-08 line of square shoulder mills that feature four cutting edges and a tangential cutter design. Designed for slotting and contouring/shouldering applications, the Square T4-08 Helical excels in machining challenging materials such as cast iron, steel and stainless steels.

Like other products within the line, the Square T4-08 Helical's pocket seats combined with multi-edge inserts improve cutting stability and allow for clean 90° walls. The inserts mount tangentially in the cutter so that the cutting forces impact the thickest parts of the inserts, allowing manufacturers to achieve the required levels of strength for increased depths of cut with small diameters.

The tool has cutting diameters that range from 0.98" (25 mm) to 2.13" (54 mm) and depths of cut between 0.87" (22 mm) and 2.52" (64 mm). Corner radii range from 0.02" (0.4 mm) to 0.063" (1.6 mm). Furthermore, the entire Square T4-08 Helical range has integrated through-coolant channels to provide extended tool life.

For more information:
Seco Tools, LLC
Phone: (248) 528-5200
www.secotools.com/us

Spectroline

INTRODUCES OL-444 INDUSTRIAL LEAK DETECTION KIT

The Spectroline OLK-444 Industrial Leak Detection Kit is a kit that pinpoints leaks in any size oil-based fluid system. It locates leaks in hydraulic systems, compressors, engines, gearboxes and fuel systems, preventing equipment breakdowns and potential environmental problems.

The kit features the Opti-Lux 400 violet light LED leak detection flashlight. It has power comparable to a 150-watt lamp. The unit is compact, lightweight and rechargeable. Its violet light enables dyes to fluoresce brighter and with greater contrast than with standard blue light inspection lamps.

Also included in the kit is a 473 ml twin-neck bottle of patented Oil-Glo 44 concentrated oil dye, which is compatible with all synthetic and petroleum-based fluids. When a leaking industrial system is scanned with the Opti-Lux 400, the dye glows a bright yellow/green color to reveal the location of all leaks.

Rounding out the kit is a 237 ml spray bottle of Glo-Away dye cleaner, a charging cradle with AC and DC cord sets, dye treatment tags and fluorescence-enhancing glasses.

For more information:
Spectronics Corporation
Phone: (800) 274-8888
www.spectroline.com

Rego-Fix

INTRODUCES HI-Q/ERMX MINI-NUT

Rego-Fix, a manufacturer of Swiss precision tooling, recently introduced the Hi-Q/ERMX Mini-Nut for Swiss automatic machine tool applications. The nut has an anti-slip locking design that is engineered to prevent the locking wrench from slipping off the nut during assembly and disassembly.

Milled slots on the outside diameter of the nut mate with corresponding features of the wrench to prevent slippage during the tightening and loosening processes. Benefits include operator safety as well as prevention of damage to other tools. The Hi-Q design includes a special surface treatment to enhance clamping forces and extend the life of the nut by protecting against corrosion.

For more information:
Rego-Fix
www.rego-fix.com

SMT

RELEASES MASTA 6

Smart Manufacturing Technology (SMT) recently announced the release of its CAE software, Masta 6.

Masta is for transmission and driveline design, analysis, simulation and manufacture. Its modular structure makes it tailored to the responsibilities of its user and is applicable to the entire development cycle for the automotive, energy, aerospace, marine and rail industries. Masta integrates and interfaces with a multitude of other platforms including Gleason's Cage software for manufacture and CAD modelling software for design and analysis.

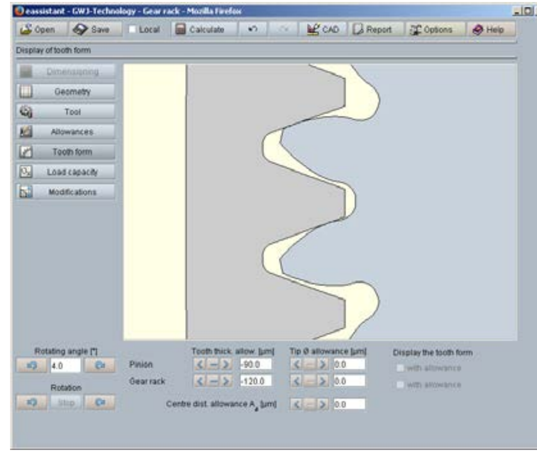
A user interface overhaul allows the user to make faster accurate results in an ergonomic workflow allowing engineers to achieve higher levels of quality. Improvements include advanced customizable reporting features as well as importing and exporting CAD model enhancements.

New modules for fluid film bearings, plunge shaving micro geometry and shaving cutter dynamics have also added to Masta's repertoire.

For more information:
Smart Manufacturing Technology
Phone: +44(0)115 9419839
www.smartmt.com

GWJ Technology

UPGRADES EASSISTANT SOFTWARE



GWJ Technology GmbH, headquartered in Braunschweig, Germany, has upgraded its web-based calculation software *eAssistant* with three new modules for the calculation of rack/pinion gear pairs as well as single external and internal cylindrical gears.

In addition to various calculation modules for many different machine elements (e.g., shafts, rolling bearings, shaft-hub connections, bolts, cylindrical gears, planetary gear trains, bevel gears), GWJ has released three new modules. Two modules can be used for the determination of single cylindrical gears. One module allows the calculation of single external cylindrical gears, the other supports the calculation of single internal gears. Both modules enable *eAssistant* users to determine the gear geometry, test dimensions and allowances including the accurate gear tooth form. The user can export the tooth form as DXF.

The third new module makes it easier to calculate rack/pinion gear pairs. Spur and helical gears are possible to calculate. Profile shift on the pinion will be taken into consideration. The number of teeth or the length of the gear can be specified for the gear rack. The user can decide between rectangular or round gear racks. In addition to geometry, allowances and gear tooth form, the load capacity according to DIN 3990 and ISO 6336 Method B can be calculated. Herewith the safeties for fatigue or limited life strength and static strength can be determined. The calculation of surface durability (pitting), tooth bending strength and scuffing according the flash and integral temperature method is carried out.

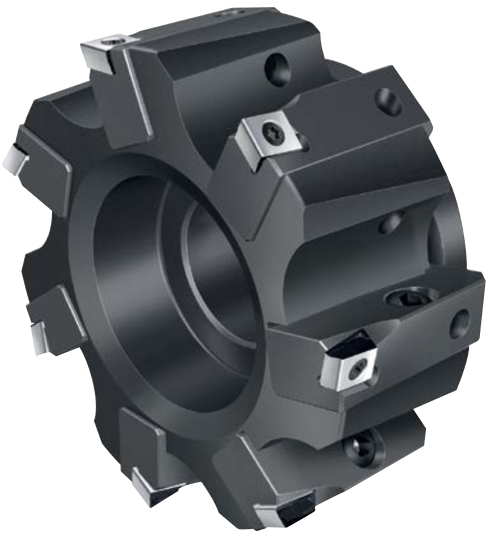
There is also a calculation of load spectra. For 2-D CAD systems, the standard format DXF is available. The *eAssistant* 3-D CAD plugins support the creation of 3-D models. With one click, the design table with all manufacturing details can be placed on the manufacturing drawing.

For more information:
GWJ Technology GmbH
Phone: +49 (0) 531129 399-0
www.gwj.de

Walter

INTRODUCES TWO INDEXABLE INSERT CARTRIDGES

Walter, a producer of precision cutting tools for milling, drilling, turning, boring and specialized tools, recently introduced two new indexable insert cartridges for the Walter F2010 face mill. These new cartridges, the FR751M and FR752M, bring the flexibility and performance of Walter BLAXX tangential indexable inserts to the Walter F2010 face mill. The family of indexable milling tools includes shoulder, helical and slitting mills.



The Walter BLAXX shoulder mill produces precise 90° shoulders. That system is only available for tool diameters up to 160 mm. The F2010 face mill, equipped with the FR751M or FR752M cartridge, can bring this technology up to a diameter of 315 mm. In addition, the F2010 can now be used for fine finishing because the indexable inserts can be adjusted axially with micrometer precision.

These inserts come in two geometry variants: the L55T, a universal geometry that can be used on most materials, and the L85T, which has a particularly sharp cutting edge for machining aluminum.

For more information:
Walter USA, LLC
Phone: (800) 945-5554
www.walter-tools.com/us

Oelheld

RELEASES 'THREE MAGIC HELPERS'

Oelheld U.S. Inc. recently released three new products to aid with nagging shop problems: Oelheld LubTool 2000, Oelheld LubTool 4000 and Oelheld LubTool 6000.

Oelheld LubTool 2000 is a fully synthetic, PAO based lubricating oil that lubricates, cleans, protects and removes corrosion, even in extremely low temperatures. LubTool 2000 is NSF H1 approved, so it can be used around food stuff and it is neutral to all common plastic-and elastomeric materials. LubTool 2000 is free of silicon, acids and resins.

Oelheld LubTool 4000 is a universal cleaner that can remove multiple contaminations. LubTool 4000 is designed for the removal of resin, oil and grease, most coatings, paints and crayon marks, as well as cleaning of soiled machinery components. LubTool 4000 is also suited for surface prep, prior to bonding and painting. The product is free from hydrocarbon and evaporates residue free.

Oelheld Tool 6000 is a corrosion protection for precision-tools which forms a thin, grease-like protective film. It offers corrosion-protection on metal parts for long-term indoor and outdoor storage.

LubTool 6000 does not form any resins and can be removed after long-term storage. Treated parts can be EDM wire-cut without removing the coating first. LubTool 6000 is free from FHC, CHC and FCHC.

For more information:
Phone: (847) 531-8501
www.oelheld.com

Taylor Hobson

INTRODUCES HI-RES INSTRUMENTS FOR SURFACE AND CONTOUR INSPECTION

A new series of high resolution instruments offering automated simultaneous surface and contour inspection has been introduced by Taylor Hobson, a unit of AMETEK Ultra Precision Technologies.

Precision machining and an FEA (Finite Element Analysis) optimized design combine to provide a low noise and high accuracy mechanical execution of the measuring axes. Balanced beam design allows the instruments to be used in any orientation. Traceable standards and algorithms eliminate instrument influence from the measurement results. The instruments are available in 1mm, 2mm and 5mm gauge ranges with an 18 bit gauge for improved resolution in surface detail, contour and 3D measurement. Software for analysis of surface finish and form is included.

A unique temperature compensation system monitors and feeds back changes in ambient temperature, ensuring consistent system performance and high measurement integrity, regardless of environmental effects.

For more information:
Phone: (630) 621-3099
www.taylor-hobson.usa@ametek.com

Schunk

INTRODUCES WSG SERIES SERVO-ELECTRIC 2-FINGER PARALLEL GRIPPERS

Schunk recently introduced the WSG series of servo-electric 2-Finger Parallel Grippers. They are designed for parts handling and assembly processes where flexibility and sensitivity is required. Schunk has now expanded the series with a long-stroke version and a compact small parts version.

The WSG has a long stroke which allows reliable handling of different components and grip force can be controlled internally. These grippers have part detection and integrated grip force control system.

Through standard sensor interfaces in the base jaws, sensors are directly integrated into the gripping process without any additional cabling or interfering contours. By using the optionally available force-measuring fingers, forces which occur at the gripped component can be recorded and allow reliable handling of fragile components.

A belt drive ensures high jaw speeds and short cycle times achieving speeds of 400 mm/s.

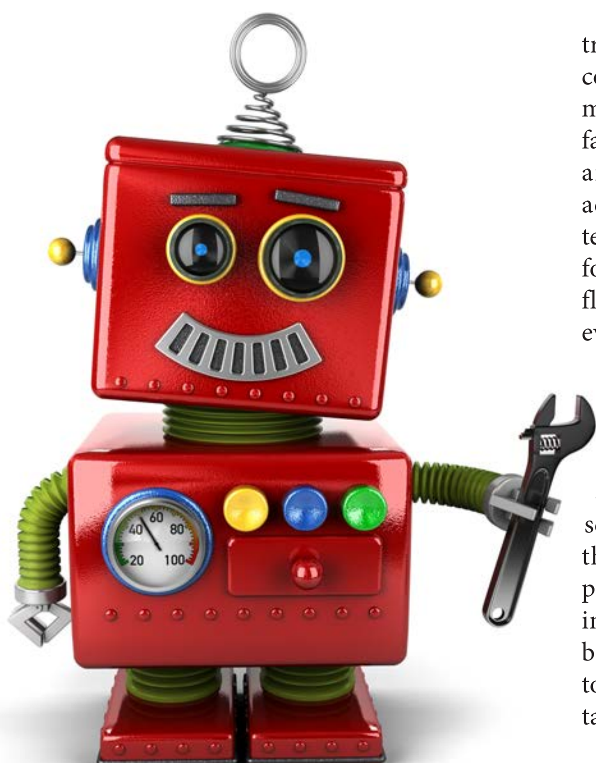
For more information:
Phone: (919) 572-2705
www.schunk.com

Robots are a Man's Best Friend

Erik Schmidt,
Assistant Editor

Pretty much everyone old enough to utter the familiar, dual syllabic refrain of "beep boop" in the electro-mechanical, monotone pitch from every sci-fi movie ever made has the same idea of what a robot looks likes.

And, coincidentally, everyone is *dead wrong*.



It turns out that modern day robots — at least the ones that are functioning parts of everyday industrial life — aren't all metallic chrome finishes and stiff, rudimentary movements straight from an early 80s music video. No, these robots are far less about following a futuristic color scheme and more about getting the job done, often with their one long, dexterous arm painted the vibrant shade of citrus fruits.

No frills, no bells and whistles, and certainly no "beep boop." Which is good, because the gear industry is a no frills kind of place. In fact, it's the kind of place that typically aligns itself with blue collar, bygone clichés like "elbow grease" and "sweat of his brow" over the flashy gizmos of tomorrow.

Then again, why would any sane person do a job with ten people when they can do it with two?

Picking a Winner

Machines are becoming more human.

This is an inarguable truth, one that the gear industry can confirm with the utmost authority by merely taking a stroll down to their factories for a quick once-over. Robots aren't infallible, but with recent advancements in vision and sensor technology, they can increasingly perform tasks just as efficiently as their fleshy counterparts — and oftentimes even more so.

Now some people will take that information, fret wildly over an already diminished ration of available jobs (even though the old song and dance in manufacturing is the scarcity of skilled labor workers) and then retreat to a place of fear and paranoia — think Will Smith's pie-eating, gun-slinging character in "iRobot," a movie one would hope proves to be a woefully inaccurate representation of the future.

"We actually have our own 3D scanning software that we're very high on," added Geoff Dawson, account manager of Fanuc's North American distribution group. "Sometimes companies will buy our robots but are more comfortable designing their own software."

Dawson and Andy Glaser, vice president of sales at Yaskawa America Motoman Robotics (West Carollton, OH), both agreed that bin picking has been the major development in gear robotics in the past couple years.

Yaskawa Motoman DX1350 deburring robot.

Arrow Pointing Up

Robots are synonymous with the future, really. Blame the futurist helmsman of yesteryear like Fritz Lang and Stanley Kubrick all you want for etching the symbiotic bond into humanity's subconscious decades ago. The fact remains that they'll forever be linked like nuts and bolts, as inseparable as the two sides of a shiny red penny.

But even in a field as forward-thinking and rapidly changing as robotics, sometimes it can be of great use to stop the upward trajectory for a moment and simply linger on the present for a pause or two– or, in Arrow Gear's (Downers Grove, IL) case, the past.

Roughly eight years ago, Arrow President Joseph Arvin invented an apparatus and method for chamfering and deburring in which gears are mounted to an indexable chuck, which is then used to position the gears for various machining operations.

Well, the calendar is freshly flipped to 2015 and Arrow's latest robotic advancement is still Arvin's from the George W. Bush administration. As the famed saying goes — if it ain't broke, why build an entirely new robotic interface to replace it?

"I can't say that we really have anything new," said Kerry Klein, Arrow's vice president of sales and marketing. "We have been using robotics in deburring. Arrow Gear actually developed a machine used for deburring, but that was many years ago. We haven't really updated that at all and we're not really looking at any additional robotics at this time.

"We're looking to increase our deburring capacity, but we're actually looking at five-axis technology for that."

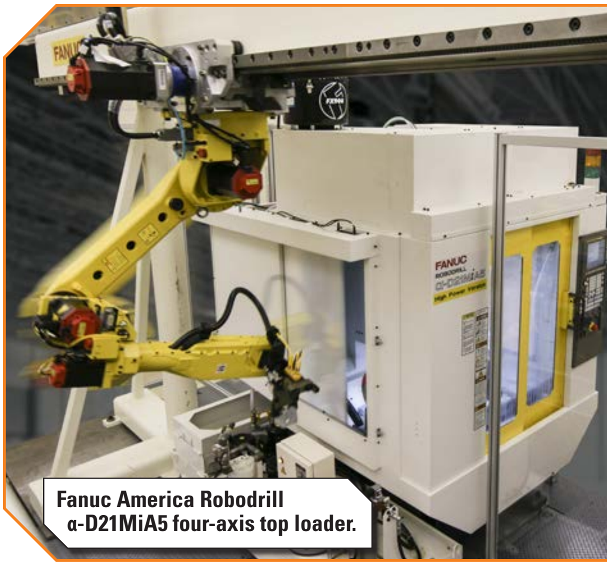
Klein said that while Arrow hasn't made any significant changes — or slight changes, either — in terms of robotic machinery, they'll be on the lookout to potentially make some improvements in 2015. It all comes down to sense and sensibility.

"We manufacture gears, so if it makes sense to buy robotics to improve our processes and improve our efficiencies or something like that, certainly we could [add more robotic technology]," Klein said. "Sometimes it makes sense in medium to high volume manufacturing is auto load and auto unload, where the robot is actually loading the part instead of a person.

"We don't do a large enough batch volume to justify doing that. I've seen it at other gear facilities but not here."

So for Arrow — and for the majority of gear manufacturers, to be fair — the main need for robotic technology is with deburring. Arrow currently has two deburring robots at their facility.

"Every time you hob a gear or grind a gear, you create sharp edges," Klein said. "The sharp edges have to be taken out for safety reasons and also for mechanical reasons. You can do that with a grinding wheel on a drill, basically. You have air and you hook it up to an air gun and then the wheel spins and you just do it by hand, which we do quite a bit of


Fanuc America Robodrill α-D21MiA5 four-axis top loader.

that as well. Of course, by doing it by hand you're risking that the hand operator is going to make a mistake and do it too deep or too shallow, touch something other than the tip of the tooth, whatever.

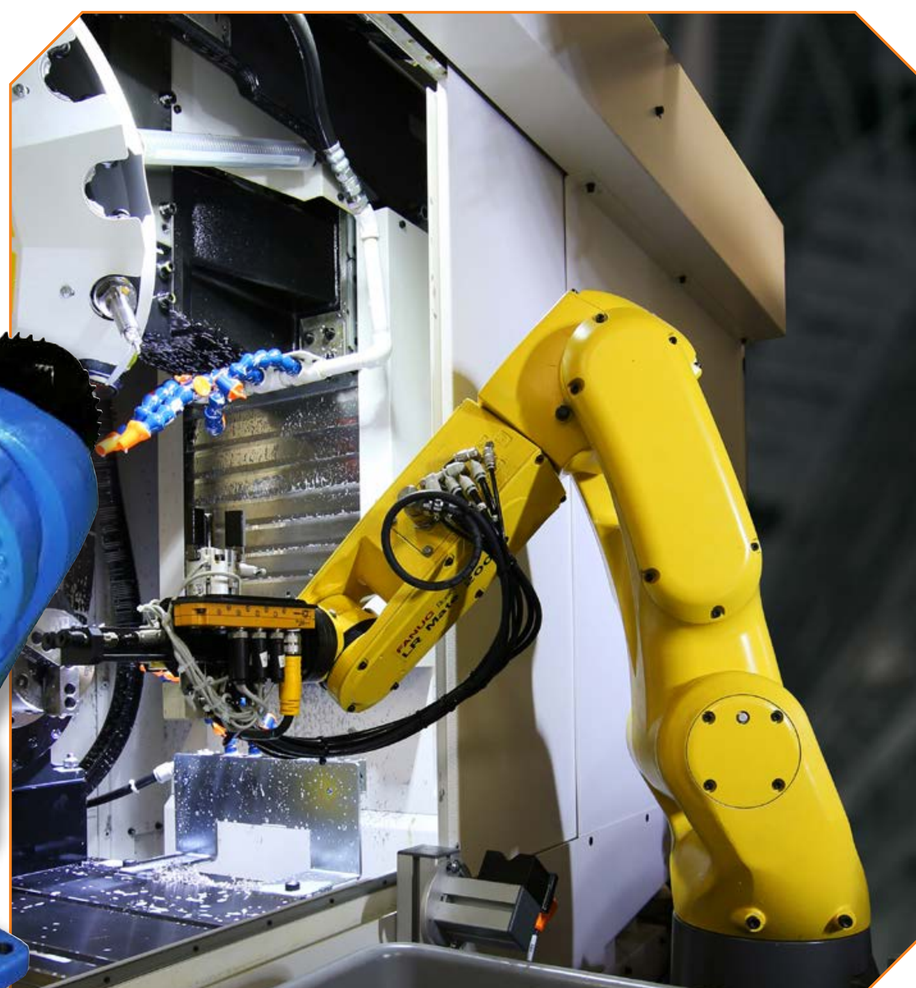
"One other way of doing it is with a robotic arm, because once you've programmed that arm to do it, it should do it repetitively. If you've got 60 teeth it's going to do it exactly the same on all 60 teeth. It's going to be repetitive and it's not going to care. It's going to do it over and over and over. It's not going to get tired. It's not going to vary.

"Of course, you have to program that into the machine. You have to develop that for each and every part. The tradeoff is that if you're running a batch every hour, then you're programming every hour, which becomes ridiculously time consuming, whereas if I'm doing it by hand the operator can adjust to every part no problem. So it's a mix."

Staring across the way at the other end of the plane is sales manager Alex Miller of ABB Robotics (Auburn Hills, MI), who reaffirmed Klein's position that deburring robots are still the cherry on top of the robotic/gear sundae, but first mentioned ABB's latest innovation released in the past year — a system that places and removes gears from heat treating furnaces.

"It has vision and it handles the gears very gently," he said. "You know how they're kind of malleable when they come out and it's a system that's foolproof to make sure the gears are treated correctly. That's probably the newest thing we have."

"Of course, we also have deburring robots, but that's nothing new."



Domo Arigato

OK, that's all well and good. Retro is en vogue right now, anyway. But *what of* the future?

If you ask Glaser, vice president of sales at Yaskawa America Motoman Robotics (West Carollton, OH) the future looks strangely similar to the present — just with a few nuanced tweaks and improvements.

"The robot — and I hate to say it, because I'm a robot guy — but it's really a dumb device [in the case of gear manufacturing]," Glaser said. "But what we do is equip it with some very smart sensor technology. That's really what has changed the landscape of robots in the gear industry.

"A six-axis robot today is not a whole lot different than the six-axis robot of 10 years ago. What's changed is vision technology; what's changed is force-sensing technology and calibration tools to achieve very high-tolerance deburring.

"The robots are the same but their capabilities are improving drastically."

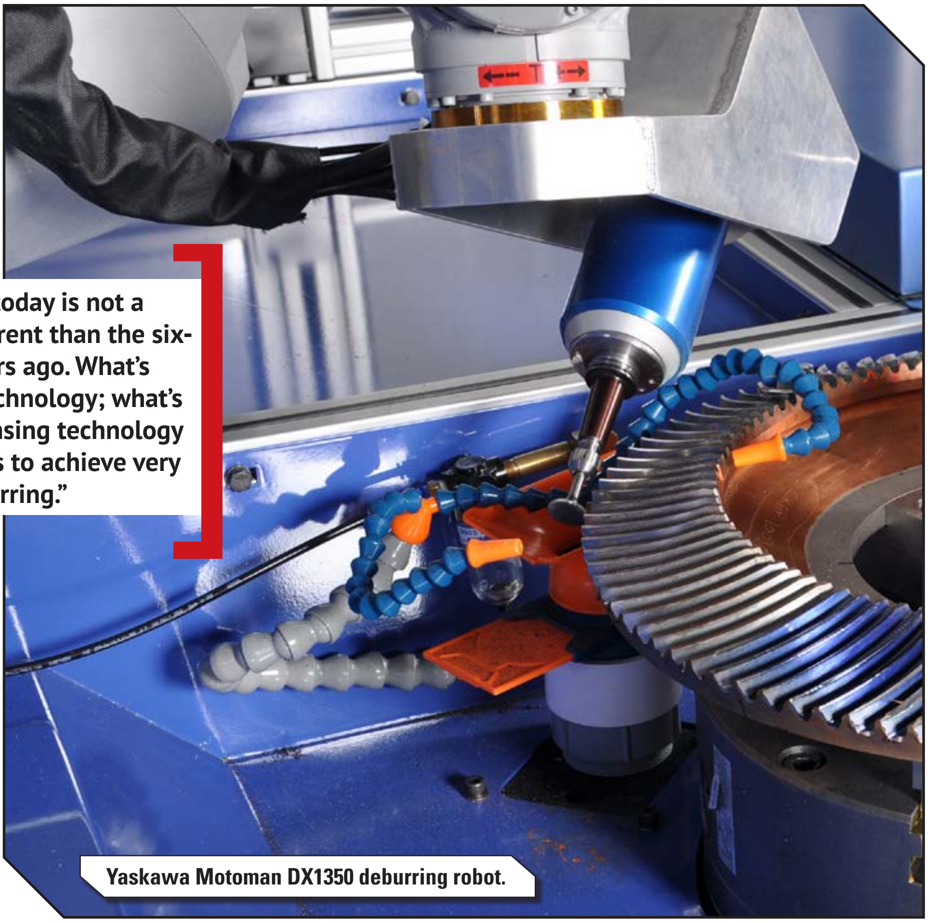
"I would have to agree with that statement," said Dawson. "We're the largest robotics supplier in North America, so we're constantly looking to advance our product and stay ahead of the competition. We pride ourselves on being a robot company — we use our robots to build robots. So we really stay true to ourselves and always want to be the one with the latest advancement."

The most recent of these advancements, according to Glaser and Dawson, is random bin picking

"Over the last two years, bin picking technology with vision has really come on strong," Glaser said. "We use a company called Universal Robotics in Tennessee, and they make what is what I think is the world's leading 3D vision packages. Where others fail, they succeed. Their sensors overcome heat, they're much more industrial and they're much more cost-effective sensors.

"The bin picking is more of new advent where you can just directly grab these forgings or machine pieces right out of a bin that are loosely located."

While Glaser noted that gear robots have seen significant improvements in the areas of vision, heat resistance



Yaskawa Motoman DX1350 deburring robot.

"A six-axis robot today is not a whole lot different than the six-axis robot of 10 years ago. What's changed is vision technology; what's changed is force-sensing technology and calibration tools to achieve very high-tolerance deburring."

and overall durability in the last several years, there remains one hindrance to the machines' advancement.

"I will say the gripper is still an issue in this particular market," he said. "The gripper technology still has not changed that much. If you're going to do bin picking, a lot of times what you have to do is roughly grab the piece out of the bin, and then you'll have to qualify it and then regrip it.

"You're not going to simply just go and grab a part out of a bin like a human, orientate it automatically while you're picking it up and place it like a human would."

It would seem that, despite the advanced state of robotics in the gear industry at present, humans are in no danger of being completely replaced by robot overlords—at least not anytime soon.

All of data collected equates to a win-win. Robots are here to help and here to stay, but their station as underlings and minions is well-secured. Detective Del Spooner can put down his sweet potato pie, holster his hand cannon and sleep soundly for the time being.

For more information:

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www.fanucrobotics.com

ABB Robotics
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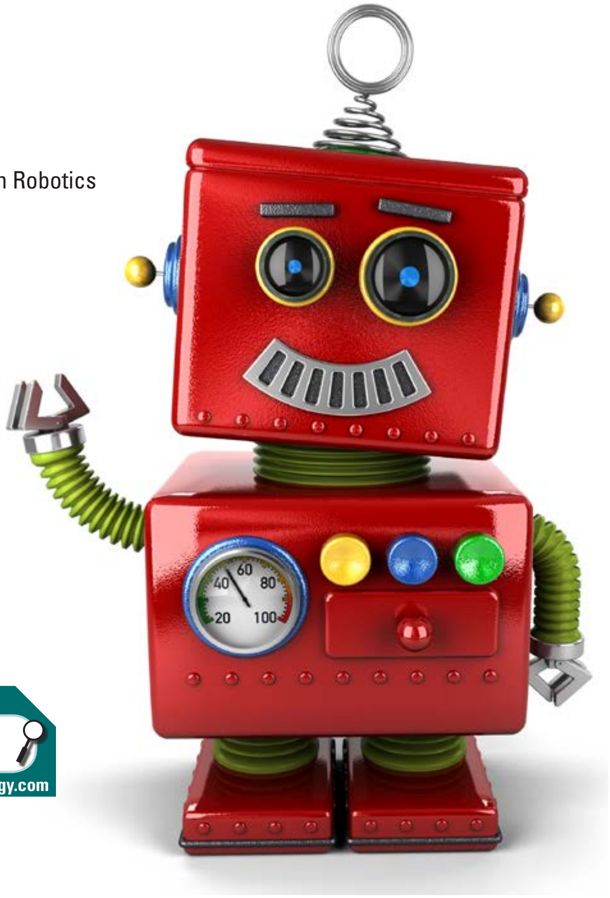

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On the Cutting Edge

Erik Schmidt, Assistant Editor

Sentences that start off with some variance of *"I don't want to brag, but…"* are generally a good indicator that it's precisely what the speaker intends to do and typically end with bold proclamations that are immediately and eminently quotable — the kind of quotes perfect for beginning a feature story with an eye-catching artistic flourish.

And, true to form, Stephan Hecht didn't disappoint.

"I don't want to sound stuck-up, but…" began Hecht, the senior executive vice president for Oelheld U.S., "we are a business out of Germany and we are really rapidly growing here in the U.S. The reason for it is, you know, a lot of operations in Europe are using our product. Based on higher wages and social benefits, they have to operate on the cutting edge.

"That's what's happening to us here in the U.S. Word is spreading and companies are finding that our products are definitely worth the extra money. They increase productivity by up to 30 percent."

OK, so maybe it's not exactly Muhammad Ali and Joe Frazier trading barbs in Manila, but as far as smack talk in the cutting fluids community goes, this was off the charts.

Thirty percent.

That's a significant number, one that Hecht delivered with the ease and confidence of a man who fully believes it to be true. And if it is true, those in the gear industry utilizing cutting fluids are going to be pretty happy.

A Different Animal

Oelheld fancies itself an "innovate fluid technology," which, according to Hecht, isn't a far cry from the truth. But if it's not exactly that, then it's at least a different one. Go ahead and Google it.

On the front page of its website there is a picture of a tiny chameleon, striped with all the colors of the rainbow, postured peacefully atop a beaker of green mystery fluid. Directly to its right — and no less out of place on a site for a lubrication company — is a photo of a shirtless man brandishing a katana.

Behold: This is how Oelheld does the Internet.

So it really shouldn't come as a surprise that "different" is also how Oelheld does cutting fluids.

"Our latest product is our DiaMill HEF 1100, which is a high-performance cutting fluid," Hecht said. "It uses a whole high-performance additive package for extremely high pressures. It makes this product very popular with high-speed operations.

"Since we are a European-based company, we are a little more careful with what we put in our additive packages. We have no chlorine in any of our products or any heavy metal additives. Nevertheless, we managed to reach or have better performance even without those harmful substances."

The DiaMill HEF 1100 was released by Oelheld roughly three years ago but remains the company's top cutting fluid product. It's based on hydrocrack oils, has nearly no odor and is resistant to aging.

According to Hecht, DiaMill is also more physiologically safe than most other cutting fluids on the market because of its lack of damaging ingredients, which is the positive result of essentially being backed into a corner by stricter European guidelines, Hecht said.

"Basically, some of the environment and work safety specifications are a little tighter in Europe than here," he said. "That's basically the main reason. We were forced into it — but it does work very well. If you put your mind to it you can find solutions that work even better."

"A lot of gear hobbing places use us in the United States. It's also a tremendous product for cutting. It's good for steel, aluminum and all non-ferrous materials, which are all the important materials."

Then, for good measure, Hecht delivered his knockout punch, not with the sting of a bee, but with sophisticated German eloquence:

"It's like pure gold."

Trail Blasers

Just a southbound doggy paddle from Hecht's home country of Germany across Lake Constance, tucked neatly in the frosted forests of Hasle-Rüegsau, Switzerland, is Blaser Swisslube, another European-based lubrications company with an aversion to the status quo.

Randy Templin, vice president of product line management and custom-

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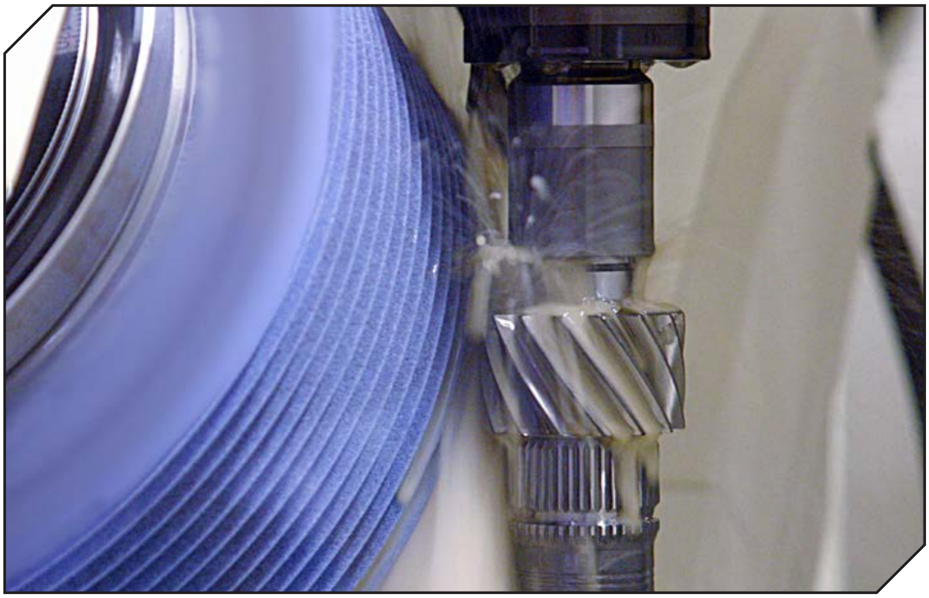

er service at Blaser Swisslube America (Goshen, NY), spoke about his company's latest cutting fluid advances while openly defying Hecht's comments on forceful compliance to "European specifications."

"It's a bit of misunderstanding about Europe," Templin said. "Blaser's headquarters are in Europe and we still sell a tremendous amount of chlorinated products. It depends where. For example, Italy and the United Kingdom have no issues with it. Some parts of Germany use chlorine quite a bit, it's just more expensive to transport it."

Still, that doesn't mean Blaser is dumping chlorine in its products by the gallon all willy-nilly. On the contrary — its latest product, Vascomill CSF 35, which was first made widely available in the United States about a year ago, is as environmentally friendly and work-safe as anything else on the marketplace, according to Templin.

"Our Vascomill cutting oil has an ester-based stock," he said. "The ester is derived from vegetable sources and it's completely chlorine free.

"We found it really works well in gear manufacturing, especially with gear hobbing. Customers were having smoke problems and burnt chips. We go in there and eliminate the smoke and it really improved the tool life, as well. Or we were able to speed the machine up and get the production rate accelerated.

"It's really a special oil with a very, very high flashpoint and very high lubricity."

Whereas Hecht was confident enough in Oelheld's product to declare a 30 percent production increase, Templin's

statements on the matter were a bit more reserved and tempered — nonetheless, he was confident about an ability to make a significant improvement.

"It really depends on the customer's application," Templin said. "What kind of tooling they have, the way they run the tooling, the coating, the kind of oil they had in there before and how it was maintained. So it's difficult to say every time you go in there you're going to guarantee a certain percentage of productivity gain. Every customer will be different.

"At the same time, we've seen tremendous cases of success from tripling tool life to increasing the productivity on the throughput side by 5 to 10 percent."

Not Cooling Off

As several European-based upstarts continue to leak gradually into the American market, Cimcool — who likens itself as the "leader in fluid technology worldwide" — has had to swing back strategically in order to maintain its global positioning as "cutting fluid champ."

Its latest haymaker is its InSol lubrication, released in the fall of 2014.

"InSol technology puts lubricant at the cut zone-tooling interface so the lubricant and cooling are optimized," said Bruce Koehler, product manager of Cimcool. "Since InSol technology works through controlled water solubility, this great performance lasts longer due to low depletion rates. Best of all, InSol technology can help out on tough-to-process alloys without using materials that can drive waste hauling costs up.

"When you couple that with process savings, lower tooling usage and more productivity output, this is what manufacturers need to help control costs and improve efficiency."

InSol is, like DiaMill and Vascomill, a chlorine-free lubricant. It's composed of a blend of raw materials that have solubility ranges from limited to complete and, because the material is mostly water soluble, it virtually never depletes when regular makeup concentrate is added.

"The reason these new products are so special is that we have seen grinding ratios increase by 50 percent and cutting forces decrease by 30 percent or more, both of which drive productivity and cost savings for our customers," Koehler said. "Imagine using a fluid that virtually looks like water that can increase your productivity so significantly.

The InSol technology is available in the Cimtech 300 and Cimtech 600 series, which also contain Cimcool's Milacron synthetic lubricants.

Fluids containing the InSol lubricant boast "excellent multi-metal performance without the use of extreme pressure additives" and can increase productivity by "up to 20 percent when compared to chlorinated lubricants," according to Koehler.

When looking at DiaMill, Vascomill and Cimcool's cutting fluids containing InSol — three elite products from three of the industry's leaders — there would seem to be no shortage of available lubrications to enhance and ease the gear manufacturing process.

The best part? They're all different.

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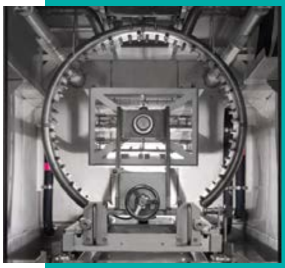

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Hub of the Gear Industry

Gleason Celebrates 150 Years

By Randy Stott, Managing Editor

The name Gleason is practically synonymous with gear manufacturing. Since the company was founded in 1865, the technology of gear manufacturing has been its focus, its core and its competitive advantage.

Staying true to that focus has been one of the keys to the company's longevity, according to Chairman James S. Gleason. And he should know. Aside from the fact that his family name is still on the door, James S. Gleason has been with the company since 1959. "I was a so-called college trainee," he says. "I started out in the foundry, doing pretty simple, fundamental, physical things. I systematically went through training with almost every part of the company."

And through the years, he's seen both the ups and the downs.

"We're almost unique in terms of machine tool companies in the sense that we know more about the end product that our customers produce, in general, than they do." — JAMES S. GLEASON

"When most history is told, there is almost always some sort of editing that goes on," Gleason says. "Clearly there is a tendency to emphasize all the wonderful things that have happened and not put too much light on those things that weren't. I think for any company, particularly ours, it's probably more important that you learn from the mistakes than it is to celebrate the triumphs."

For James S. Gleason, that means sticking to what you know. He points to the company's time as a publicly traded company as one period when their focus was allowed to drift.

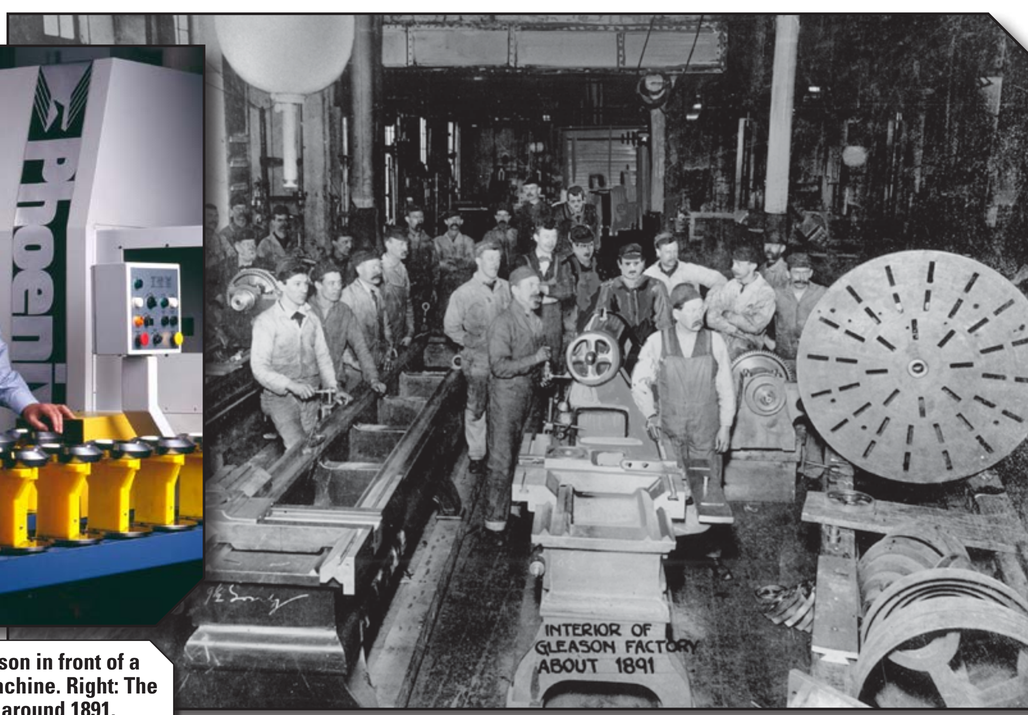
"That was not a very good fit for our business," he says. "It tends to focus your attention on each quarter, and the cycle time of a lot of the events that are important to us don't function very well on a quarterly basis."

In the 60s and 70s, the company also made a number of acquisitions in an attempt to grow the business. Those acquisitions included a company that produced telephonic exchange equipment and a number of parts producing companies, Gleason says. "Fundamentally, these were not businesses that we knew much about."

But embracing those failures was an important turning point in the company's history, Gleason says. It forced the company's executives to reevaluate their strengths and refocus on what had made them successful for so many years.

That meant staying true to and recommitting to their focus on gears.

"We're almost unique in terms of machine tool companies in the sense that we know more about the end product that our customers produce, in general, than they do," Gleason says.



Above: Chairman James S. Gleason in front of a modern Phoenix gear cutting machine. Right: The interior of the Gleason factory around 1891.

Gleason employees outside the company's original factory, located at Brown's Race, overlooking the Genesee River (circa 1889).

In fact, in order to stay atop their niche, the company has not only strived to *understand* the current state of the art, but they've also continuously sought ways to *advance* it. Part of their mission is to find better and more productive ways to manufacture gears, inventing new technologies, processes and tools along the way.

"We have never been known as a high-tech company — except that we really are," Gleason says. "We have almost always had at the head of our R&D department and gear technology core the top people in the world. That has always been a hugely important part of our leadership."

That thought is echoed by John J. Perrotti, president and CEO.

"Technology is the engine that drives our company," Perrotti says, adding that "Gleason continues by far to issue the most patents of anyone related to gear production."

Of course, the focus on R&D and invention is nothing new. In fact, the company's founder, William E. Gleason, was a well-known inventor and craftsman who had apprenticed in the Rochester, NY machine shops of Asa R. Swift and I. Angell & Sons, and who also worked during the Civil War at Colt's Armory in Hartford, CT. In 1865, he returned to Rochester and took over the Kidd Iron Works, which eventually evolved into the Gleason Works. In 1874, William E. Gleason invented the bevel gear planer, and the rest is gear history.

Through the years, many inventions have followed, including highly specialized machines for manufacturing all types of bevel gears. But in addition to his knack for invention, the company's founder also passed on an attitude and a way of doing business that still resonates today.

In the lobby of the Gleason Works facility in Rochester, a large bronze tablet commemorates William E. Gleason. The inscription reads:

A MASTER CRAFTSMAN
ENDOWED WITH AN INDOMITABLE WILL
A SPIRIT OF INDEPENDENCE AND BROAD VISION
WHO CREATED A NEW TYPE OF MACHINE TOOL
AND FOUNDED THIS BUSINESS ON
IDEALS OF SERVICE AND FAIR DEALING

That last part about service and fair dealing are important parts of the Gleason culture.

"I often describe Gleason as a company with the values and culture of a small, family-owned business, but with the sophistication of a very large, multinational company," Perrotti says. "Gleason has survived for 150 years I think first and foremost because of its integrity and its fairness — its fairness to its customers and its fairness to its employees. That's a value we insist on."

The company's management continues to put a high value on its employees. And the employees — both current and former — seem to have a high level of loyalty towards Gleason as a result. This was clearly in evidence at the WZL Gear Conference USA, which was held at the Gleason Works in November.

"A lot of the people who are here today as visitors are former Gleason employees," said Perrotti at the event. "I think they all, for the most part, have favorable memories."

"We've coined the expression Gleason 4.0, which is really our vision for the smart factory, digital manufacturing and the connection between the theoretical and mathematically proven way of optimizing both the design and the manufacturing." **— JOHN J. PERROTTI**

But keeping employees happy is only part of the battle. Keeping customers happy is the bigger part, says Perrotti, and Gleason focuses heavily on service as a significant part of what it offers.

"We have always tried to change and adapt as we've seen the markets evolving and as we see our customers' needs," Perrotti says. "We've tried to sharpen our focus on customer service, so we've invested more and more in developing better information systems, training programs, and part stocking strategies to support our customers."

One of the keys to providing better and better service is creating the technology that allows for it, Perrotti says. "More and more of our industry will be pointed toward service, but not in the classic way of a guy carrying a toolbox."

Instead, the company is working hard to develop incremental ways where it can provide value to its customers. For Gleason, that means smart systems that gather information, encapsulate gear manufacturing knowledge and allow customers to make quick decisions.

The pattern shop inside The Gleason Works, 1954.

“We’ve coined the expression Gleason 4.0, which is really our vision for the smart factory, digital manufacturing and the connection between the theoretical and mathematically proven way of optimizing both the design and the manufacturing,” Perrotti says. “Gleason 4.0 is everything from machine monitoring to creating expert systems that gather data, do sophisticated data analytics and feed that knowledge back to the design and manufacturing process.”

“We’re proud of our past but even more excited about our future.” **— JOHN J. PERROTTI**

Even though Gleason 4.0 seems to be focused on technology, it’s really more about service, Perrotti says. Building these systems is how the company can best help customers take advantage of Gleason’s 150 years of gear processing knowledge.

“One of the key things every customer will tell you is that we don’t have enough skilled people,” Perrotti says. “That’s why we need to continue to create expert systems and tools that help provide some of that process knowledge, so it doesn’t require having somebody with 30 years of experience to make those judgments.”

Clearly, innovation in products and a focus on service have been hallmarks of the company from the beginning. But perhaps just as important has been Gleason’s focus on global markets.

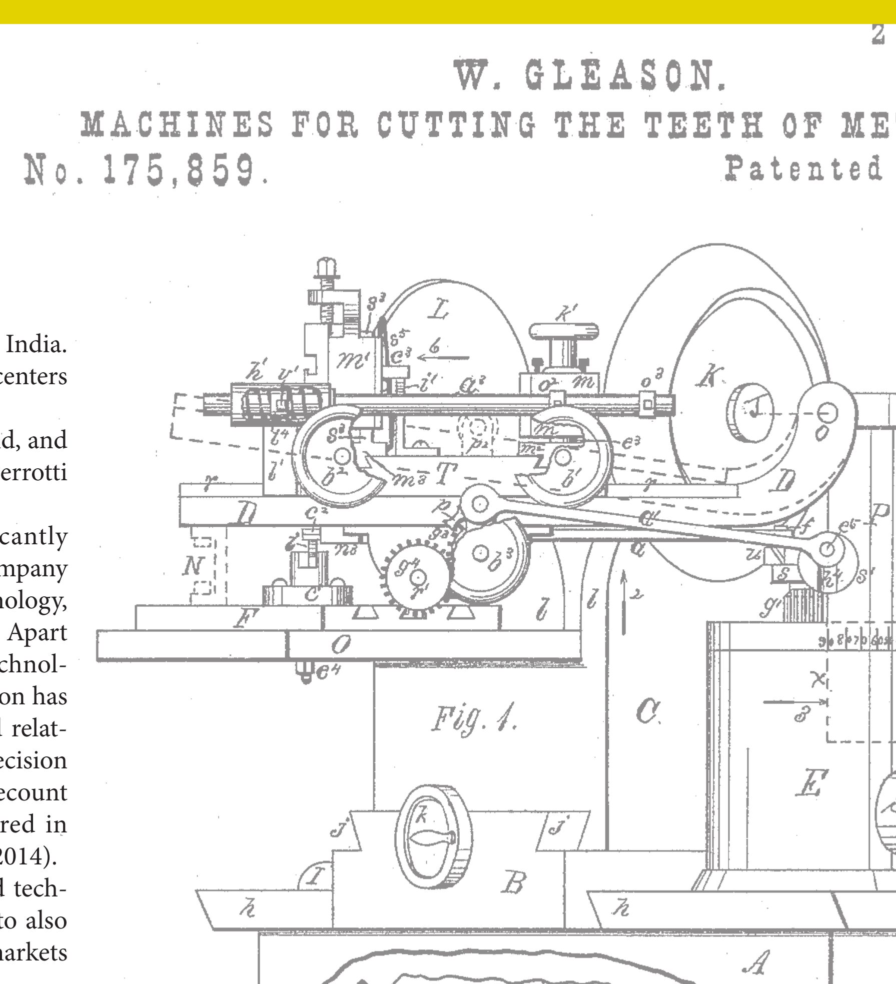
“At a very early stage, we said the world is our market,” James S. Gleason says. “As a matter of fact, my great aunt Kate was at the forefront of pushing the company, certainly into the European market, but ultimately, the world.”

Kate Gleason, daughter of the company’s founder, began working with her father at age 11, helping with the bookkeeping. After attending Cornell University and studying engineering (the first woman ever enrolled there to do so), she returned to the Gleason Works, serving as secretary-treasurer and becoming the company’s chief salesperson at age 25. She traveled unaccompanied to Europe and sold Gleason machines in England, Scotland, France and Germany. In 1917 she was the first woman elected to membership in the American Society of Mechanical Engineers.

The global focus of the company has continued throughout its history. Today, Gleason says, the company does roughly a third of its business in the United States, a third in Europe and a third in the Far East.

Of course, the global nature of the company has expanded dramatically over the past couple of decades. In 1995, Gleason Works (India) was established, and the company also acquired Carl Hurth Maschinen und Zahnradfabrik. In 1997, they acquired the assets of the Pfauter group of companies. In 2007, a factory was established in Suzhou, China, for the manufacturing of Genesis hobbers. In 2009, they added cutting tool manufacturing at Suzhou, and in 2012, a new 156,000 square foot facility was built in Suzhou to combine the machinery and cutting tool manufacturing under one roof. In 2013, they acquired Saikuni of Japan and IMS Koepfer Cutting Tools of Germany. These acquisitions greatly expanded Gleason’s global footprint in terms of manufacturing locations. Today, new Gleason machines and cutting tools are manufactured

Gleason Cutting Tools facility in Loves Park, IL.



in the USA, Germany, Switzerland, China, Japan and India. In addition, of course, there are numerous technical centers and sales offices around the world.

"We have 13 manufacturing plants around the world, and we have Gleason people in more than 25 countries," Perrotti says.

Gleason's recent acquisitions have also significantly expanded its product offerings. Whereas once the company was known mostly for its strength in bevel gear technology, now it aims to be the "Total Gear Solutions Provider." Apart from significantly expanding its cylindrical gear technology through the acquisitions mentioned above, Gleason has also added significant other gear manufacturing and related technology, including gear inspection (M&M Precision Systems acquired in 2005); expanding mandrels (Lecount acquired in 2007); plastic gears (K2 Plastics acquired in 2011); and automation (Distech Systems acquired in 2014).

"In effect, we've taken little pieces of expertise and technology and systematically added those, with an eye to also making sure that our geographic strategy of world markets was an inherent part of that," says James S. Gleason.

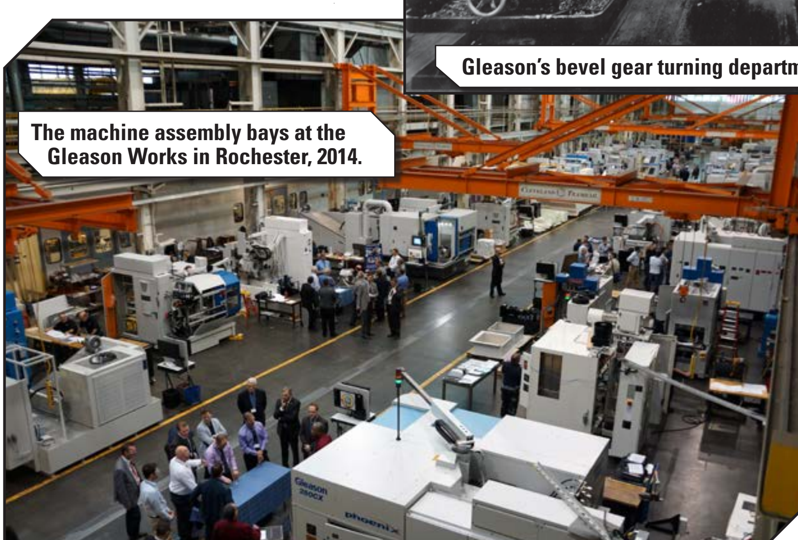
"We are always looking at opportunities which are aligned with supporting our customers and that we think are not too far from our core competencies, and that main competency is gear process knowledge," Perrotti adds.

Officially, Gleason's 150th anniversary doesn't take place until June. "We're going to have a large gala celebration here in Rochester," says Perrotti, "with a lot of our local employees, our leadership and our sales representatives from around the world."

But clearly the celebration has already begun.

"We thank all of our employees, literally the tens of thousands of employees who have worked for Gleason over the years," Perrotti says, "and we thank our customers, many of which with whom we've had relationships that go back more than a century. We're proud of our past but even more excited about our future."


Gleason's bevel gear turning department, circa 1911.


The machine assembly bays at the Gleason Works in Rochester, 2014.

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'Getting in Gear' with the Chain of Innovations

Frank Burke

At the dawn of the Industrial Revolution, so-called mechanics were tasked with devising the precise methods that would make mass production possible. The result was the first generation of machine tools, which in turn required improved tooling and production methods. The demand/response dialectic — known as the "chain of innovation" — remains operative in the present day and has in fact been especially energized by new technologies — even in traditional, mature industries.

Ring gear hobbing set-up.

In the gear making industry, the leading edge is represented by those shops involved in prototype development. One example is Delta Research Corporation of Livonia, Michigan, active since 1952 in the manufacture of prototype transmissions and gear components for the automotive, aerospace, defense, mining, and other industries. And with the acquisition of its sister company, Delta Gear, the company has combined prototyping with production capabilities and today produces over 1.5 million gears per year.

According to Tony Werschky, director of sales and partner at Delta Research, "Our primary production includes parallel access gears, including spur and helical configurations up to 30 inches; most are actually less than 20 inches. We also make spiral bevel gears up to 20 inches. We now have three facilities totaling 132,000 sq. ft., and as we've grown, we've realized that in order to achieve the highest quality standards for our customers, we would have to embrace high-precision, automated methods and develop a workforce of highly trained professionals. The fact that we can offer the services and achieve the production we do indicates that it was the right formula."

Tony Werschky, director of sales and partner at Delta Research (left), and Pete diMascio, director of Gear Technology.

Because of the company's longstanding relationships and experience in the automotive industry, Delta Research recently experienced a "chain of innovation" moment. As Pete DiMascio, director of gear technology at Delta Research, explains:

"The increased interest in both hybrid and all-electric cars has resulted in an urgent demand for a silent transmission. Transmissions have come a long way in terms of noise reduction, but the whole or partial elimination of the sounds produced by an internal combustion engine demand even quieter operation. This translates to higher precision in the gear design in order to reduce noise.

"Also, in an effort to conform to CAFE (mileage) standards set by the government, virtually every component is being reviewed in terms of weight and performance. As a result of the new requirements and technology that is available to the industry, we're currently producing gears previously undreamed of in the automobile industry."

The development process includes the processing of different grades of steel as they are tested for durability and wear. Steels include case hardened or carburized 5120, 4320, and 8620, as well as induction hardened and nitride 4140.

DiMascio comments, "When we deal with automotive prototypes, we have to be aware that we are not just manufacturing the prototype. We offer manufacturing feasibility to our customers, keeping in mind that these gears, shafts

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or assemblies will eventually be produced in high volume, once the optimum design is selected. Even though we typically produce only 20 to 50 to 100 pieces in prototype runs, our production experience has helped us and our customers develop the future manufacturing model.

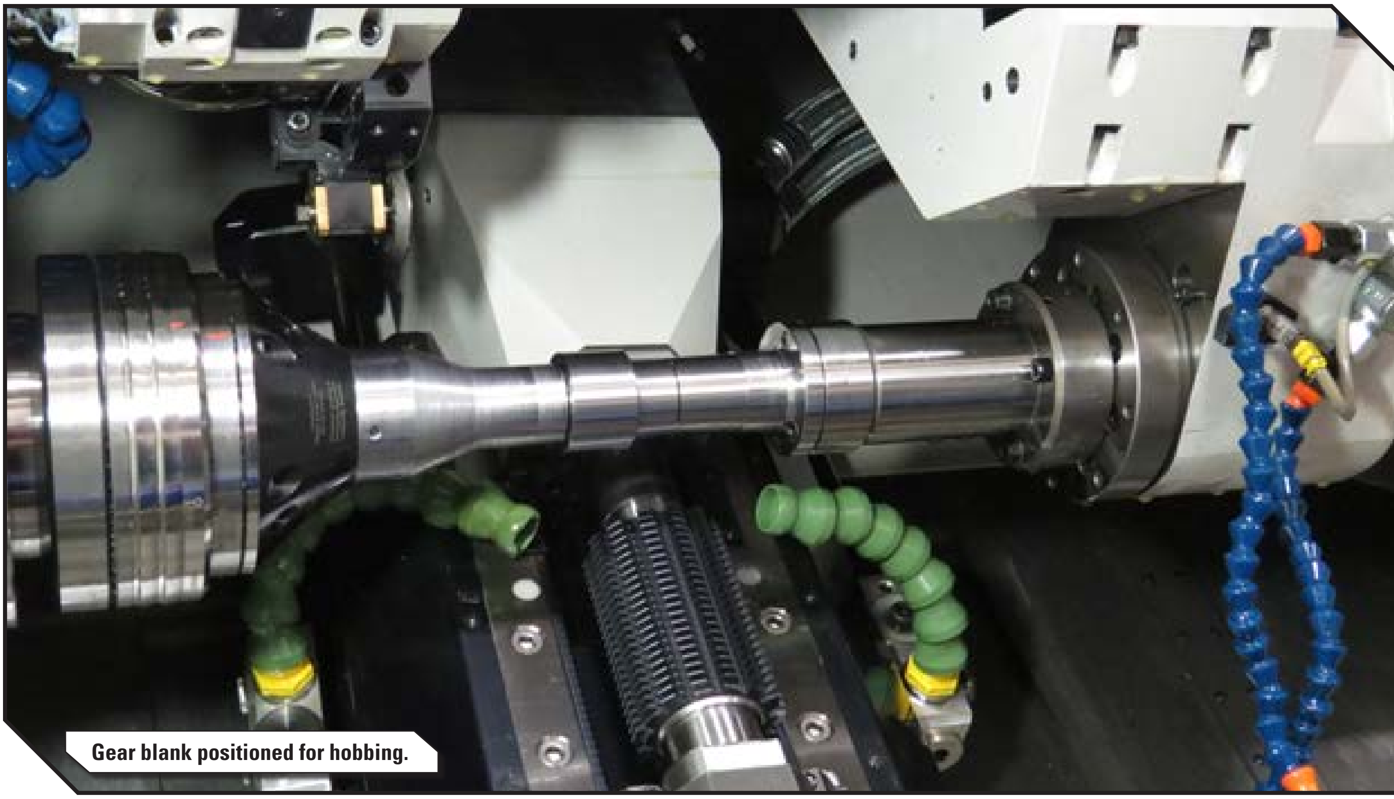
Key to the process is precision workholding, and Delta has standardized on Hainbuch precision chucks and arbors in the gear making process. Werschky recalls, “When making larger volumes of prototype gears, we could no longer indicate every piece prior to finish machining. We needed precise yet flexible part-holding. Custom tooling required us to finish the part-holding diameters and faces to highly precise and consistent tolerances; this was not optimal for us. Using the Hainbuch expandable arbors allowed us to continually produce consistent, high-precision parts without having to indicate or over-machine the finished part-holding tolerances.” DiMascio adds, “The Hainbuch chucks give us expansion capabilities up to 0.010 inch, depending on the diameter of the collet.”

The Hainbuch chucks’ Quick Change capabilities also offer significant advantages in that it is possible to change the collet size within minutes — without having to change the base chuck (which can take hours).

Typically, teeth are roughed out with lower-cost tooling but finished with high precision grinding up to, in some cases, .00004 inch. “Hard-finished teeth at that degree of precision haven’t previously been used in automotive transmissions,” Werschky says, “but the combination of hardened materials, precision, and fine surface finish not only reduces noise but results in longer gear life.” The change to precision workholding has resulted in other improvements as well, DiMascio explains.

“We have developed a tooling library to optimize the Hainbuch advantage.

Ring gears before and after machining.



Gear blank positioned for hobbing.

These chucks work extremely well with robot and/or gantry load/unload systems, and have proven invaluable to our automated processes. Also, we've saved tens of thousands of dollars in tooling costs since we've equipped all of our gear making machines with Hainbuch chucks."

For Hainbuch's Larry McMillan, "Precision machining, especially in automated systems, begins with workholding, and the Hainbuch expanding arbor design offers several significant advantages. It expands to plus or minus 250 microns (.010 inch); it's available in different sizes, so it's both easy and economical for shops to standardize; and it eliminates additional support operations.

"If there is such a thing, I would consider Delta Research a 'gear boutique.' They're defining the solutions that will ultimately become standards for the automotive industry."

Werschky agrees. "Today, everyone is operating smarter. For test purposes, the automotive industry will ask us to do 100 samples — rather than 20 — and finish them at different stages — providing them with a library of samples in which to test." As Delta's DiMascio observes, "When changes have to be made, we can do it in real time. And the ability to meet that demand is what makes Delta Research an excellent partner for our customers — and the latest link in the chain of innovation."

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Hainbuch system showing collet prior to part loading.

Frank Burke has over 35 years of experience in the machine tool and allied industries. He started his career with Cincinnati Milacron and subsequently worked with White-Sundstrand Machine Tool Corp. Burke has twice presented to Canada's Advanced Technology Think Tank and has written extensively on technology and communications. He holds an MBA from The Wharton School of the University of Pennsylvania.

Non-Involute Gearing, Function and Manufacturing Compared to Established Gear Designs

Dr. Hermann J. Stadtfeld and Jasmin K. Saewe

Introduction

The standard profile form in cylindrical gears is an involute. Involutes are generated with a trapezoidal rack — the basis for easy and production-stable manufacturing (Fig. 1). However, the resulting involute shape not only fulfills the law of gearing for a smooth transmission of rotation and torque; it also presents the most robust mathematical profile function regarding center distance changes and other misalignments. Involutes can be modified with a profile shift in order to avoid undercut and to provide a strength balance between pinion and gear. The profile shift can also be used to accommodate certain center distances that are considerably afar from the theoretical center distance for a standard gearset. Involute gearing has line contact between the two mating members. Under load, the contact lines change to elliptical contact areas.

The elasto-hydrodynamic of involute gears is well known and easily optimized. The pitch line (pitch point in Fig. 2) separates the addendum and the dedendum of the tooth profiles. The sliding and rolling velocities move the profile contact from the top of the gear tooth to the pitch point. The direction of the sliding velocity changes at the pitch point but the rolling velocity direction remains constant. The sliding velocity directional change at the pitch point causes a zero sliding velocity condition in an infinitesimally small area "around" the pitch point. In other words, only a relative rolling without any sliding exists between the two mating profiles.

The absence of sliding presents a critical caused by the deteriorating hydrodynamic conditions around the pitch point, or pitch line. High load and low speed reduce the ability of the lubricant

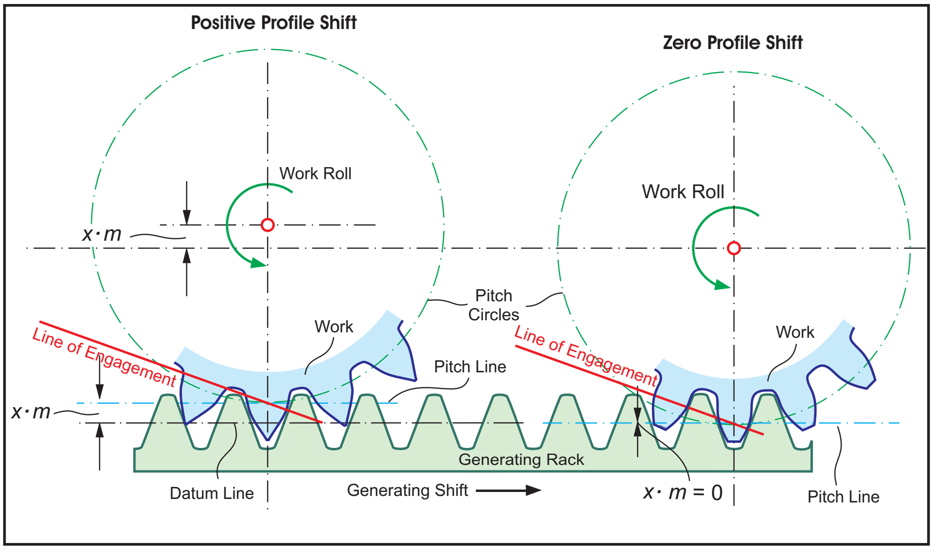

Figure 1 **Generating principle of involute gearing.**

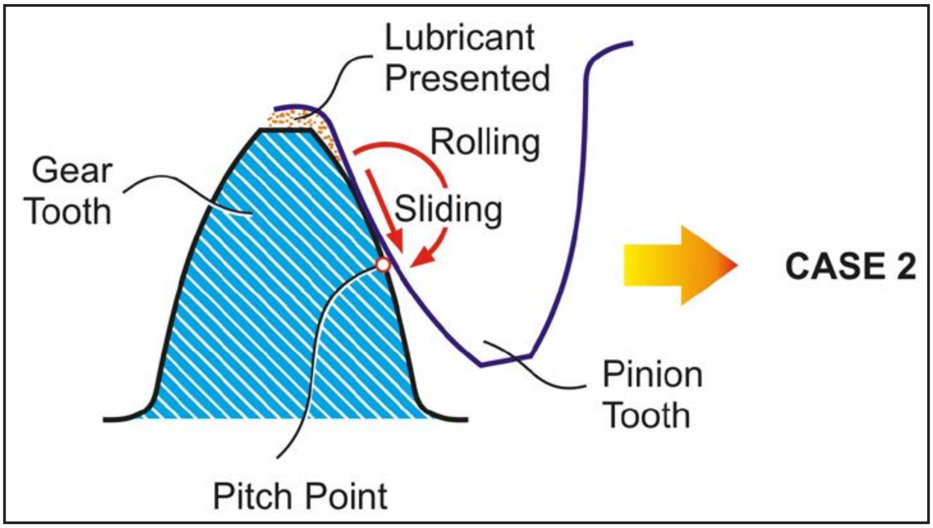

Figure 2 **Profile sliding and rolling of involute profiles.**

This paper was first presented at the Gleason Corp-hosted 5th (2014) U.S./ WZL Gear Conference.

to maintain a surface separating film. Good gear design and modern, high-performance oils can eliminate this pitch line phenomenon (Ref. 1).

Scientists and inventors frequently introduce new, non-involute gear profiles. The major target of those profile or tooth forms is the reduction of the relative curvature between the two contacting flanks in every roll position. Many of the proposed systems seem to have a close relationship to the cycloidal tooth profile as it is used in clocks and watches — or to the Wildhaber-Novikov design, first introduced by Ernest Wildhaber in 1910.

The main argument — often quoted as explanation — as to why those gear types have not been discussed and examined much earlier is the fact that current computation technology and mechanical machine tools of the past were incapable of utilizing both the complex tools as well as the complicated machine motions needed in order to create the non-involute profiles.

This paper discusses the proposed non-involute and involute-related profiles with their advantages and disadvantages. The criteria of the discussion are:

- Design calculation
- Analysis and optimization possibility
- Ease of tool manufacturing
- Accuracy of tool geometry
- Production-stable manufacturing
- Robust operating performance

After an analysis of alternative cylindrical gear tooth profiles, some new bevel and hypoid gear geometries that have been proposed during the past decade are discussed as possible replacements for the traditional face hobbing and face milling systems.

Involute-based cylindrical gears — as well as bevel and hypoid gears — went through a multiplication of their power density during the past 20 years. In order to create a fair discussion with objective comparisons, the last part of this paper is devoted to present the latest advancements of "traditional" involute gearing using the example of asymmetric cylindrical gear designs.

Cycloidal gears. Cycloidal gearing has been described as center distance maintaining. The S-shaped profile of the generating rack teeth will form S-shaped teeth and generate a force in the center distance direction in order to move the meshing gears to the correct center distance location (utilizing the axes play of the gears in watches).

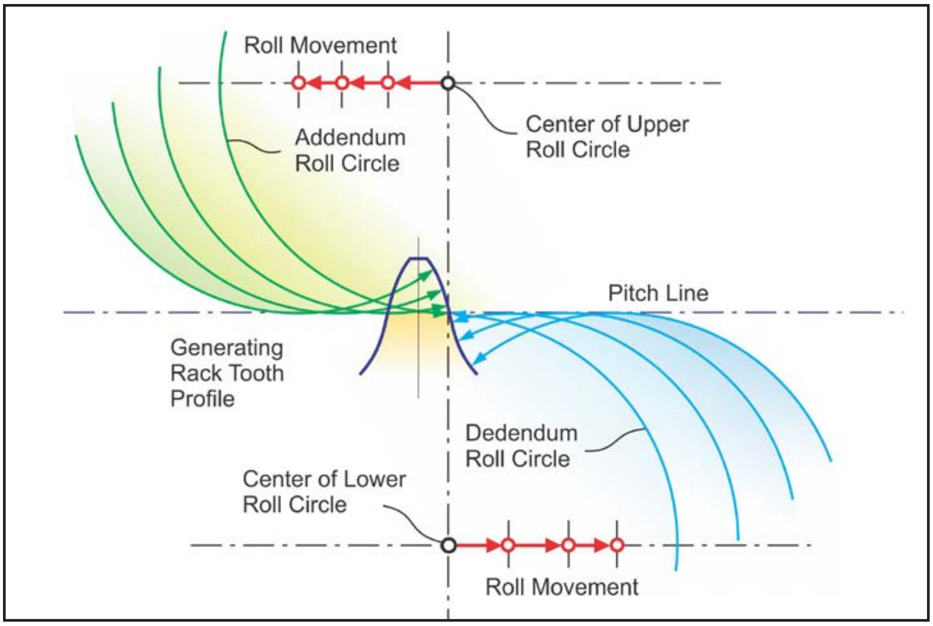

Figure 3 Cycloidal generating rack profile development.

A development of a cycloidal generating rack tooth profile is shown in Figure 3. The reference line or pitch line separates the addendum and dedendum of the tooth. One roll circle, that is located above the pitch line, rolls to the left and generates — with one fixed point — the addendum of the right flank. A second roll circle rolls on the pitch line from below and generates the dedendum of the right flank (Fig. 3). The two profile sections meet at the pitch line, where both cycloids have an infinitely high curvature. The cycloidal tooth profile is "S-shaped," which achieves in the rolling interaction between mating flanks a large contact area on the flank surfaces. The convex addendum has constant rolling contact with the concave dedendum. Surface stress is greatly reduced compared to involute gears due to this arrangement, while the root bending stress can potentially be somewhat lower because of the concave dedendum profile, which blends without curvature reversal into the root fillet radius.

Cycloidal gear profiles can be generated with generating rack tooth profiles, like the one shown in Figure 3.Those profiles must be calculated and manufactured dependent upon the individual gear pair. Standard generating profiles — like the straight line in involute gearing — are not possible. Another possible process to manufacture cycloidal tooth profiles uses a pointed tool, which follows the cycloidal profile, guided either by cams or interpolating axes motions.

The tools to manufacture cycloidal gears are either special and, therefore, expensive, or the manufacturing process is very slow. The center distance-maintaining feature is only of interest if the axes' position can float. In regular power transmissions, where the center distance is rigid, but might vary from the theoretical center distance, motion error and vibration are generated.

Wildhaber-Novikov gears. The Swiss-born Ernest Wildhaber invented in 1926, shortly after his immigration to the United States and his employment as Gleason scientist, a helical gear profile which was cut with a circular arc profile rack cutter (Ref. 2). Thirty years later, Mikhail Novikov invented in Russia a similar system which featured tooth profiles that are circular in the transverse plane (Ref. 3). Because of the similarity of the two independent developments, cylindrical gears with circular tooth profile have been called Wildhaber-Novikov gears. Not only are the tooth profiles circular, but the slots of the gear have the appearance of half-circles and remind in its shape of a sprocket. Figure 4 reveals that the gear slots have profiles with two equal radii, connected with a smaller radius in the root, which blends with the flank radii. The pinion profile radii are smaller than the profile radii of the gear, and are connected at the top with a straight line.

In order to transmit a constant ratio, the contacting point between the two circular flank surfaces must be kept at the same profile location, which is preferably a point at mid-profile height with a desirable pressure angle. This point is called the "profile reference point" (Fig. 4). The different radii of pinion and gear flanks (p_1 and p_2) have to be oriented normal to the profile reference point, but with a larger gear radius value and a smaller pinion radius value (Fig. 4, left). Keeping the contacting point in the same initial profile location (Fig. 4, left) during an incremental pinion (and gear) rotation can only be realized with the introduction of a helix angle; the helix angle must be defined such that for a certain pinion rotation the profile rotates back to the initial position. Subsequently, the gear profile also has to rotate back into the initial position by an angular amount equal to the angle of the pinion rotation, divided by the ratio between the two members.

The method of corrective rotation of the tooth profile in order to transmit a constant ratio is visualized (Fig. 5). The first point of contact between the meshing teeth is shown in the upper graphic as the connecting point of R_1 and R_2. As the gears rotate to an advanced angular position, the radii R_3 and R_4 would transmit a different ratio because the vector length—as well as the normal vector direction—changed. The cylinder in the lower graphic demonstrates that if a flank line with a particular helix angle is used that rotates the contacting point for incremental rotations into the horizontal axis connecting plane, then contact movement (Fig. 6) can be expected. The ratio will remain constant in this case because the radii—and the normal vectors in the horizontal plane along the reference cylinders—remain constant.

A simple example*: *A pitch angle of 24° and a contact ratio of 1.0. If the pinion is rotated by 24° and the initial contact at the profile reference point is located at the front face of the teeth, then the back rotation of the profile has to occur as the contact moves along the face width to the back face of the teeth.

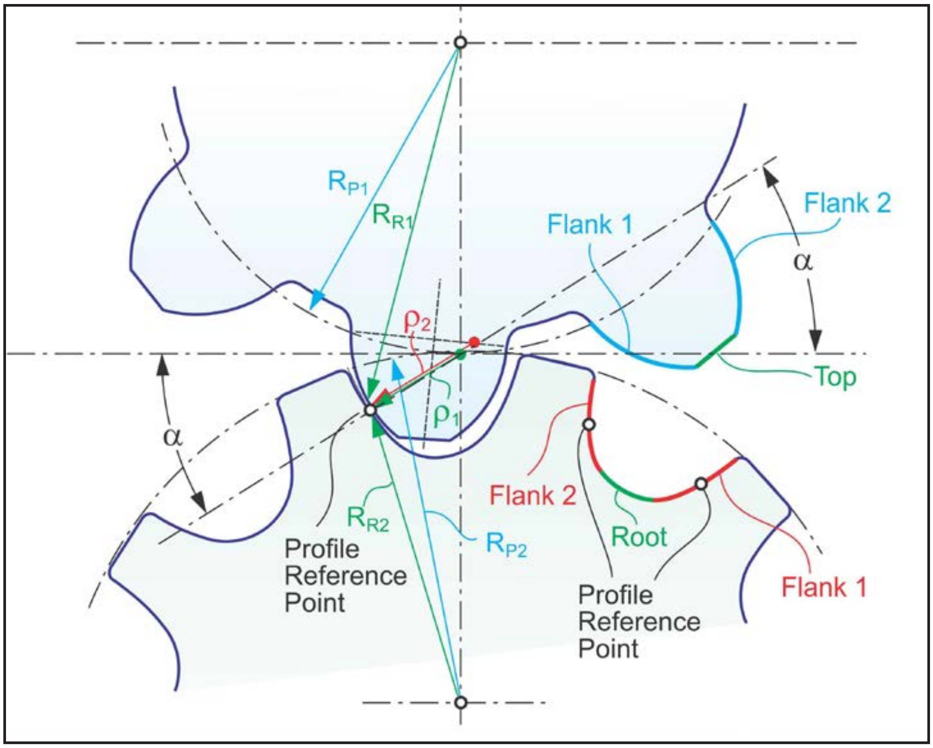

Figure 4 Wildhaber-Novikov tooth profile design.

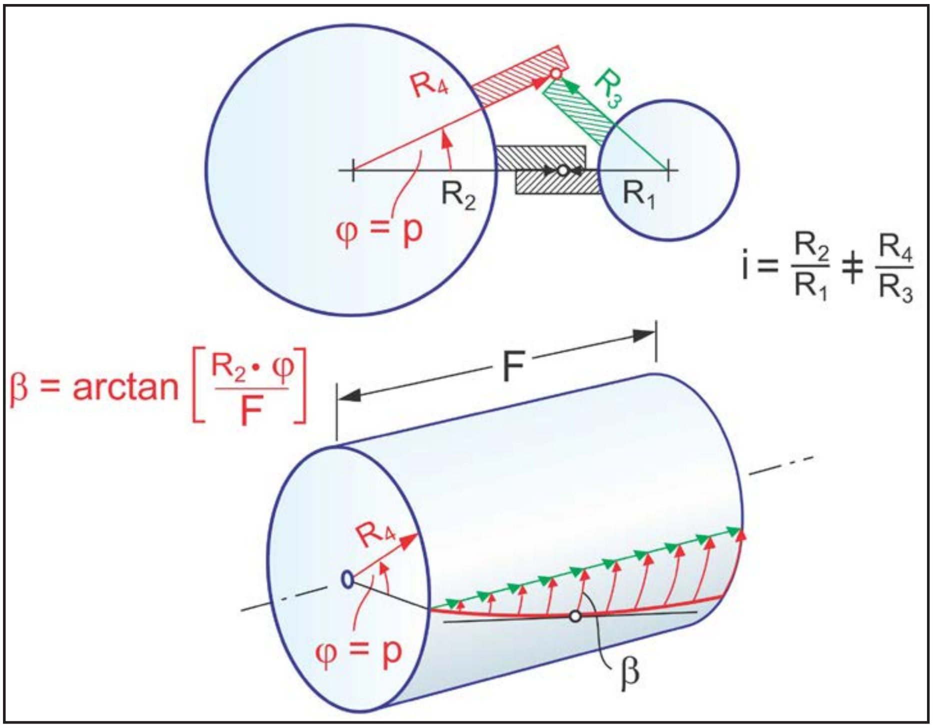

Figure 5 Line of engagement is kept at centerline connecting plane.

The helix angle at the reference radius is calculated: $ß_R = \arctan(R_R \cdot P/F)$

Example:

Given:

Ratio $i=2$
Face width $F=50$ mm
Pinion pitch radius $R_{P1}=38$ mm
Pinion reference radius $R_{R1}=41$ mm
Pinion angular pitch $P_1=24°$
Gear pitch radius $R_{P2}=76$ mm
Gear reference radius $R_{R2}=73$ mm
Gear angular pitch $P_1=12°$
Wanted helix angle along pitch line in case of face contact ratio = 1.0:
Pinion helix angle at Ref. rad.: $ß_{R1} = \arctan(41 \cdot 24°/180° \cdot \pi/50) = 18.95°$
Pinion helix angle at pitch rad.: $ß_1 = \arctan(\tan(18.95°)/41 \cdot 38) = 17.66°$
Gear helix angle at Ref. radius: $ß_{R2} = \arctan(73 \cdot 12°/180° \cdot \pi/50) = 17.00°$
Gear helix angle at pitch radius:
$ß_2 = \arctan(\tan(17.00)/73 \cdot 76) = 17.66°$

The example shows that a particular Wildhaber-Novikov gear design requires a particular helix angle that depends on the desired contact ratio and the face width. The explanation and the calculation also show that the transverse contact ratio of Wildhaber-Novikov gears is zero and the modified contact ratio is equal to the face contact ratio.

The advantages of circular tooth profile are the large contact area. Russian studies from the 1950s and 1960s report about three-to-five times the load-carrying capacity, without detrimental pitting or wear. The reports also state that the circular wedge geometry between the contacting circles that moves along the face width, pumps the lubricant into the contact area and generates oil film thicknesses up to 10 times that of involute gearing, which should also improve efficiency (Chironis). Disadvantages include the more complicated rack tool geometry, the high influence of the helix angle to the smoothness of transmission, as well as the sensitivity of center distance changes. The helix angle in Wildhaber-Novikov gears is not a design freedom like in involute gearing, but is exactly given for each particular design. The operating vibration and noise of Wildhaber-Novikov gears has been reported to be higher than that of comparable involute gears.

The original Wildhaber-Novikov tooth profiles are basically half-circles, which call for a certain pressure angle change between top and root. The end of the internal circle towards the top and the external circle towards the root are given by a pressure angle that drops below 5°.

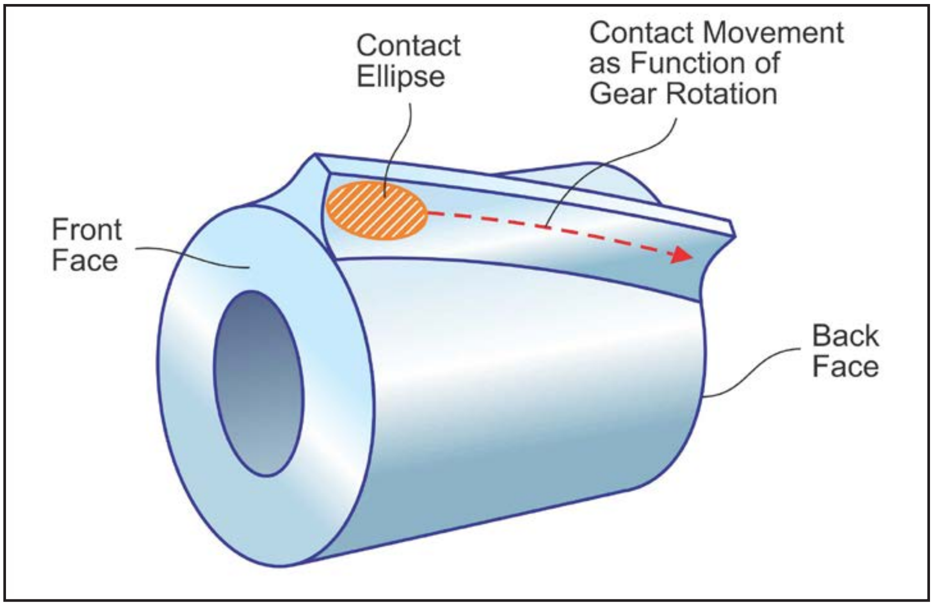

Figure 6 Contact movement maintains constant ratio.

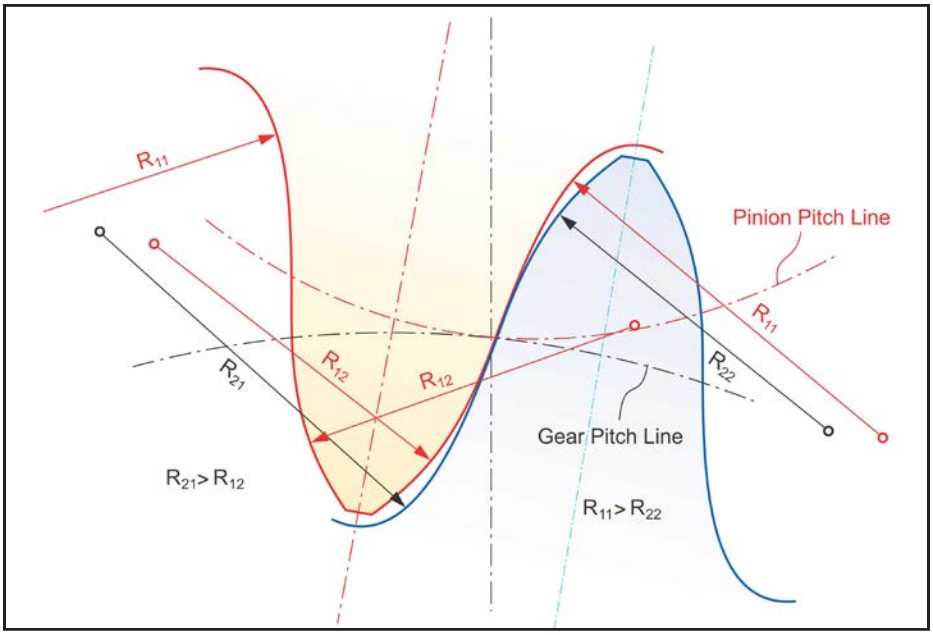

Figure 7 Extended version of Wildhaber-Novikov gears.

Because of this constraint, Wilhaber-Novikov teeth consist of less than a half-circle, which results in tooth depths that are about 1.2 times the module, compared to 2.2 times the module for standard involute gears. The pressure angle change along the profile-per-unit-length in case of less than a half-circle is a multiple of the involute curvature change. This is an additional reason to the non-involute profile function for the high sensitivity to center distance changes of pure circular profile forms. The low-profile teeth show a very high stiffness, which often is falsely judged as an advantage and a contributor to high power density. More optimal is high stiffness at the root of the teeth and elasticity from mid-dedendum to the tip. The elasticity contributes to a reduced entrance impact during meshing at different loads and improves the load sharing between consecutive tooth pairs. In order to account for those facts, Wildhaber, as well as Novikov, mentioned in their teachings the possibility to extend their ideas to double-circular profiles that consist of a convex circle at the addendum and a concave circle at the dedendum (Fig. 7).

All variations of Wildhaber-Novikov gears can be manufactured by the hobbing and shaping processes. Depending upon whether the tooth normal profile or the tooth transverse profile should be of circular shape, the cutter rack profile must consist of modified curves (no circles) to accommodate for the generating motion between cutter and work. Also, the use of circular-shaped rack cutters is mentioned in the literature, which would of course generate complex non-circular profile curves.

Profile development. Shigeyoshi Nagata, a professor at the University of Tokyo published a paper in 1981 where he discusses a proposed improvement of the extended Wildhaber-Novikov profile design (Ref. 4). Nagata bases the profile definitions not on the gear teeth, but on the rack cutter or reference profile. The basic construction of this profile is represented in Figure 8. The new profile has a circular addendum and a dedendum that consists of two involutes that blend at mid-dedendum. The upper dedendum is developed with a cord—unrolled from the upper base circle—where the lower dedendum is developed with a cord that unrolls from the lower base circle. The addendum is circular (Fig. 8) and has a nominal pressure angle at mid-addendum.

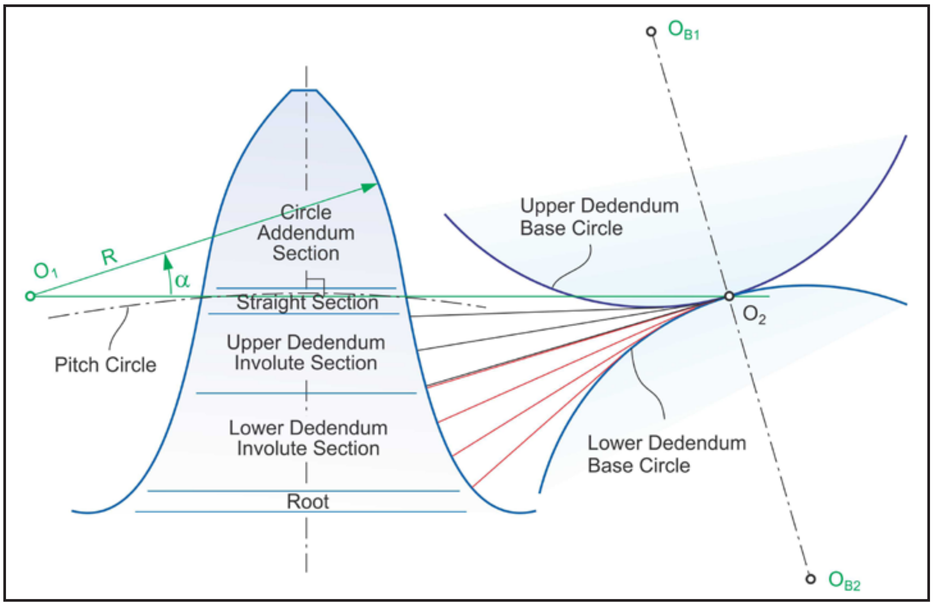

Figure 8 Wildhaber-Novikov-Nagata profile construction.

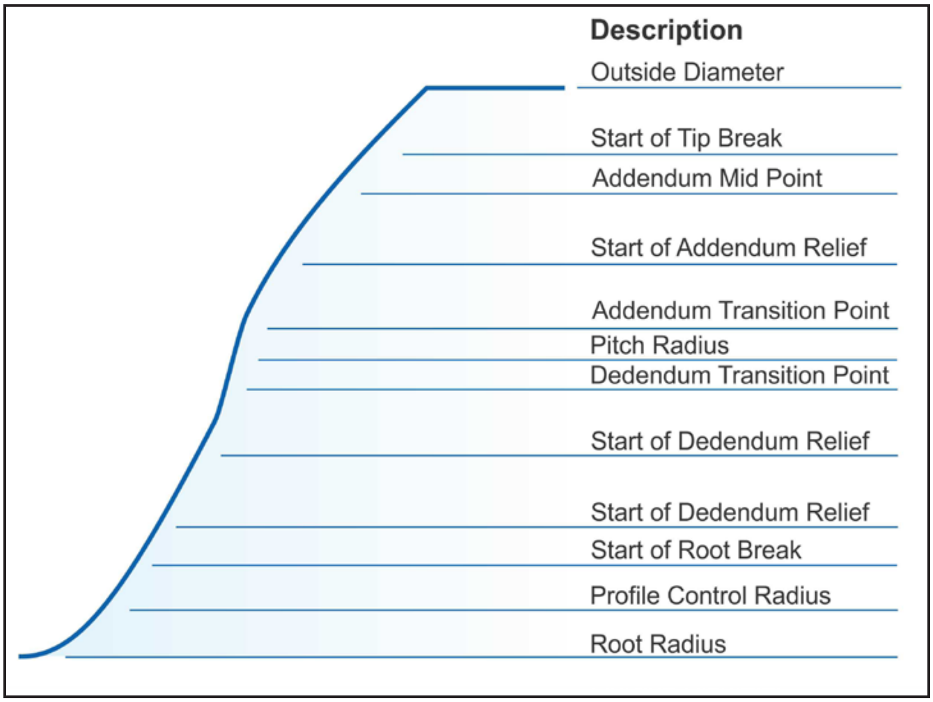

Figure 9 Convoloid tooth profile.

Nagata shows in a theoretical evaluation a significant reduction in center distance sensitivity of the improved profile combination of circular and involute elements. In a following study, Nagata tested a variety of Wildhaber-Novikov-Nagata gears and published the results with recommendations for optimal parameters in 1985 (Nagata 85). The manufacture of Wildhaber-Novikov-Nagata gears is possible by hobbing and shaping. All common hard-finishing methods can also be applied if the tool profile is formed accordingly. Like in standard Wildhaber-Novikov gears, the helix angle is required and differs depending on the individual gear design.

Convoloid gearing. Bernard Berlinger and John Colbourne introduced in a paper, published in 2011, a tooth form called Convoloid (Ref. 5). The new tooth form appears optically very similar to the Wilhaber-Novikov-Nagata development (Fig. 9). The addendum has a convex shape, while the dedendum is concave. The transition zone at the pitch point seems to be "S-shaped" rather than the straight section of Nagata's development. The authors report that the tooth profiles are computer calculated as a point cloud for each application case individually.

One interesting conclusion of Berlinger's and Colbourne's findings is the fact that while involute gearing fit well with traditional, mechanical gear manufacturing machines, it is outdated for today's engineering and manufacturing environment. Test rig investigations of Convoloid gears resulted in 20%-35% increased torque levels vs. involute gearing. The center distance insensitivity of involute gears seems not to be given, but the inventors state that the Convoloid gears can withstand the customary deflections given in modern gearboxes.

An interesting aspect of Convoloid gears is that the tooth contact can move from root to top while maintaining the correct ratio. This makes Convoloid gears independent from the helix angle and allows a choice of suitable helix angles, depending on gearbox application requirements. The Convoloid profile of Figure 9 refers to the final teeth, not to the rack profile. In order to establish the rack cutter profile, the kinematic relationships, e.g., of a hobbing process, have to be employed to calculate a point-based cutting edge definition.

S-shaped tool profile for spiral bevel gear cutting. Stepan Lunin discussed a Wildhaber-Novikov-style profile for a bevel gear cutting tool in a paper published in 2001 (Ref. 6). The profile consists of radii and straight lines (Fig. 10). The pitch line of spiral bevel gears is in all cases of non-miter gears located towards the pinion root (positive profile shift) which will create profile sliding at the location of the transition wave. Profile sliding during the generating process will eliminate or mutilate the transition wave, which makes the intention of the mid-section of the proposed profile questionable.

The goal of using such a profile might be the reduction of unit surface pressure with an increase of power density. This could be accomplished with the extended Wildhaber-Novikov profile that would also eliminate the complicated tool mid-section, which is not believed to serve any practical purpose. The paper doesn't mention the relationship between profile and spiral angle. Because of the circular profile sections, it is assumed that the tool profile in Figure 10 requires — just as with the Wildhaber-Novikov gears — a particular spiral angle in order to maintain the correct transmission ratio during the meshing of the mating members. This will make the gearsets generated by the tool profile in Figure 10 sensitive to housing tolerances and deflections.

Toroidal drive. The inventor M.R. Kuehnle developed the idea of a compact and high-power- density, high-reduction planetary unit. The "heart" of the unit is a toroid which consists of a mounted upper and a lower "half-toroid" (Figure 11 shows the upper-half of the toroid ring gear). The toroid has internal spherical threads that are the grooves for balls that connect the toroid with a sun gear via planets and planet carrier. The arrangement between center unit (sun gear worm), planets and planet carrier motion is shown in Figure 12. The sun gear unit is a multi-start, spherical worm (similar to a throated worm) (Ref. 7).

The toroid-shaped unit is normally used as the transmission housing. If the sun unit is used as an input shaft, then the planets will rotate along the grooves of the internal toroidal threads that initiate a slow cage rotation (cage as output shaft). The principle of planet and cage rotation is shown in Figure 13. The inventive properties of the toroidal gearbox are high reduction with compact gearbox (high power density) and low wear.

In order to streamline the design of the toroidal gearbox and verify the attributes of its functionality with scientific data, the inventor consulted the Institute of Machine Elements of the Technical University of Aachen. The scientists and engineers at the institute brought all components to a high level of mechanical design and manufacturability.

Kuehnle stated his toroidal transmission will out-perform worm gear, planetary and cycloidal transmissions for medium to high ratios. Center worm and planet units seem straightforward in manufacturing and assembly. However, the spiral grooves in the split, internal toroidal gear components are difficult to manufacture and will, post-assembly, present a disturbance in the smooth rolling of the balls at the fitting seam.

Globoidal gearing. Yakov Fleytman in 1999 invented a tooth form that mostly applies to hypoid gears. Fleytman

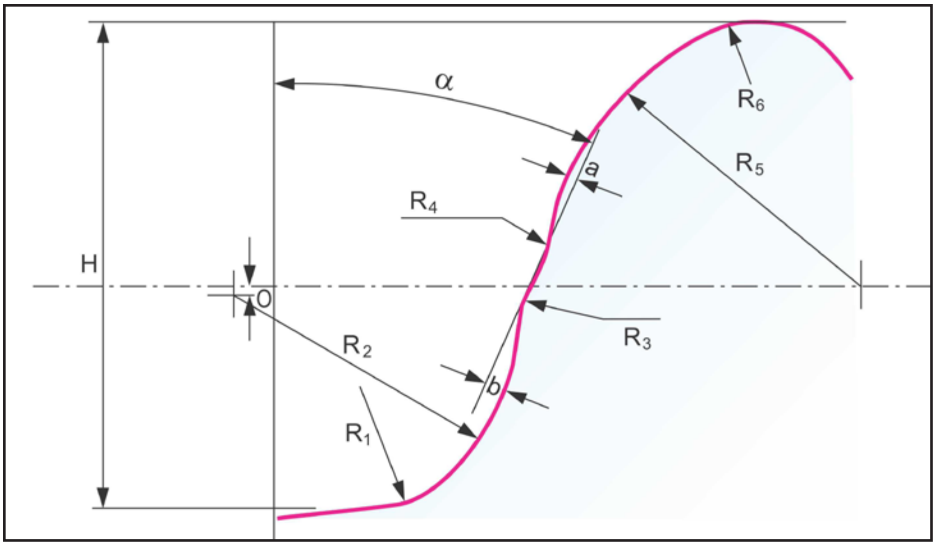

Figure 10 S-shaped cutting blade profile for spiral bevel gears.

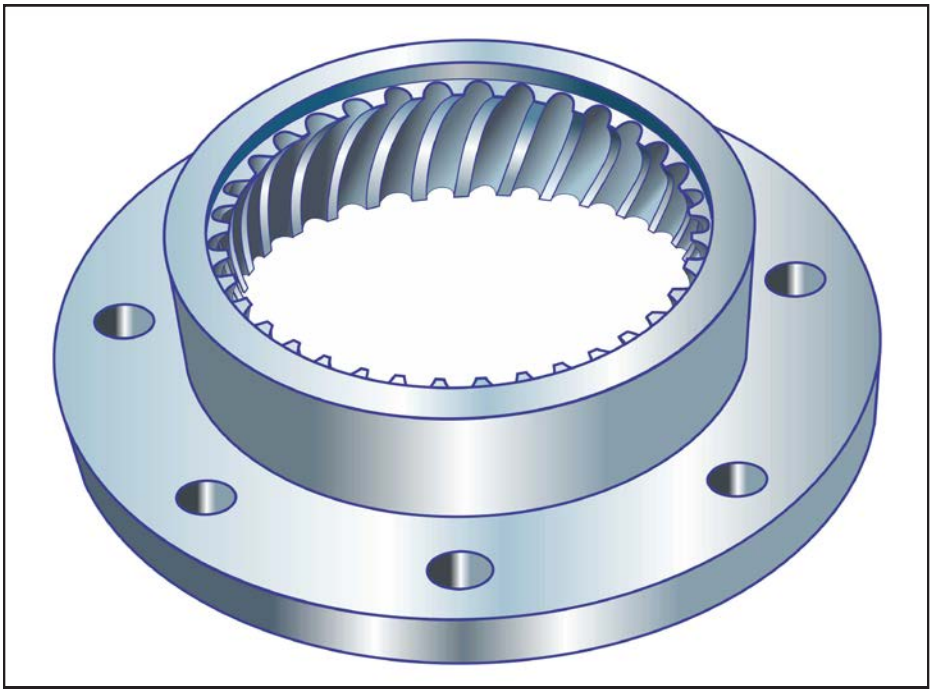

Figure 11 Upper-half of the toroidal "ring gear."

claims the strength of his new hypoid gear design is three times that of traditional hypoid gears (Ref. 8). It seems that the creation of the gear tooth was done by using simple straight or twisted surfaces. The pinion flank surfaces might have been generated with simulation software, similar to *Vericut*. The gear can be defined as a tool and the axis positions of pinion and gear in a given hypoid gear box can be used as tool and work position in order to simulate the generating process of the pinion flank surfaces. Fleytman uses the kinematic coupling condition to generate the pinion teeth where the gear is used as a generating element. Flank profile and tooth lead form seem different to common bevel and hypoid gears because no customary profile requirements are mentioned and the equivalent pitch elements are not related to the transmission ratio (Fig. 14).

Globoidal gears cannot be manufactured using traditional manufacturing methods. Prototypes have been manufactured with 5-axis machines, but no reports of evaluation results have become public.

Cosine gears. HPG in the Netherlands, a company that developed 5-axis machining technologies for the soft and hard manufacture of bevel gears, introduced in 2007 a bevel gear with a sinusoidally formed flank line with the claim of 40% increased load-carrying capacity (Ref. 9). The teeth of that system have some similarity with the "herringbone" teeth in cylindrical gearing. The observer of the photographs in Figure 15 notices large variations of the tooth thickness and a curvature inflection point at each side of the center. It appears that the reason why the inventor anticipates a higher strength could be given by the curved profile in the center of the face width. The reversal with a lowering of the spiral angle towards the ends of the teeth seems unjustified and results basically in teeth with no spiral angle — which gives them similar properties to ZEROL bevel gears. Real herringbone gears are two connected helical gears with opposite helix angle directions. The advantage is a complete cancellation of all axial forces, combined with a very smooth mesh characteristic in their operation. The two opposing sections of herringbone gears are separated by a groove in order to eliminate the singularity at the point of helix angle change. This common herringbone gear design takes advantage of the smooth meshing and the high strength of helical gears without the disadvantage of rolling disturbance in the transition area between right- and left-hand sections.

It appears that the developers of the gear in Figure 15 supposed that the separation groove of herringbone gears is strictly the result of a manufacturing limitation of the traditional manufacturing methods and believed that the curved flank line at the center of the face width would increase the strength. The additional reversal of the flank line curvature

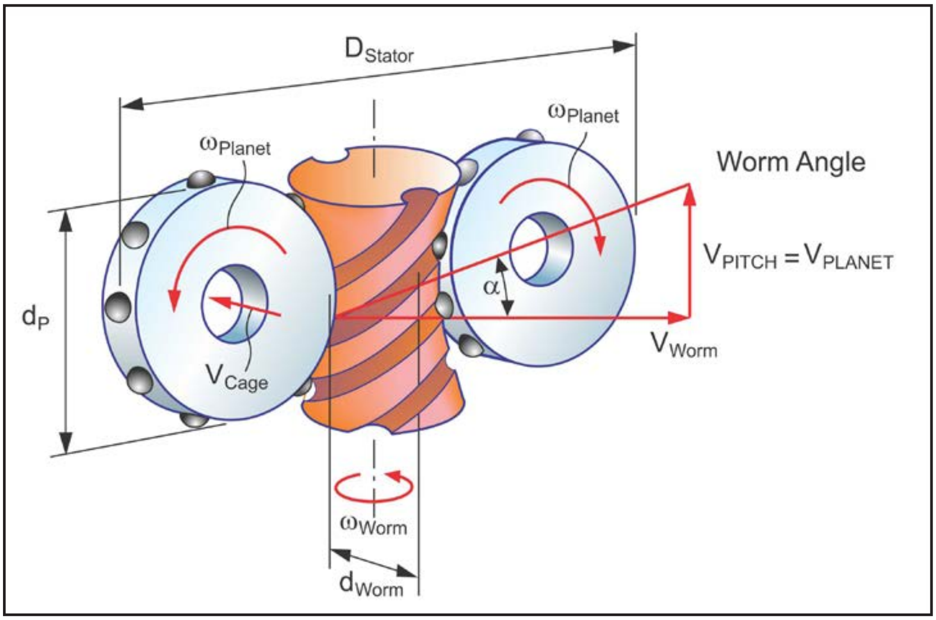

Figure 12 Worm (sun gear), planets and planet carrier cage motion.

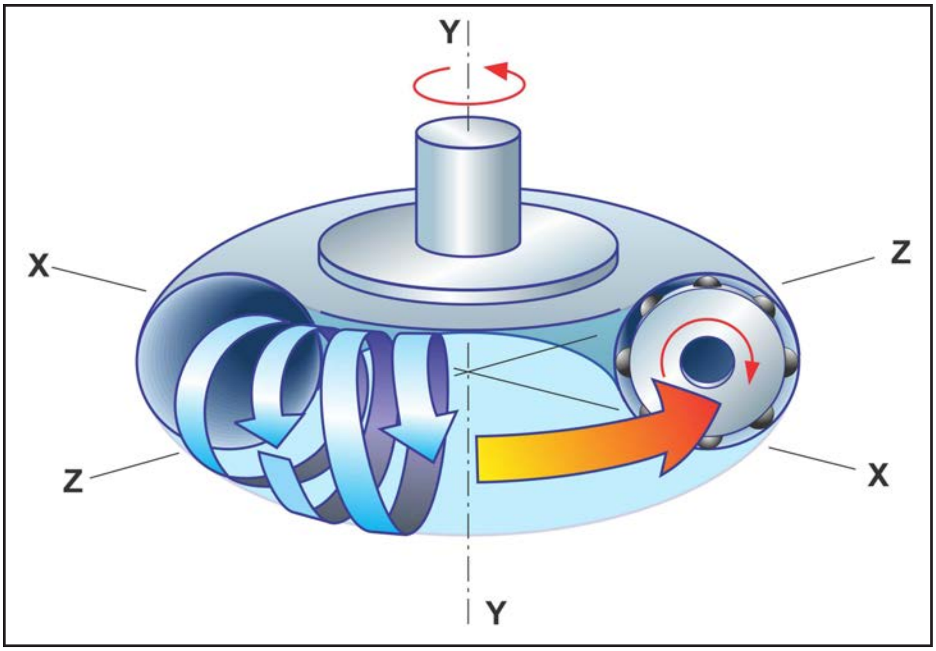

Figure 13 Toroidal, spiral motion and cage rotation.

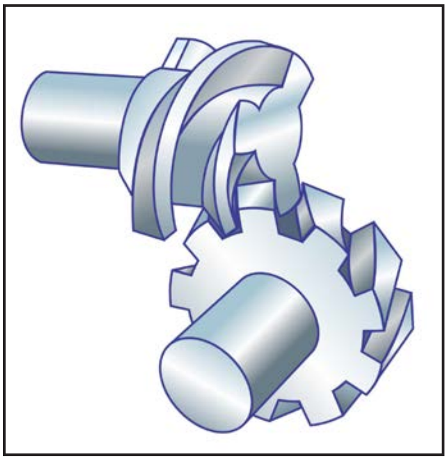

Figure 14 Globoidal, angular gear pair.

towards the end of the teeth is probably also only done because it wouldn't be possible in traditional manufacturing.

Meshing conditions of bevel gears without a spiral angle are best with straight bevel gears and deteriorate with ZEROL bevel gears. The smooth screwing into mesh like in spiral bevel gearing is not possible with the cosine teeth in Figure 15. The face contact ratio is slightly above zero and will not contribute to improved strength. The cosine-shaped tooth form prevents elastic deformation under load, which in spiral bevel gears is used to achieve a smooth meshing and to increase the load-sharing between consecutive tooth pairs. Hartmuth Müller published theoretical investigation results of bevel gears with sinusoidally shaped flank lines and concluded that their rolling performance — as well as their strength properties — is far below any average spiral bevel gear set (Ref. 10).

Asymmetric tooth gears. The two flank profiles of involute gearing are generally developed from a common base circle. In this case both flank profiles have the same pressure angle and are mirror images from each other. With the development of hypoid gears, Ernest Wildhaber in 1930 developed the asymmetric tooth profile (Ref. 11). Wildhaber's development eliminated the conflict that the path of engagement of the drive-side flanks and the coast-side flanks was not equal if hypoid gears were manufactured with equal pressure angles.

Today, asymmetric spur gear profiles that have been proposed for more than 20 years are discussed and applied to practical applications. The goal is not to extend the angle of engagement, as it was for Wildhaber, on the drive-side of hypoid gears. Extending the active line of engagement would require a reduction of the pressure angle. Alfonso Fuentes et al. (Ref. 11) proved in an analytic comparison that especially flank surface stress is reduced on the driving side by increasing the pressure angle. A tooth mesh with asymmetric pressure angles is shown in Figure 16. Alexander Kapelevich promoted asymmetric cylindrical gears for many years (Ref. 12) and wrote calculation software that allows design calculations for optimized geometries.

The problem is not only the manufacturing of asymmetric spur gears. It seems to be the fact that additional optimizations — like circular top relief — have to be applied in order to make the improvement visible. Fuentes developed first an optimal top relief for a baseline design and then converted the gearset to asymmetric profile. However, he created comparable gearsets with symmetric and asymmetric profile and was able to achieve contact stress reductions in the vicinity of 10%.

Several bevel gear manufacturers accepted the publications' findings and research in asymmetric spur gears and applied moderate amounts (up to 4°) of asymmetric pressure angles to their traditionally symmetric spiral bevel gears in order to improve the load-carrying capacity of mostly unidirectional-used angular transmissions. The positive experiences with spiral bevel gears allow the conclusion that, not only spur gears, but also helical gears would benefit from asymmetric profiles. Because of the individually ground cutting blade profiles, this technology seems to gain more acceptance in bevel gearing. For cylindrical gears the introduction of asymmetric profiles would require a departure from standard hobs and may require additional profile corrections in order to work out the full advantages of asymmetric gearing, which seems to be a large step and thus precludes ready acceptance in the industry.

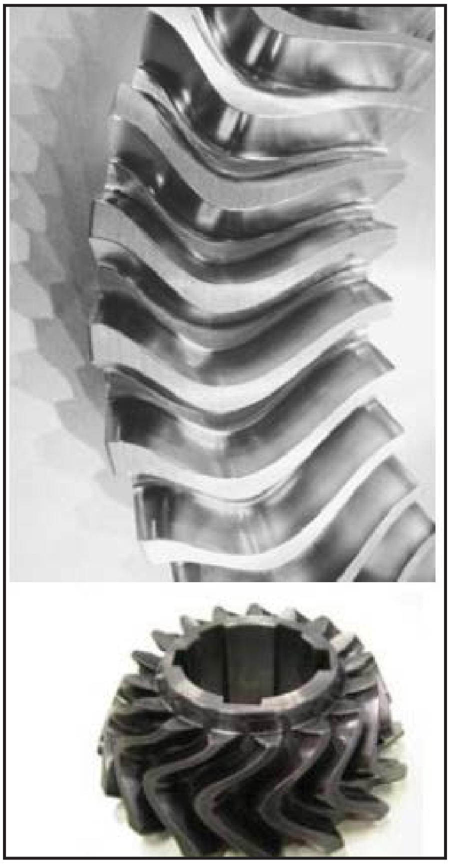

Figure 15 Ring gear and pinion with cosine teeth (Source: hpg-nl.com).

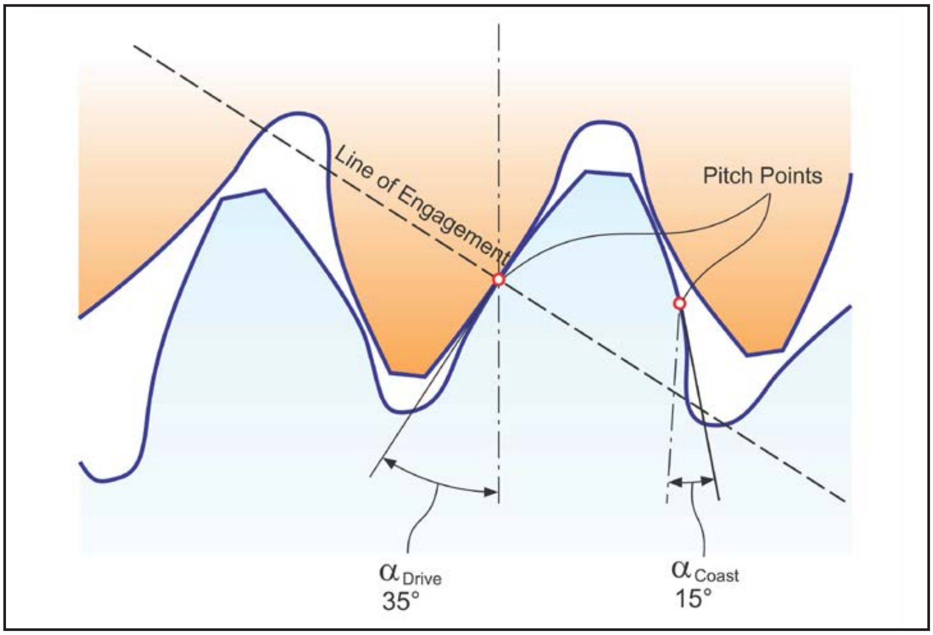

Figure 16 Asymmetric tooth engagement.

Summary

The tooth shapes discussed here can be sorted into those with interesting physical properties and those without sufficiently proven functionality. It is quite true that validating a new system is difficult if the technical community rejects the idea based on solely subjective reasons. This would prevent any private or public research funding. However, many of the new tooth profile solutions discussed in this paper are based on brilliant ideas that failed to have a breakthrough for similar reasons, as why, for example, the Wankel engine never replaced the stroking piston engine.

Cycloidal gears have been used for watches and clocks. Even though they are center distance-sensitive, the watch designer allows rather large center tolerances in connection with axle bearing play. The "S-shaped" profiles of the mating cycloidal gears develop a self-centering force that forces the gears to roll with correct center distance. The advantage of this design was the manufacturing cost reduction due to large bearing position tolerances and large axle play. The large bearing play in turn would guarantee low friction in the sleeve bearings, which achieves one important objective of chronometers. Manufacturing of the cycloidal requires specially formed tool profiles, or pointed tools, that move along a cycloidal path. The advantages cycloidal gears have in watches cannot be duplicated in industrial power transmissions.

Wildhaber-Novikov gears have proven their increased load-carrying capacity, yet show significant center distance sensitivity, are difficult to manufacture, require non-standard tools and depend on a specific, pre-determined helix angle in order to transmit a constant ratio. Changes in center distance and axes inclinations due to tolerances and deflections will introduce significant motion errors and transmission vibrations, which would increase the cost for shafts, bearings and/or housing in order to reduce tolerances and deflections. Even then, the robustness and "mechanical intelligence" of involute gearing that provides them with smooth rolling through many million cycles could not be achieved. The extended version of the Wildhaber-Novikov profile has an "S-shape"—just like the Cycloidal profile that adds the self-centering ability to the properties of the "half-round" profile of Figure 4.

The Nagata development is very similar to the extended Wildhaber-Novikov, but requires rather more complicated tool geometry. The "S-shaped" profile makes it an additional version of the Cycloidal gear type with similar physical properties. Center distance sensibility and difficult manufacturability also prevented the introduction of this gear type in power transmissions.

Convoloid gears, with their dedendum transition point, which is a "flat spot" in a finite profile section, cannot accept significant center distance changes. The flat section of the two mating profiles must be located precisely during the rolling process to separate addendum and dedendum rolling. The separation may interrupt the hydrodynamic lubrication, and misalignments may cause rolling of the transition flat into addendum or dedendum, which will create roll interference. The transition flat prevents or complicates the profile generation with a reference profile on a tool like a hob. Convoloid profiles seem to present the disadvantages of cycloidal profiles, with increased vulnerability around the pitch line.

The "S-shaped" bevel gear profile is very similar to the Convoloid profile. However, where the Convoloid profile is the result of an analytical mesh and contact area optimization, the singularity of the "S-shaped" bevel gear profile in mid-profile will not permit relative profile sliding in this section; this makes this proposed profile unusable in practical applications.

Globoidal gears use the kinematic coupling conditions of formate gears. The profile of the gear member is basically chosen to be straight and the pinion member is generated with respect to the desired ratio, shaft angle and center distance. The principle of interacting pitch elements is not applied, which leads to high relative sliding and can cause partial mutilation to the flank surface.

Cosine gears have been discussed to also elaborate on flank line ideas which do not conform to the common mathematical flank line functions. Cosine gears might have the ability to hold higher torques in a non-rotating, static condition. The attempt to design a gearset with performance advantages resulted in this case in load-carrying capacity similar to straight bevel gears, and a rolling performance that cannot compare to standard spiral bevel gears.

Asymmetric gears build upon the strength of involute gearing, with the acknowledgement that in case of a preferred driving direction, the properties of the driving flanks can be improved by taking away from the non-driving, or coasting, flanks. The practical results of transmissions with asymmetric gears show a significant increase of power density due to an improvement of root bending strength and higher surface durability. Investigations showed that the full advantage of asymmetric gearing vs. gears with symmetric involutes can only be realized if sensible tip relief modifications are applied. This in turn creates a problem for many manufacturers—even those that mass-produce, say, automotive transmissions. The wealth of experience that has been compiled over decades that found its way into the international standards, as well as the material application tables, has no or only limited use for the dimensioning and design of asymmetric gears. Also, the cutting tools are now not standard tools anymore. Different pressure angle offsets for different applications and gear design parameters in connection with circular tip relieves of different amounts will not only make existing tooling obsolete but also eliminate today's standards in hobs and even shaper cutters which will result in increased cutting tool cost and contribute to longer tooling lead times. The fact that asymmetric gears have not had a breakthrough yet is the result of those obstacles. However, the symmetry offset, as well as tip reliefs or other corrections, could be standardized, depending on module and application, which would remove the major obstacle for the broad application of asymmetric involute gears.

Conclusions

The motivation to change from involute profiles and proven straight or curved flank lines to alternative shapes is fueled by the logic that, in today's time and age, more than just incremental improvements should be possible, applying new theories and sophisticated computation technology. Those dramatic improvements would consequently lead to geometries that would appear exotic if observed with the traditional viewpoint. The objective of this paper was to observe the published alternative tooth forms with an open mind in order to find objective answers to the question of why the interesting and sophisticated tooth form proposals haven't had a breakthrough in the gear manufacturing industry.

In angular gear drives, the absence of tight standards, as they exist for cylindrical gears, led to many gear types with different profile and lead functions. The fact that bevel gear cutting tools have never been standardized opened the door for this variety of different processes and tooth forms. The downside is that bevel gear design and manufacturing is perceived as complicated, not straightforward — and expensive. The standards in cylindrical gears, which are based on standard reference profiles and involutes, make design and manufacturing transparent and keep the cost of cylindrical gear manufacturing relatively low.

The center distance insensitivity of involute gears also applies in the relationship between generating rack and work gear and therefore makes hobbing a very robust process. The fact that every point along the involute has a normal direction that is tangent to the base circle gives the involute its robustness during manufacturing and in operation (Fig. 17) (Ref. 13). All of the discussed non-involute gears are sensitive to center distance changes and require individual tool designs. Standardization is not possible or difficult, which presents an additional risk in design and manufacturing. If higher load-carrying capacity, lower noise and increased efficiency are goals of new gear geometries, then the absence of standards and higher design and manufacturing cost might be acceptable in some cases. However, the physical properties of involute gearing are superior to most of the discussed non-involute gears. The potential of asymmetric, involute tooth profile will allow significantly improved cylindrical gears by maintaining the advantages of involutes. A broader interest on asymmetric gears could initiate the development of new standards and would — over time — allow the gear community to gain sufficient experience in this advanced system.

Nevertheless, it seems fair to say: "The involute is here to stay."

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Dr. Hermann J. Stadtfeld in 1978 received his B.S. and in 1982 his M.S. in mechanical engineering at the Technical University in Aachen, Germany; upon receiving his Doctorate, he remained as a research scientist at the University's Machine Tool Laboratory. In 1987, he accepted the position of head of engineering and R&D of the Bevel Gear Machine Tool Division of Oerlikon Buehrle AG in Zurich and, in 1992, returned to academia as visiting professor at the Rochester Institute of Technology. Dr. Stadtfeld returned to the commercial workplace in 1994—joining The Gleason Works—also in Rochester—first as director of R&D, and, in 1996, as vice president R&D. During a three-year hiatus (2002-2005) from Gleason, he established a gear research company in Germany while simultaneously accepting a professorship to teach gear technology courses at the University of Ilmenau. Stadtfeld subsequently returned to the Gleason Corporation in 2005, where he currently holds the position of vice president, bevel gear technology and R&D. A prolific author (and frequent contributor to Gear Technology), Dr. Stadtfeld has published more than 200 technical papers and 10 books on bevel gear technology; he also controls more than 50 international patents on gear design, gear process, tools and machinery.

Upon high school graduation **Jasmin K. Saewe,** from April to June 2011, completed basic training in metalworking during her internships with German-based TRW Automotive and Aleris Rolled Products. In October 2011 she enrolled as a student of mechanical engineering at the RWTH Aachen University. At the Aachen University Jasmin became a student research assistant at the WZL, where she was involved with practical gear cutting trials and tool life investigations;this spurred her interest in an internship with Gleason. Saewe in April 2014 began an internship in the R&D department at The Gleason Works in Rochester, New York. As of January 2015, Jasmin continues her studies at the RWTH-Aachen University in order to finish her Bachelor's degree, while continuing her employment as student research assistant at the WZL.

On the Correlation of Specific Film Thickness and Gear Pitting Life

Timothy L. Krantz

The effect of the lubrication regime on gear performance has been recognized, qualitatively, for decades. Often the lubrication regime is characterized by the specific film thickness defined as the ratio of lubricant film thickness to the composite surface roughness. It can be difficult to combine results of studies to create a cohesive and comprehensive data set. In this work gear surface fatigue lives for a wide range of specific film values were studied using tests done with common rigs, speeds, lubricant temperatures, and test procedures. This study includes previously reported data, results of an additional 50 tests, and detailed information from lab notes and tested gears. The data set comprised 258 tests covering specific film values (0.47-5.2). The experimentally determined surface fatigue lives, quantified as 10-percent life estimates, ranged from 8.7-86.8 million cycles. The trend is one of increasing life for increasing specific film. The trend is nonlinear. The observed trends were found to be in good agreement with data and recommended practice for gears and bearings. The results obtained will perhaps allow for the specific film parameter to be used with more confidence and precision to assess gear surface fatigue for purpose of design, rating, and technology development.

Introduction

The power density of a gearbox is an important consideration for many applications and is especially important for gearboxes used on aircraft. One factor that limits gearbox power density is the ability of the gear teeth to transmit power for the required number of cycles without pitting or spalling. Methods for improving surface fatigue lives of gears are therefore highly desirable.

Gear and bearing performance is strongly influenced by the lubrication condition and the topography of the contacting surfaces. Research to understand and optimize the performance of systems using gears and bearings has a long history, and studies continue today to refine the qualitative understanding and quantitative relationships. The lubrication condition and surface topography have a strong influence on all of friction, scoring and scuffing, wear, micropitting, and surface fatigue of gears and bearings.

The effect of oil viscosity and surface finish on the scoring load capacity of gears was investigated experimentally more than 50 years ago (Ref. 1). Patching (Ref. 2) evaluated the scuffing properties of ground and superfinished surfaces using turbine engine oil as the lubricant. The evaluation was performed using case-carburized steel discs. The discs were finish ground in the axial direction to orient the lay perpendicular to the direction of rolling and sliding, thereby simulating the conditions normally found in gears. Some of the discs were superfinished to provide smoother surfaces. The Ra of the ground discs was about 0.4 μm (16 μin), and the Ra of the superfinished discs was less than 0.1 μm (4 μin). They found that compared with the ground discs, the superfinished discs had a significantly higher scuffing load capacity when lubricated with turbine engine oil and subjected to high rolling and sliding speeds. They also noted that under these operating conditions, the sliding friction of the superfinished surfaces was the order of half that for the ground surfaces. Others have reported similar trends while producing more refined understanding of the relationships of surface texture and operating conditions to gear scoring and scuffing (Refs. 3-6).

The influences of lubricant viscosity and additives on gear wear were evaluated by Krantz and Kahraman (Ref. 7). Gears tested to study surface fatigue were evaluated to quantify gear wear rates as influenced by lubricant viscosity and additives. The gears of that study were case-carburized and ground finished. The wear rates when gears were lubricated by a nine-centistoke oil were about 10 times lower than the wear rates when lubricated by a three-centistoke oil. The measured gear tooth wear rates strongly correlated to the lubricant viscosity.

Studies of rolling element bearings have shown that the bearing surface fatigue life is influenced by the lubricant viscosity and the surface roughness (Refs. 8-11). The influences have been condensed using the concept of specific film thickness, also often termed the "lambda ratio." The specific film thickness is a ratio of the lubricating oil film thickness to the composite surface roughness of the two contacting surfaces. When the specific film thickness is less than unity, the service life of the bearing is considerably reduced. The Society of Tribologists and Lubrication Engineers (STLE) has published a recommended life factor for bearings that is a function of specific film thickness (Ref. 12). Some investigators have speculated that the effect of specific film thickness on gear life could be even more pronounced than is the effect on bearing life (Ref. 13). To improve the surface fatigue lives of gears, the film thickness may be increased, the composite surface roughness reduced — or both approaches may be adopted. These two effects have been studied separately for gears.

Townsend and Shimski (Ref. 14) studied the influence of viscosity on gear fatigue lives using seven different lubricants of varying viscosity. Tests were conducted on a set of case-carburized and ground gears, all manufactured from the same melt of consumable-electrode vacuum-melted (CVM) AISI 9310 steel. At least 17 gears were tested with each lubricant. They noted a strong positive correlation of the gear surface fatigue lives with the calculated film thickness and demonstrated that increasing the film thickness does indeed improve gear surface fatigue life.

Several investigations have been carried out to demonstrate the relation between gear surface fatigue and surface roughness. One investigation by Tanka (Ref. 15) involved a series of tests conducted on steels of various chemistry, hardness, and states of surface finish. Some gears were provided with a near-mirror finish by using a special grinding wheel and machine (Ref. 16). The grinding procedure was a generating process that provided teeth with surface roughness quantified as *Rmax* of about 0.1 μm (4 μin). A series of pitting durability tests were conducted and included tests of case-carburized pinions mating with both plain carbon steel gears and through-hardened steel gears. They concluded that the gear surface durability was improved in all cases because of the near-mirror finish. They noted that when a casehardened, mirror-finish pinion was mated with a relatively soft gear, the gear became polished with running. They concluded that this polishing during running improved the surface durability of the gear.

Nakasuji (Refs. 17-18) studied the possibility of improving gear fatigue lives by electrolytic polishing. They conducted their tests using medium carbon steel gears and noted that the electro polishing process altered the gear profile and the surface hardness as well as the surface roughness. The polishing reduced the surface hardness and changed the tooth profiles to the extent that the measured dynamic tooth stresses were significantly larger relative to the ground gears. Even though the loss of hardness and increased dynamic stresses would tend to reduce stress limits for pitting durability, the electrolytic polishing was shown to improve the stress limit for which the gears were free of pitting by about 50 percent.

Hoyashita (Refs. 19-20) completed a third investigation of the relation between surface durability and roughness. They conducted a set of tests to investigate the effects of shot peening and polishing on the fatigue strength of case-hardened rollers. Some of the shot peened rollers were reground and some were polished by a process called barreling. The reground rollers had a roughness average (Ra) of 0.78 μm (31 μin). The polished rollers had a Ra of 0.05 μm (2.0 μin). Pitting tests were conducted using a slide-roll ratio of −20 percent on the follower with mineral oil as the lubricant. The lubricant film thickness was estimated to be 0.15 ~ 0.25 μm (5.9 ~ 9.8 μin). The surface durability of the rollers that had been shot peened and polished by barreling was significantly improved compared with rollers that were shot peened only or that were shot peened and reground. They found that the pitting limits (maximum Hertz stress with no pitting after 107 cycles) of the shot peened/reground rollers and the shot peened/polished rollers were 2.15 GPa (312 ksi) and 2.45 GPa (355 ksi), respectively.

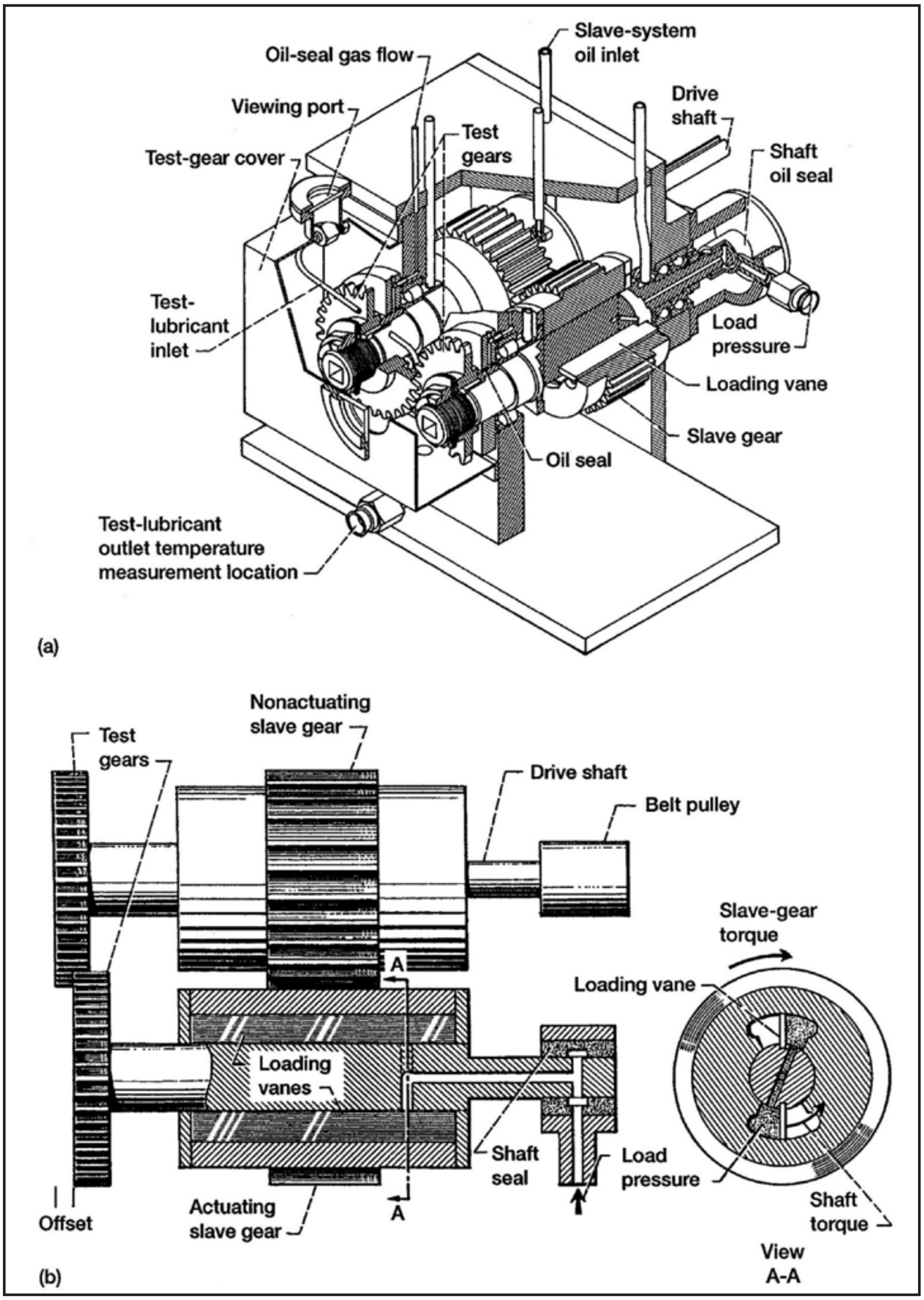

Figure 1 NASA Glenn Research Center gear fatigue test apparatus: (a) cutaway view; (b) schematic view.

Krantz (Refs. 21-22) studied the surface fatigue of gears with an improved surface finish using case-carburized gears made from AISI 9310 steel. Testing was done on the same high-speed power recirculating gear tester used by Townsend and Shimski (Ref. 14). The AISI 9310 gears with improved surface finish had longer lives as compared to standard ground gears by a factor of about four times. Motivated by these results, similar testing was later done using the same test rigs and test methods using gears made from aerospace quality, case- carburized AMS 6308B alloy steel (Ref. 23), and the relative life improvement was a factor of about three.

All of these previous works (Refs. 1-23) provide strong evidence that the specific film thickness parameter is an effective engineering concept for assessing the surface fatigue lives of gears. The review of previous works just presented is not exhaustive; other work has been published offering results that, from a qualitative view, are consistent with the preceding discussion. However, it has been difficult to combine the results of these studies of the surface fatigue lives of gears to provide a comprehensive quantitative correlation of the lubrication conditions and surface fatigue lives. Because of differing test rigs, specimen geometry, gear alloys and processing, and ranges of operating conditions such as speed and load, it is challenging to combine results. The present study was therefore carried out to quantify the correlation of the surface fatigue lives of gears to specific film thickness. In this work, experimental data from four studies are combined into one data set. All experiments were conducted on the NASA Spur Gear Test Rigs using consistent test procedures and test conditions (identical speed, torque, temperature, oil jetting and filtration, test gear geometry, and test gear manufacturing quality). This study comprises 258 gear surface fatigue tests. The fatigue data for the majority of the data set have been published previously (Refs, 14, 21 and 23). Townsend and Shimski (Ref. 14) reported results of gear tests using seven lubricants. Later, using gears made from the same melt of steel as used in (Ref. 14), Townsend completed an additional 50 tests using three more lubricants, but he did not widely disseminate the data. Those 50 fatigue tests are included into the data set for this study. Along with previously reported information in (Refs. 12, 21 and 23), many of the tested gears and laboratory records were still available, and access to this information provided a unique opportunity to compile sufficient detail of information to correlate the experimentally measured gear surface fatigue lives to a wide range of specific film thickness.

Table 1 Spur test gear design parameters

Number of teeth	28
Module, mm	3.175
Diametral pitch (1/in)	8
Circular pitch, mm (in)	9.975 (0.3927)
Whole depth, mm (in)	7.62 (0.300)
Addendum, mm (in)	3.18 (0.125)
Chordal tooth thickness ref. mm (in)	4.85 (0.191)
Pressure angle, deg.	20
Pitch diameter, mm (in)	88.90 (3.500)
Outside diameter, mm (in)	95.25 (3.750)
Root fillet, mm (in)	1.02 to 1.52 (0.04 to 0.06)
Measurement over pins, mm (in)	96.03 to 96.30 (3.7807 to 3.7915)
Pin diameter, mm (in)	5.49 (0.216)
Backlash reference, mm (in)	0.254 (0.010)
Tip relief, mm (in)	0.010 to 0.015 (0.0004 to 0.0006)

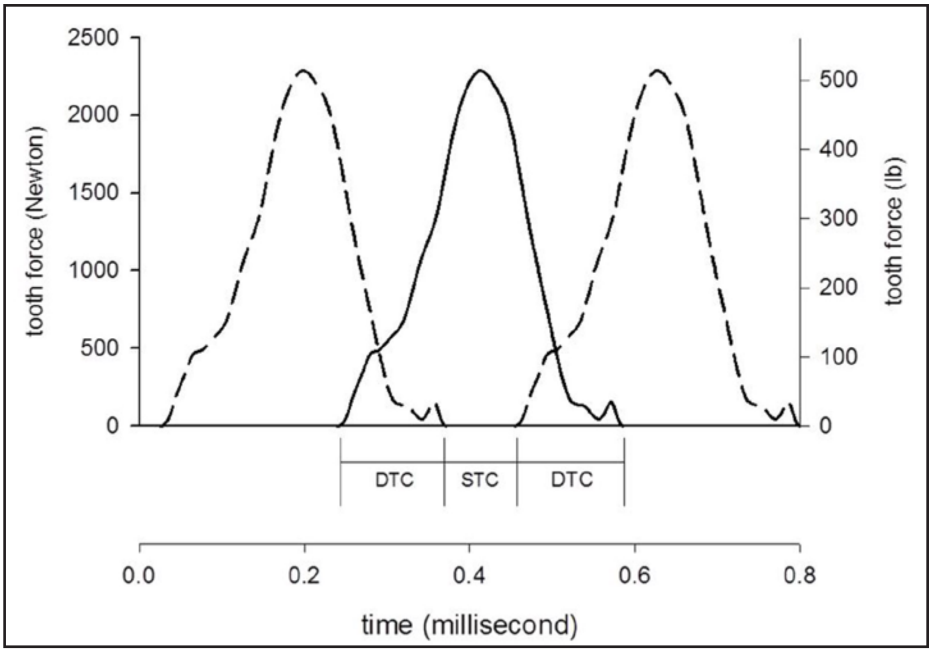

Figure 2 Measured dynamic tooth force at nominal test conditions (Ref. 22). The solid line is the measured data, and the dashed lines are replicates of the measured data spaced along the ordinate at the equivalent of one tooth pitch. The zones of double tooth contact (DTC) and single tooth contact (STC) are illustrated.

Test Facility and Testing Procedure

The gear fatigue tests were performed in the NASA Glenn Research Center's gear test apparatus. The test rig is shown in Figure 1(a) and described in Reference 24. The rig uses the four-square principle of applying test loads, and thus the input drive only needs to overcome the frictional losses in the system. The test rig is belt driven and operated at a fixed speed for the duration of a particular test.

A schematic of the apparatus is shown in Figure 1(b). Oil pressure and leakage replacement flow is supplied to the load vanes through a shaft seal. As the oil pressure is increased on the load vanes located inside one of the slave gears, torque is applied to its shaft. This torque is transmitted through the test gears and back to the slave gears. In this way power is circulated, and the desired load and corresponding stress level on the test gear teeth may be obtained by adjusting the hydraulic pressure.

The two identical test gears may be started under no load, and the load can then be applied gradually. To enable testing at the desired contact stress, the gears are tested with the faces offset as shown in Figure 1. By utilizing the offset arrangement for both faces of the gear teeth, a total of four surface fatigue tests can be run for each pair of gears. The test gears were run with the tooth faces offset by a nominal 3.3 mm (0.130 in) to give a nominal surface load width on the gear face of 3.0 mm (0.120 in). The precise width of the running track will be influenced by gear tooth facewidth tolerances and by the shape and radius of the edge breaks. In this work, post-test inspections were used to determine the running track widths, as will be discussed later in this report.

All tests were run-in at a torque load of 14 Nm (130 in-lb) for at least one hour. The torque was then increased to the test torque of 72 Nm (640 in-lb). For this test torque, the peak of the Hertz pressure distribution for line contact condition at the pitch-line and static torque equilibrium is 1.7 GPa (250-ksi). Typical dynamic tooth forces have been measured using strain gages located in tooth fillets. Using calibration coefficients determined by specialized calibration experiments (Ref. 25) typical gear tooth forces were calculated from measured tooth fillet strains (Fig. 2). The resulting peak dynamic tooth force is about 1.3 times greater than the force for static equilibrium, and the resulting peak of the Hertz pressure distribution for this peak dynamic force is 1.9 GPa (285 ksi). The Hertz pressure values stated herein are idealized stress indices assuming perfectly smooth surfaces and an even pressure distribution across a 2.79 mm (0.110 in) line contact (the line length is less than the face width allowing for the face offset and the edge break radius).

The gears were tested at 10,000 rpm, which gave a pitch-line velocity of 46.5 m/s (9,154 ft/min). Inlet and outlet oil temperatures were continuously monitored. Cooled lubricant was supplied to the inlet of the gear mesh at 0.8 liter/min (49 in/min) and 320 ± 7K (116 ± 13°F). The lubricant outlet temperature was recorded and observed to have been maintained at 348 ± 4.5K (166 ± 8°F). The lubricant was circulated through a 5µm (200 µin)-rated fiberglass filter to remove wear particles. For each test, 3.8 liters (1 gal) of lubricant were used.

The tests ran continuously (24 hr/day) until a vibration detection transducer automatically stopped the rig. The transducer is located on the gearbox, adjacent to the test gears. For purposes of this work, surface fatigue failure was defined as one or more spalls, or pits, covering at least 50 percent of the width of the line contact on any one tooth. If the gear pairs operated for more than 500 hours (corresponding to 300 million stress cycles) without failure, the test at the test engineer's discretion was usually suspended. Some superfinished gears were operated for longer than 300 million cycles. The longest test exceeded 1,000 hours (600 million cycles) without surface fatigue occurring.

Test Gears

The dimensions for the test gears are given in Table 1. The gear pitch diameter was 89 mm (3.5 in) and the tooth form was a 20° involute profile modified to provide linear tip relief of 0.013 mm (0.0005 in) starting at the highest point of single tooth contact. The gears have no lead crowning, but do have a nominal 0.13 mm (0.005 in) radius edge break at the tips and sides of the teeth. The gear tooth surface finish after final grinding was specified as a maximum of 0.406 µm (16 µin) rms. Tolerances for the gear geometries were specified to meet AGMA 2000-A88 quality level class 12 (Ref. 26). Typical data from gear coordinate measurement machine inspections to verify the gear involute and lead form quality are provided in Figure 3.

All gears included in this study were made from forged bars; the gears were made from two alloys. One alloy was per specification AISI 9310, the other per specification AMS 6308B. The chemical compositions of the two alloys are given in Table 2. All of the gears made from

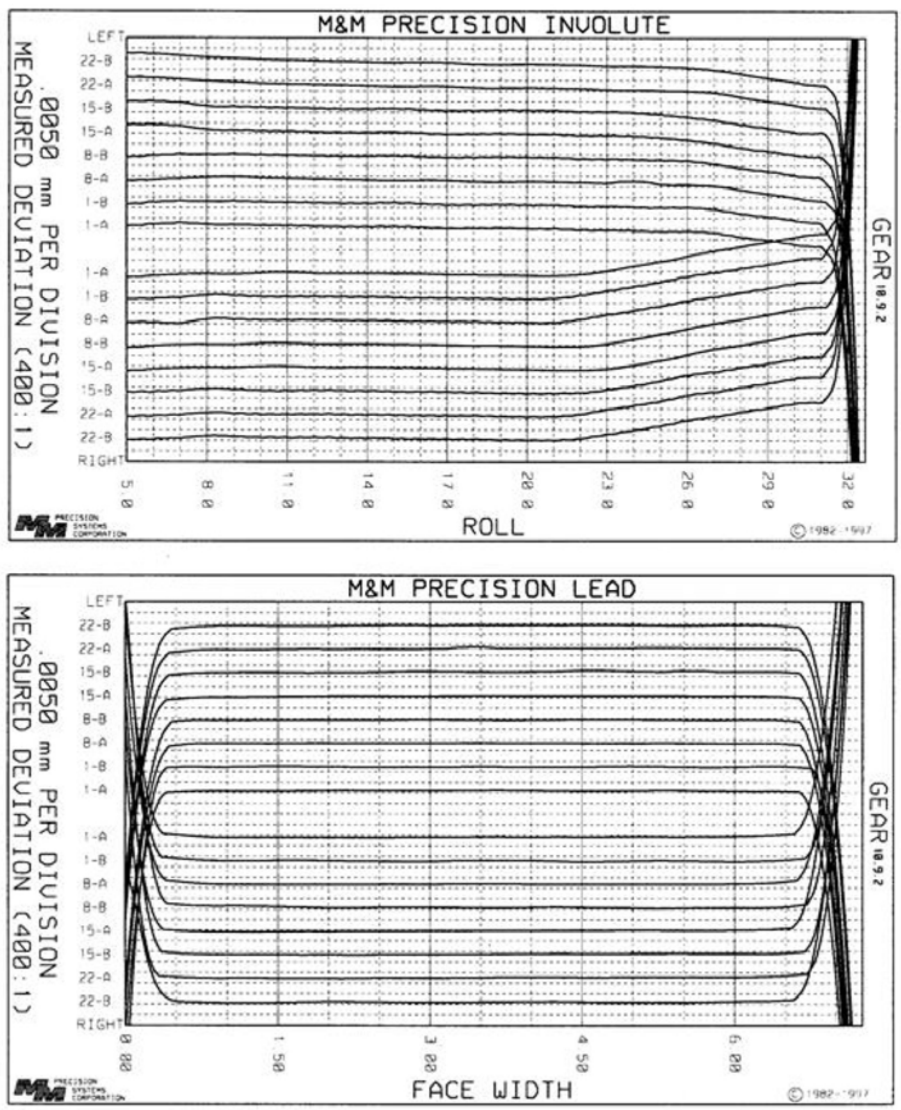

Figure 3 **Involute and lead inspection charts of a typical 28-tooth test gear. Two lead and involute traces for both sides of teeth 1, 8, 15 and 22 are shown (NOTE: *Aspect ratio of plot is scaled as X:Y=100:1.*)**

AMS 6308B were made from a single melt of vacuum-induction melt vacuum arc re-melt (VIM-VAR) processed steel, and were manufactured as a single lot; i.e. — all rough machining, hobbing, heat treatment, and final grinding were accomplished together as a single lot of gears. The gears made from AISI 9310 steel were from two melts of steel; one melt made via air-melt vacuum-arc-re-melt (VAR) process and the other melt made using a consumable electrode vacuum melt process (CVM). One can expect that the CVM-processed steels had fewer impurities than did the VAR steel. The gears made from the VAR 9310 were manufactured in one lot; those made from the CVM 9310 steel were made in three lots. Gears were case-carburized and tempered following aerospace practice to achieve a surface hardness of minimum Rc 58 — with a typical surface hardness of Rc 60 and case depth of 1.0 mm (0.040 inch). Additional details concerning the heat treatment process, typical microstructure of case and core, hardness profiles, residual stress profiles and surface metrology are available in (Refs. 13, 14, 21-22, 23 and 27).

To correlate the specific film thickness to gear fatigue lives, the surface roughness of the test gears is needed. As just mentioned, gears were made from three melts of steel. Furthermore, for one of the melts, gears were made in three lots — for a total of five manufacturing runs of gears with ground teeth. For two studies of superfinishing a lot of ground gears was divided into two groups — one group remaining in the as-ground condition and the other subjected to superfinishing. Therefore, in total there were seven groups of gears — five groups with ground surfaces and two groups with superfinished surfaces.

Superfinishing was done using one of two processes described in (Refs. 3 and 7). The surface roughness for each of the seven gear groupings was re-measured and quantified using the root-mean-squared roughness parameter (*Rq*). Measuring was done using a 2-μm radius, conisphere-tipped stylus profilometer, and the data were digitally processed using an ISO-conforming Gaussian roughness filter having a 0.8 mm cutoff.

The 0.8 mm cutoff is a value typically available for many surface roughness measuring instruments and software. In this work the concept of "functional filtering" was employed. The concept is that the concentrated contact acts as a mechanical filter, and therefore the wavelengths of surface roughness that influence the machine element performance depend on the breadth of the contact. Using a line-contact assumption, the gear geometry, operating torque and classical Hertz contact theory, the breadth of the Hertz contact at the pitch point was calculated as 0.47 mm — a smaller length than the 0.8 mm value of the cutoff for the digital filter. The roughness values were therefore adjusted by the method proposed by Moyer and Bahney (Ref. 28), and also recommended by the AGMA (Ref. 29) as:

$$Rq_{\text{eff}} = Rq_{0.8\,\text{mm}} \sqrt{\frac{A}{0.8}} \qquad (1)$$

where

Rq_{eff} is effective roughness parameter

$Rq_{0.8\,\text{mm}}$ is roughness parameter determined using a 0.8 mm filter cut-off value

A is contact breadth in direction of rolling, millimeters

Typical plots of surface topography of gear teeth, as measured by profilometer tracing after application of the roughness filter to the data, for three lots of the ground gears tested by Townsend and Shimski (Ref. 14), are provided (Fig. 4). Note that each set has a differing surface texture and roughness value.

Although not directly stated by Townsend and Shimski (Ref. 14), when they presented a correlation of fatigue data to specific film thickness, they used the maximum *Rq* roughness value permitted by their test gear specification to estimate the specific film thickness. So, while the correlation they provided is qualitatively consistent with the correlation to be derived herein, their correlation is quantitatively different from the present work because they did not account for differing actual roughness of test gears in their correlation, and they did not employ the concept of functional filtering.

Table 2 Spur test gear steel chemical compositions

Element	AISI 9310[1]	AMS 6308B[2]
	Weight %	
Carbon	0.10	0.11
Nickel	3.22	1.84
Chromium	1.21	1.07
Molybdenum	0.12	3.32
Copper	0.13	2.06
Manganese	0.63	0.38
Silicon	0.27	0.77
Sulfur	0.005	< 0.005
Phosphorous	0.005	< 0.010
Vanadium	N/A	0.08
Iron	Balance	Balance

NOTES:
1) Nominal composition per specification
2) Verified composition and within specification

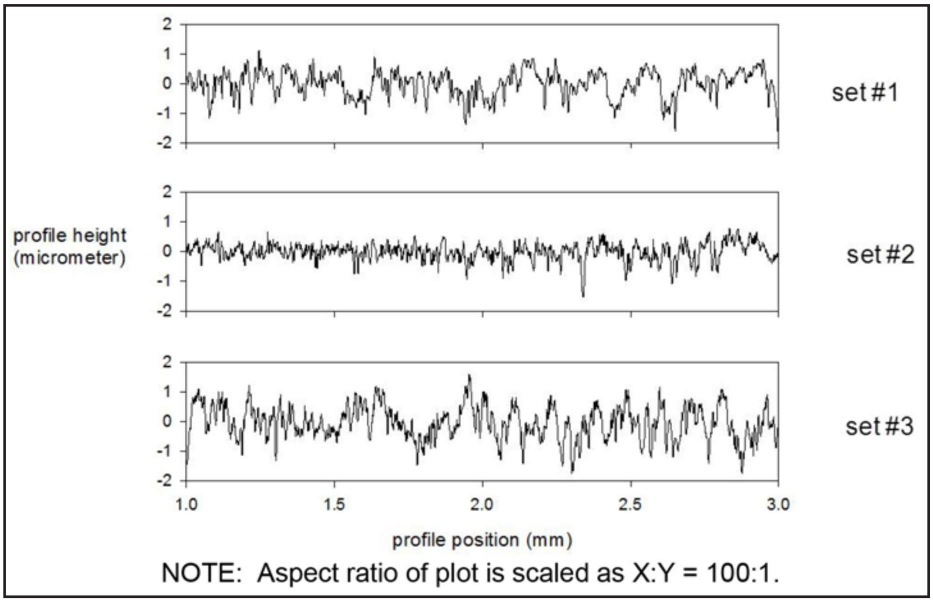

Figure 4 Examples of surface roughness data after application of roughness filter with a 0.8 mm cutoff. The three sets are ground gears manufactured from the same melt and to same specification, but from three different manufacturing lots.

Figure 5 provides a pair of typical surface roughness data sets for the ground and superfinished gears included in this study. The measurements were made with aid of a fixture and a precision-relocation technique (Ref. 27) such that the roughness was measured at the same position on the tooth — both before and after superfinishing. The superfinish processes removed asperity features and, as a result, only valley features of relatively small depths remained. The superfinishing resulted in a near-mirror surface quality (Fig. 6).

The Rq_{eff} effective roughness parameter for each of the seven groups of gears in this study ranged from 0.07-0.45 µm (2.7-17.9 µin). The full set of data is provided in Table 3. For sets denoted as set IDs 4-7 in Table 3, the Rq parameters were calculated from previously published Ra values using the following relationship (Ref. 27) to estimate Rq from Ra (Ref. 30):

$$Rq = \sqrt{\left(\frac{\pi}{2}\right)} \quad (2)$$

Table 3 Test gear surface roughness

Reference	Material	Set ID	Finish method	Roughness, *Rq*, µm (µin)
[14]	CVM AISI 9310	1	Ground	0.42 (16.7)
		2	Ground	0.24 (9.4)
		3	Ground	0.45 (17.9)
[21]	AM-VAR AISI 9310	4	Ground	0.37 (14.6)[1)]
		5	Superfinished	0.07 (2.7)[1)]
[23]	VIM-VAR AMS 6308B	6	Ground	0.32 (12.7)[1)]
		7	Superfinished	0.08 (3.3)[1)]

NOTE:
1) Denotes *Rq* calculated from published Ra values.

Lubricants and Specific Film Thickness

The tests considered in this study made use of twelve different lubricants. The lubricant viscosity at (95-100°C) ranged from 3.2-9.1 cSt. Most of the lubricants were fully formulated lubricants, including proprietary additive mixtures. Nine of the 12 lubricants were polyolesters; the other three lubricants were a polyalkylene-glycol, a naphthenic mineral oil, and a synthetic paraffinic. The synthetic paraffinic is termed herein as "NASA standard"-lubricant, as this lubricant has been used in the manner of a reference lubricant for many gear fatigue studies, including more than 140 tests of AISI 9310 steel gears (Ref. 22). The NASA standard lubricant includes 5% additive by volume; the additive content includes phosphorous and sulphur. For all tests the lubricants were filtered using a 5-micron-rated fiberglass filter element.

The operating film thickness for each lubricant was calculated using the minimum-film-thickness equation (Ref. 31). The dimensionless (normalized) formula used was:

$$H_{min,\,r} = 2.65 U^{0.70}\, G^{0.54}\, W^{-0.13} \quad (3)$$

where

U is speed parameter, proportional to the absolute viscosity of the lubricant

G is material parameter, proportional to the pressure-viscosity coefficient of the lubricant

W is load parameter, independent of the lubricant

The needed lubricant physical parameters were obtained from referenced works (Refs. 14, 22 and 23), in most cases. Some of the needed lubricant physical parameters had not been published, but were determined from laboratory records and notes of Townsend (Refs. 13-14). The lubricant physical properties are functions of temperature. For purposes of calculating film thickness, the lubricant properties used were those for the mean of the oil jet and oil outlet (drain) temperatures, i.e. — 330°K (57°C, 134°F). The minimum film thicknesses as calculated from Equation 3 ranged from 0.28-0.75 µm (11-30 µin).

Combining the results of surface roughness evaluations (Table 3) and the minimum film thickness calculations, the specific film thickness ratio was determined for each of the 14 groups of gears that were subjected to fatigue tests. Note that the roughness value to be used for the specific film thickness calculation is the composite roughness for both gears, while the table lists the roughness for one surface. The lubricants tested and the combinations of roughness, film thickness, and resulting specific film thickness values are listed in Table 4. The range of specific film thickness for this study is (0.47-5.23).

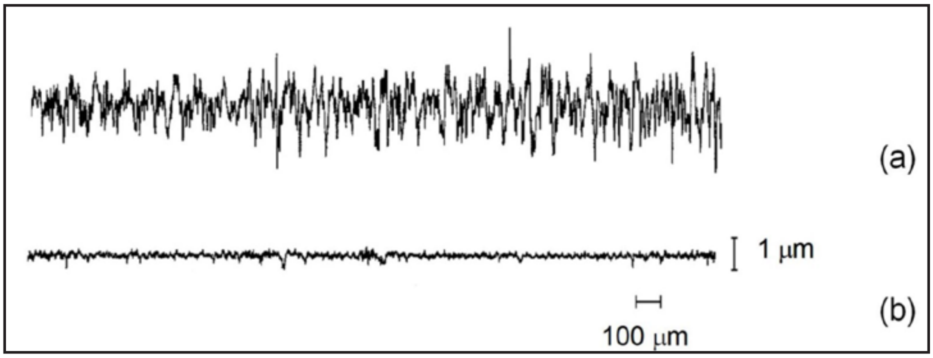

Figure 5 Examples of surface roughness features for a gear tooth prior to and after superfinishing, (Ref. 27): (a) ground surface; (b) same surface (relocated profile trace) after superfinishing.

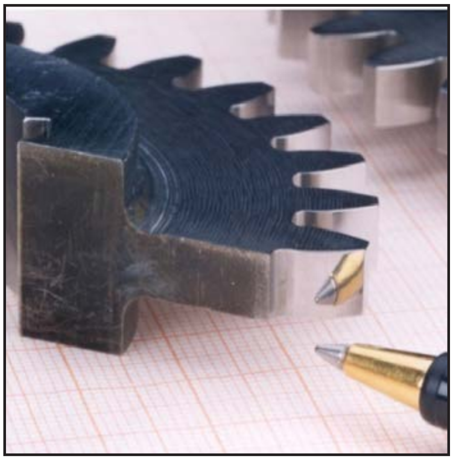

Figure 6 Near-mirror quality of a superfinished test gear.

Dataset	Lubricant description	Specification	Viscoscity at 95-100 °C, cSt	Film thickness, µm	Roughness, Rq_{eff}	Specific film thickness
1	Polyolester	MIL-L-7808	3.2	0.28	0.42	0.47 2)
2	Polyolester	None 1)	4.3	0.40	0.42	0.67 2)
3	Polyolester	MIL-L-23699	5.2	0.48	0.45	0.75 2)
4	Polyolester	DOD-L-85734	5.2	0.51	0.42	0.86 2)
5	Polyolester	DOD-L-85734	5.4	0.51	0.42	0.86 2)
6	Polyolester	MIL-L-23699	5.4	0.52	0.42	0.87 2)
7	Polyalkylene-glycol	DERD 2487	7.4	0.65	0.42	1.09 2)
8	Polyolester	None 1)	8.8	0.72	0.24	2.14 2)
9	Polyolester	None	9.0	0.73	0.24	2.17 2)
10	Polyolester	None	9.1	0.75	0.24	2.23 2)
11	Polyolester	DOD-L-85734	5.4	0.51	0.07	5.23 3)
12	Naphthenic mineral oil	None	7.1	0.60	0.37	1.15 3)
13	Synthetic paraffinic	"NASA Stnd"	5.7	0.50	0.32	1.10 4)
14	Synthetic paraffinic	"NASA Stnd"	5.7	0.50	0.08	4.20 4)

Table 4 Lubricant details, calculated film thickness, roughness of the test gears, and resulting specific film thickness

NOTES:
1) Base stock lubricants, no additives.
2) Study #1, refers to referenced works [14, 21, 23].
3) Study #2, refers to referenced works [14, 21, 23].
4) Study #3, refers to referenced works [14, 21, 23].
5) Datasets 3, 5 and 10 were part of study #1, but the data had not been previously published.

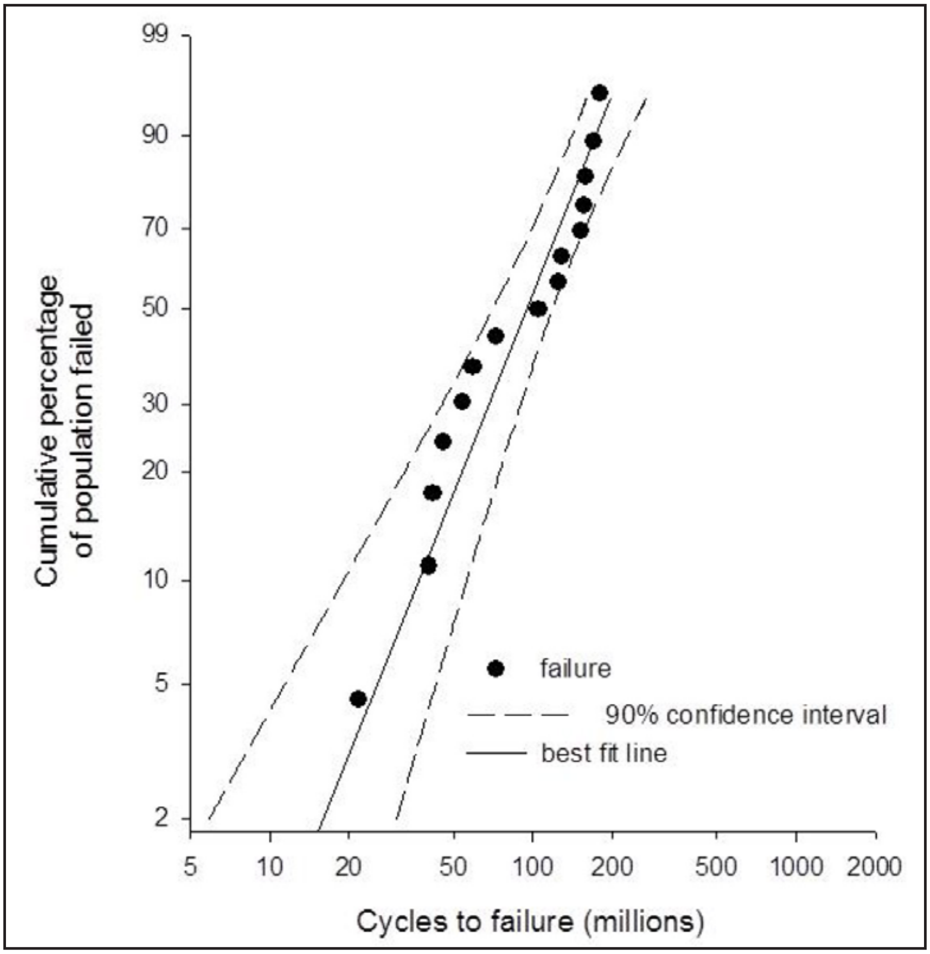

Figure 7 **Typical distribution of gear fatigue test data plotted using Weibull coordinates and showing median-rank regression solution (solid line) and 90% confidence interval (dashed lines).**

Fatigue Test Results, Statistics, and Method for Normalizing Results

Gear fatigue tests were completed for 14 groups of gears — each group being a unique combination of alloy, surface finish roughness, and lubricant. All gears were tested on the NASA Spur Gear Test Rigs using the same torque, speed, lubricant temperatures, and test procedures. Some tests were suspended with no fatigue and no indications of pending fatigue, and so such results were treated as suspended fatigue tests. Tests that were suspended completed at least 500 test hours (300 million shaft revolutions). The longest test, one using superfinished surfaces, was suspended after 1,000 hours (600 million cycles).

All of the gear failures were surface fatigue failures. This term is used to include what is sometimes considered two separate failure modes — sub-surface spalling and near-surface, or surface-originating pitting. In this work there was no attempt to determine or differentiate test results as spalling or pitting. Rather, all failures are grouped together and termed as "surface fatigue." None of the failures were of the micropitting failure mode. A surface-fatigue life evaluation for a particular group of gears comprised multiple tests, as the scatter for such fatigue tests is significant. The number of tests completed for each group ranged from 10 to 30. The average number of tests per group — average statistical sample size — was 18. The fatigue test results for each of the 14 groups of gears were modeled as best-fit, two-parameter Weibull distributions. The parameters for the best-fit Weibull distributions were determined by median-rank regression (Ref. 32). The Weibull shape parameters (slopes) for the regression solutions ranged from 1.0-2.6. A typical Weibull plot of the gear fatigue data is provided in Figure 7. From the Weibull regression solutions, the 10 percent lives (L10) were determined for each gear group. The determined (best-fit) L10 lives ranged from 5.1-100 million cycles. The total number of tests included in this study is 258 tests.

During careful inspections of the tested gears, one notes slight differences in the widths of the running tracks. Further study would reveal that the running track widths are very consistent for all gears of a particular manufacturing lot, but the running track widths varied somewhat from lot-to-lot because of two primary factors. One factor is that the gear face widths were specified with a tolerance of ± −0.13 mm (0.005 inch). The second factor influencing the running track width is that the edge breaks vary in details from lot-to-lot — even though all are within specification. As the test torque was the same, but the running track widths varied, the load intensity for all tests was not identical. To best correlate fatigue test results to specific film thickness, the fatigue lives at common load intensity was desired.

Therefore, the fatigue lives were adjusted to account for the varying load intensity. All tests were normalized to a line-contact load intensity (load divided by Hertz line-contact width) of 580 N/mm at the pitch line. This was done with the aid of digital photographs of the tested gears recorded using a low-objective-power microscope and small aperture setting to obtain needed resolution and depth-of-field.

The wear tracks were measured with the aid of image-processing software. The L10 fatigue lives were adjusted to estimate the results as if all tests had been operated at the same load intensity using the following relation (Ref. 33):

$$L10 \propto \text{load intensity}^{-4.3} \quad (4)$$

The load-life exponent of Equation 4 is one that was determined by tests of 9310-steel gears using the same rigs and test procedures as for the present study. One additional normalizing factor was applied to the two groups of gears made from AM-VAR melted materials, made in the 1970's era, to be directly compared on an absolute basis to VIM-VAR processed material made approximately 30 years later. A life adjustment factor of 2.0 was applied to the L10 lives of the AM-VAR gears to estimate the experiment results if such experiments were to be repeated using VIM-VAR material (Ref. 12). With these adjustments, a set of adjusted L10 lives was determined that could, as a cohesive set, be correlated to specific film thickness. The resulting data are provided in Table 5; included in Table 5, for ease of study, are the specific film thickness data from Table 4.

Table 5 Fatigue lives from tests quantified as 10 percent life (L10), adjusted L10 lives based on actual test load intensity, and specific film thickness

Dataset	Weibull L10, 10^6 cycles	Contact width, mm	Load intensity, N/mm	Relative load intensity[1)]	Adjusted L10 lives, 10^6 cycles	Specific film thickness
1	5.7	2.65	657	1.132	9.72	0.47[2)]
2	5.1	2.65	657	1.132	8.69	0.67[2)]
3	11	3.02	576	0.993	10.7	0.75[2)]
4	12	2.95	590	1.017	12.9	0.86[2)]
5	35	2.95	590	1.017	37.6	0.86[2)]
6	12	2.65	657	1.132	20.5	0.87[2)]
7	47	2.95	590	1.017	50.5	1.09[2)]
8	45	3.10	561	0.968	39.1	2.14[2)]
9	100	3.10	561	0.968	86.8	2.17[2)]
10	84	3.10	561	0.968	73.0	2.23[2)]
11	46	2.80	621	1.071	85.7	5.23[3)]
12	11	3.05	570	0.984	29.6	1.15[3)]
13	37	3.00	580	1.000	37.0	1.10[4)]
14	75	3.00	580	1.000	75.0	4.20[4)]

NOTES:
1) Normalized to a running load intensity of 580 N/mm.
2) Study #1, refers to referenced works [14, 21, 23].
3) Study #2, refers to referenced works [14, 21, 23].
4) Study #3, refers to referenced works [14, 21, 23].

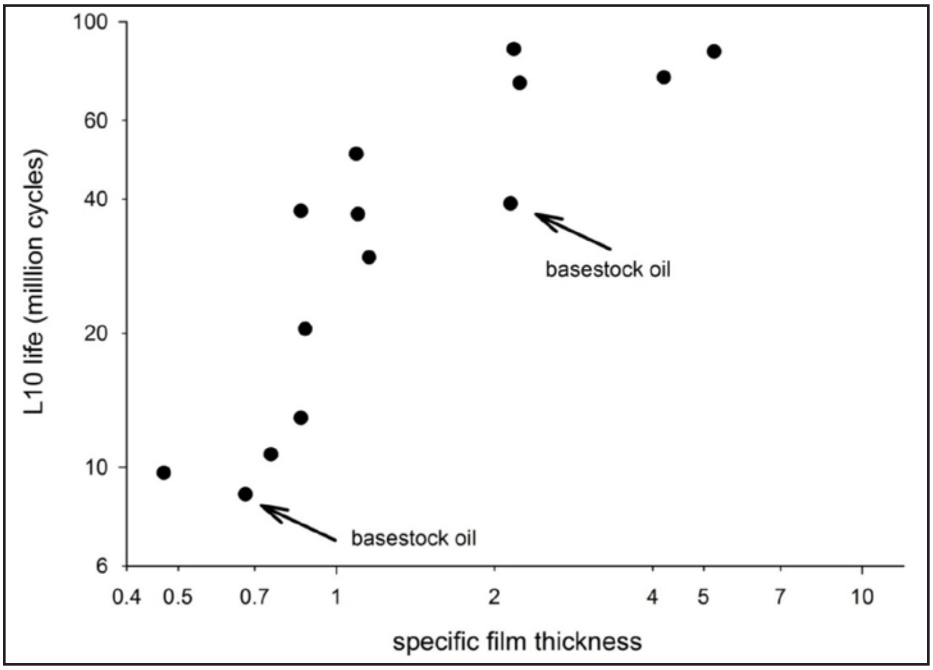

Figure 8 **Trend of adjusted L10 lives as a function of specific film thickness displayed using log-log scaling; test results using base stock oils (without additives) are noted by arrows.**

Results, Correlations and Comparisons

The correlation of the gear surface fatigue lives to the specific film thicknesses were studied by a variety of plots and comparisons to other work and data presentations. Presented first is the data of the present study, plotted using log-log scales (Fig. 8). From this plot one observes features that are qualitatively consistent with the literature, namely:

There is a strong correlation of surface fatigue life to the specific film thickness.

Over the range of specific film thickness of this study, the correlation is non-linear. Even with the use of log-log scales there is evidence of curvature to the correlation trend.

Gears operating near or above a specific film thickness of about two can operate for significantly longer time without surface fatigue (by a life-multiplying factor of approximately 8 ~ 10), as compared to gears operating at a specific film thickness of less than 0.8.

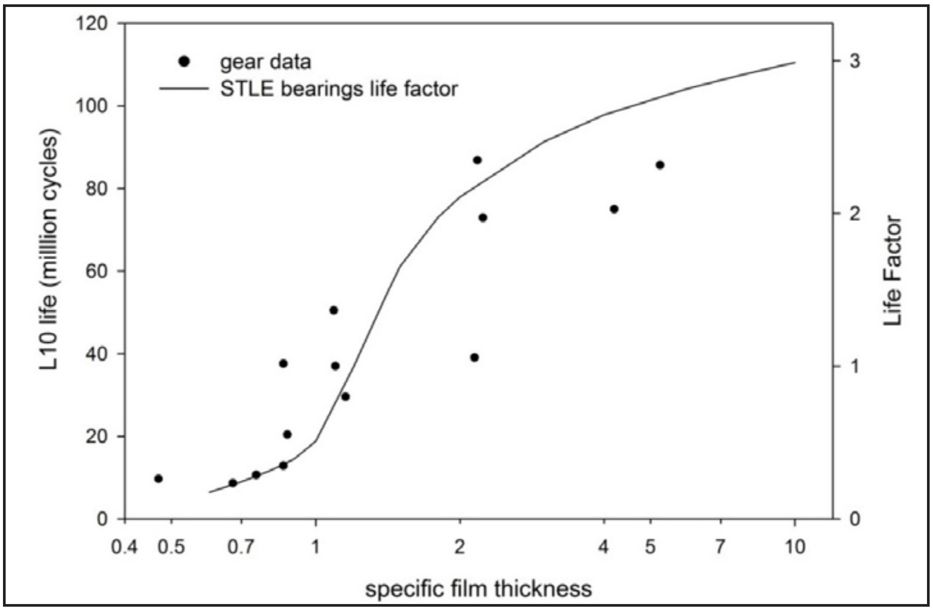

Figure 9 Comparison of the data of the present work using gears (data points) to life adjustment factor correlation recommended for life ratings of bearings (Ref. 12) (solid line).

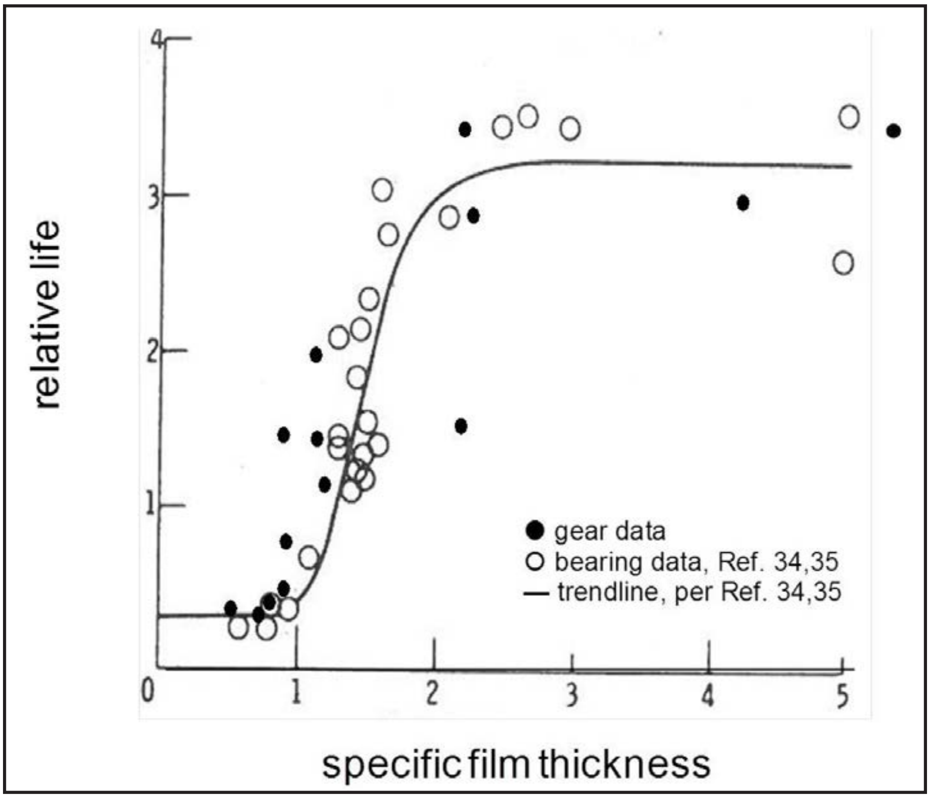

Figure 10 Compilation of the bearing life data of Skurka (Refs. 34-35) for cylindrical and tapered roller bearings (open symbols) and the gear life data of this study (solid symbols).

Also noted in Figure 8 are the two surface fatigue L10 life estimates for the gears tested using base stock oils without additives. It is interesting to note that these two data points tend toward lower bounds of the visual trend of life with specific film thickness. This perhaps points out the importance of not only the specific film thickness but also lubricant chemistry. This importance of additives is not surprising for the mixed-lubrication regime (specific film thickness ~ 0.7), but perhaps the additives and chemistry also play important roles even for lubrication regimes approaching "full lubrication." One should keep in mind that the specific film thickness is a separation of the "mean" levels of surfaces, and a specific film of one or even two does not guarantee separations of all asperity features.

The relationship of L10 surface fatigue lives to specific film thickness can be displayed by plotting the data of Table 5 in the manner of the life factor relationship for rolling-element bearings, as recommended by STLE (Ref. 12). The resulting plot of the present study — with comparison to the practice for bearings — is provided in Figure 9. This plot uses semi-log scales, matching the method of display of (Ref. 12). The gear data of this study is presented using symbols, while the STLE bearing rating life factor is presented by a line. The STLE life factor was scaled by a multiplier of 37 × 106 to provide this comparison. This scaling factor was selected to provide a "good fit by eye." We note that the gear data largely matches the trends of the bearing life factor curve. One can judge that the speculation that the influence of specific film thickness may be greater for gear life than for bearing life (Ref. 13) is not supported by the data of this study (Fig. 9).

Another bearing data set that provides an interesting comparison is the data of Skurka (Ref. 34) discussed by Anderson (Ref. 35). The data are for cylindrical and tapered rolling-element bearings. These bearings have rectangular-shaped contacts like the spur gears of this study. The data plot from (Ref. 25) was scanned and the data of this study were normalized to provide the same relative life range as for the bearings, and the gear data was overlaid. The resulting plot of the combined data set (Fig. 10) has open symbols for the bearing data, closed symbols for the gear L10 data, and a trend line suggested by Skurka. The bearing and gear data are quite similar — suggesting three regimes. There is a low-specific film thickness regime with relative life near 0.3, and a high-specific film thickness regime with relative life near three. The third regime is the transition regime for specific film of about 0.8 to about 2.5.

Some guidance for estimating gear life with respect to surface durability is given in AGMA 925-A03 (Ref. 29).

In this approach, a rating factor of the allowable stress is given as a function of the lubrication regime.

Three equations are stated, each one a straight line on log-log scales but having different slopes for each of three lubrication regimes. "Boundary lubrication," or Regime I, is defined as a specific film thickness less than 0.4. The "mixed lubrication," or Regime II, is for specific films in the range 0.4-1.0. The "full-EHL" Regime III is slated to begin for specific films greater than 1.0. The calculations to follow allow for a comparison of the AGMA 925-A03 method to the data of this study. From Figure 8, for the largest specific film thicknesses tested (full-EHL or Regime III) the L10 lives were about 80 million. Substituting this value for cycles into the AGMA equation for Regime III, the stress factor Z_n is 0.89. Now using this value for the Z_n stress factor and using the equation for Regime II (mixed lubrication), one can solve for the expected life — yielding 5.6 million. From Figure 8, the experimental data for the smallest specific film value (0.47) was a life of about 9 million. Expressing life for the beginning of the mixed-lubrication regime as a percentage of the life in the full lubrication regime, the AGMA method and the data of this study yield similar percentages — seven percent and 11 percent, respectively. The present study complements the AGMA method in helping establish the quantitative relationship in the transition between the mixed- and full-lubrication regimes.

Gear surface fatigue lives are directly correlated to the specific film thickness. The trend of the gear lives as a function of specific film is nonlinear, with a dramatic increase on the order of 8 ~ 10 times longer lives for gears operating with full film lubrication, as compared to gears operating with mixed lubrication.

Summary

In this work, gear fatigue test results from previous studies were collected, studied, and assessed so as to create a single, cohesive set of 258 gear fatigue tests that together enable a quantitative correlation of specific film values to gear surface fatigue lives. The gear tests made use of 12 lubricants with viscosities ranging from 3.2-9.1 cSt. The majority of gears in this study had ground surfaces. Two gear groups tested had superfinished surfaces. All gears were made from aerospace-grade gear steels and were case-carburized. All 258 tests were completed using the same rigs, torque, speed, lubricant temperatures, and by following the same test procedures.

This study comprised 14 groups of gears that were tested for surface fatigue, each group being a unique combination of alloy, surface finish roughness, and test lubricant. For each gear group, the surface fatigue test results were used to estimate the 10 percent lives (L10 lives) by modeling the fatigue life dispersions as two-parameter Weibull distributions and fitting the data using the least-squares median rank method. The average statistical sample size was 18.

The estimated L10 lives were adjusted to account for slight differences in load intensity due to lot-to-lot variations of gear tooth face width and edge breaks. The actual load intensities were determined by measuring the running track widths from microscope photos of tested gears, and then L10 lives normalized to common load intensity. The adjusted L10 lives of the 14 test gear groups ranged from 8.7-86.8 million cycles.

Specific film values were determined using film thickness calculated by Dowson's formula for line contacts, applying the formula to the pitch-line operating conditions. The surface roughness values used for the specific film thickness calculation were ones measured by stylus profilometer, digitally filtered using a 0.8 mm cutoff, and further adjusted using the concept of functional filtering. The specific film values for this study ranged from 0.47-5.2.

The adjusted L10 lives have a strong correlation to specific film values. The trend is one of increasing life for increasing specific film. The trend is nonlinear. The observed trends were found to be in good agreement with data and recommended practice for bearings. The L10 lives of this study in the mixed-lubrication regime were about 11 percent of the lives in the full-film-lubrication regime. This quantitative result is consistent with the relative values, as calculated by the methods of AGMA 925-A03. The specific film parameter concept has certainly been influencing the gearing practice for some time. The results obtained in this study will perhaps allow for the specific film parameter to be used with more confidence and precision to assess gear surface fatigue for purposes of design, rating, and technology development.

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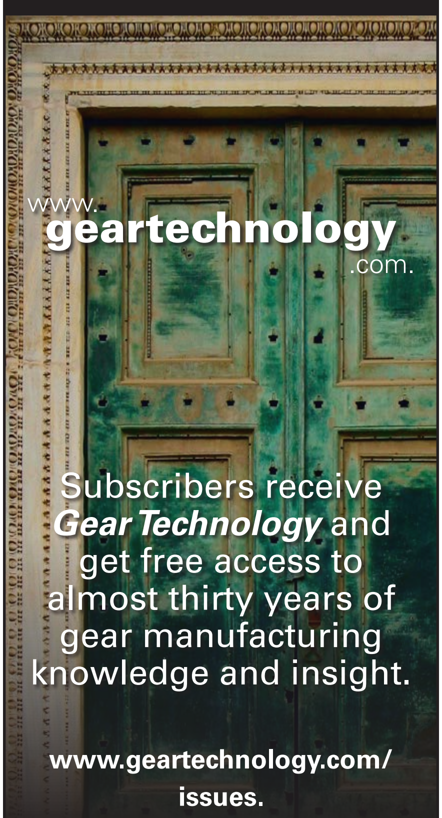

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Tim Krantz has since 1987 worked as a research engineer at the NASA Glenn Research Center—first as an employee of the U.S. Army and presently as an employee of NASA. He has researched many topics to improve power transmission components and systems, with an emphasis on helicopter gearbox technologies. He has also helped investigate several issues for the NASA Engineering Safety Center—including the space shuttle rudder speed brake actuator, space shuttle body flap actuator and the International Space Station solar alpha rotary joint mechanisms. Krantz is the current vice-chair of the ASME Power Transmission and Gearing Committee.

Quality and Surface of Gears Manufactured by Free-Form Milling with Standard Tools

Dr. Fritz. Klocke, Dr. Markus Brumm and Julian Staudt

The recently available capability for the free-form milling of gears of various gear types and sizes—all within one manufacturing system—is becoming increasingly recognized as a flexible machining process for gears. This paper addresses the manufacturing and quality of gears made by free-form milling, with an added focus on the specific process properties of the parts. Finally, the potential for free-form milling is investigated in cutting tests of a common standard gear.

Introduction

The free-form milling of gears recently becomes more and more important as a flexible machining process for gears. Due to use of standard milling tools and universal machine tools, free-form milling of gears does not depend on special tool geometries for each gear type. This makes the technology relevant for manufacturing of gears on universal cutting machines in various applications (Refs. 1–3); (Fig. 1).

With the use of standard milling tools the application area of gear types and sizes is theoretically unrestricted; accordingly, all conventional gear types and tooth geometries can be realized. Furthermore, the technology is flexible concerning new gear types.

Study Aim and Approach

Although the technology for the process design and manufacture is readily available (Refs. 4–9), there is nothing yet published concerning the potential of free-form gear milling pertaining to *gear quality*.

Gear manufacture via free-form milling with standard milling tools on universal machine tools is a combination of conventional gear manufacturing technology with special machines and integrated NC machining of complex geometries on universal cutting machines. Both domains are characterized by specific terminologies and technical terms. The fusion of both domains requires an agreement of technical terms in a disciplinary matrix for free-form milling of gears (Ref. 10).

Process capability will be analyzed in milling trials. Therefore hard-machining of a standard gear will be done with different machining strategies.

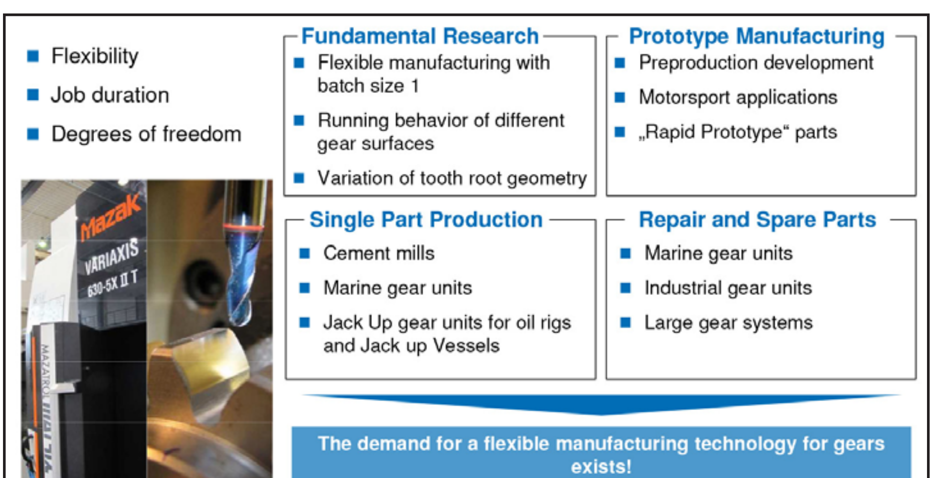

Figure 1 Motivation and area of application.

Terminology of Free-Form Milling

According to DIN 8589-3, manufacturing of gears on universal machine tools is located in the area of NC form milling (Ref. 11). The manufacturing process regarding machine tool and control unit is comparable to the manufacture of molds and dies (because of similar materials, hardness and accuracies), and to the manufacture of impellers (because of similar geometries). The process description includes the definition of process parameters, tool selection and the generation of input data (Fig. 2).

A full description of process characteristics of free-form milling of gears contains: tool selection, generation of input data and machining strategy; these three mentioned aspects will be discussed in the following sections. Characteristics beyond that are defined by terminology of gear manufacturing and NC free-form milling, and will be adapted.

Selection of milling tools. The selection of milling tools is divided into soft- and hard-machining. Between rough and fine cutting steps, a change of tools must be done because of different requirements. For the machining of tooth root, a tool change can be necessary, too. Standard milling tools are characterized by the parameters shown in the middle of Figure 2.

For stability reasons the tool diameter is chosen as large as possible. Tool length is chosen as short as possible. Tool size

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as well as the blade radius is restricted by the gear geometry.

Different types of milling tools are divided into groups by their blade geometry. Possible tool geometries are full radius, torus and shaft cutter (Fig. 2, middle). Depending on the type of tool, there is a point or line contact between tool and gear flank. The chosen machining strategy is essential for this contact condition and for restrictions of tool selection.

Generation of machine input data. In contrast to the manufacture of gears on conventional gear manufacturing machines, free-form milling of gears requires a defined geometry in the form of coordinates. Figure 3 shows the CAx process chain that is necessary for the generation of the NC code.

After gear design, the gear data is the input for the CAx process chain. In the first step, the gear data is transferred to the gear geometry. The creation of gear geometry can be done analytically or by a manufacturing simulation that includes a defined geometry off both flanks and tooth root. In the following step the gear geometry is converted into NC code. Any deviation of geometry resulting from the manufacturing process can be negated by closed-loop between manufacturing, gear measurement and generation of NC code. Depending on the correction method, different steps of the CAx process chain are necessary for this compensation (Fig. 3, right).

Machining strategy. The machining strategy includes three major aspects of the definition of the manufacturing process: 1) *lineness*; 2) *trajectory*; and 3) *indexing procedure* (see Fig. 4).

The *trajectory* defines the path of the tool in machining relative to the tooth flank. The *lineness* is the term for the quantity of tool paths required for the machining of one tooth flank and the space between the lines. The *indexing procedure* describes the systematics of machining all gaps successively. This includes the manufacturing order and movement of all axes during indexing between two teeth. All three components of the machining strategy are defined and described in detail in the following sections.

Trajectory. The definition of the trajectory is based on technological requirements for the running behavior of the

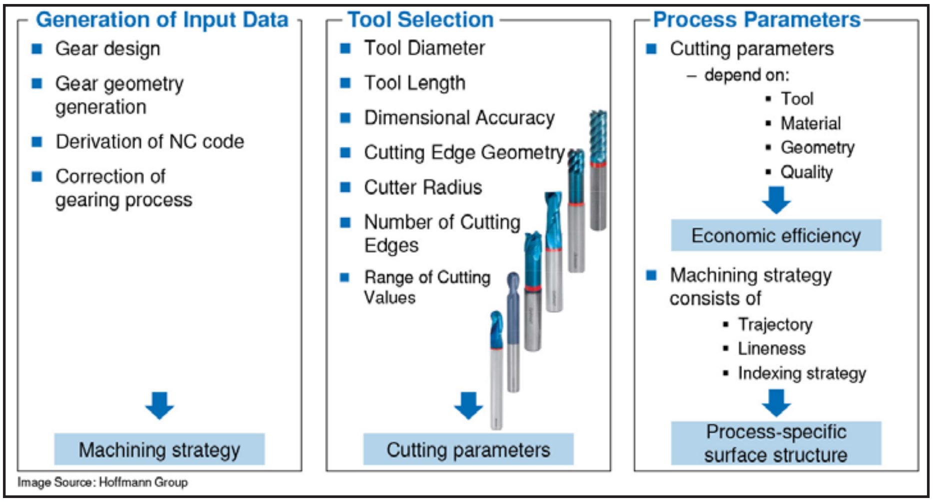

Figure 2 Process characterization of free form milling for gears.

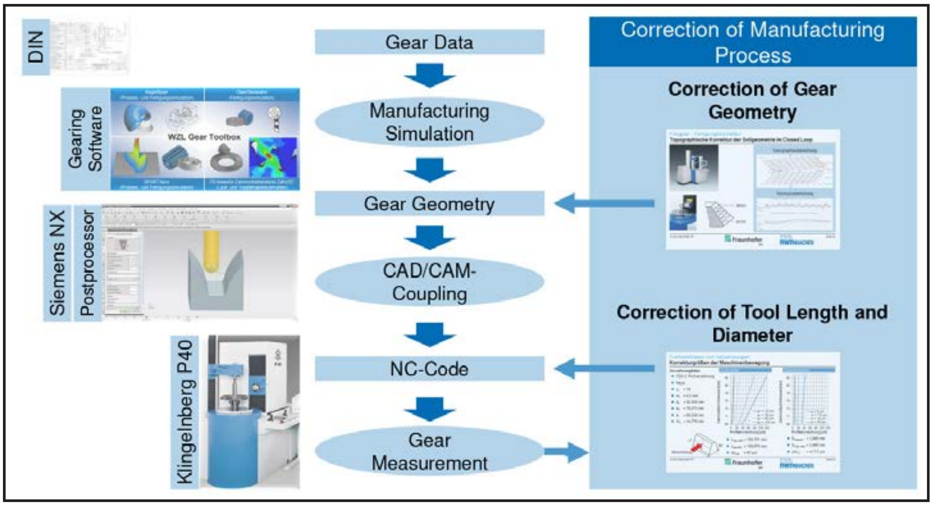

Figure 3 CAx process chain of generation of NC code.

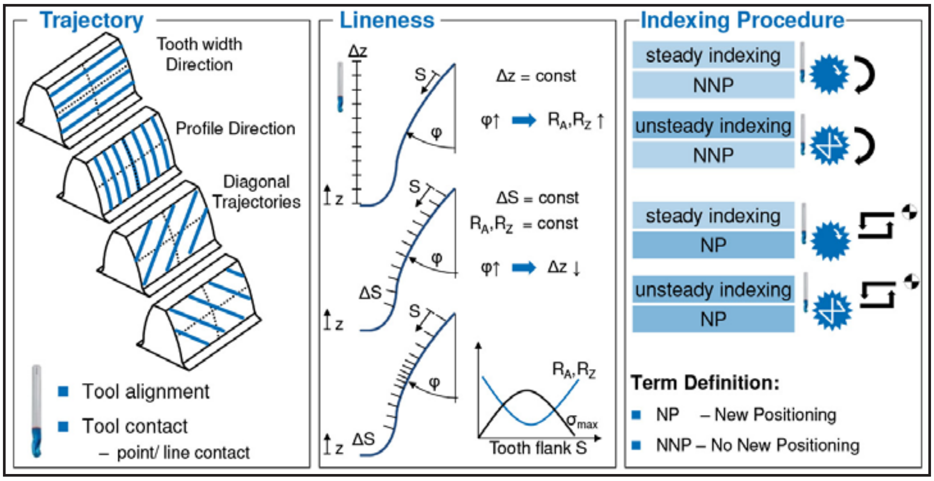

Figure 4 Machining strategy of free form milling of gears.

gears. Furthermore, the trajectory has a significant influence on processing effort and process kinematics (Fig. 4, left). The trajectory can be defined in direction of tooth width, profile direction or diagonal on tooth flank. Furthermore, common structures can be imitated (gear honing or gear finish hobbing) and new structures realized. From the manufacturing perspective, there are no technological restrictions. In terms of economical process design, the complexity of trajectories has to be taken into account, because complex trajectories require additional axes and tool movements.

Lineness. One, lineness defines the number of tool paths, which significantly influence machining time; two, lineness defines the schema, i.e. — how tool paths are located on the tooth flank. There are three possibilities that can be seen in the middle of Figure 4:

Tool feed can be equidistant for each tool path. That leads to a changing structure all over the tooth flank.

Define tool feed depending on gear geometry in order to keep the space between two paths on the gear flank constant. Surface structures at tip and tooth root are the same.

An independent definition of line spaces in tool feed and tooth profile direction. Here the structure can be defined freely and the flank surface can be realized basing on stress deviation for the whole flank. According to this, the effort for process configuration is very high in this case.

The space between tooth paths defines kinematic surface roughness (Refs. 12–13). The kinematic surface roughness can be described geometrically, so that the surface requirements can be taken into account during configuration of the milling process.

Indexing strategy. Centering of the gap for hard-machining can be realized by measuring equipment on the machine tool. The indexing strategy can be steady or unsteady.

During steady indexing the proximate gap is located next to the current one. The advantages are short movements of tool and part during machining. As a result, short machining times are attainable. Errors in part rotation and thermic influences are accumulated during

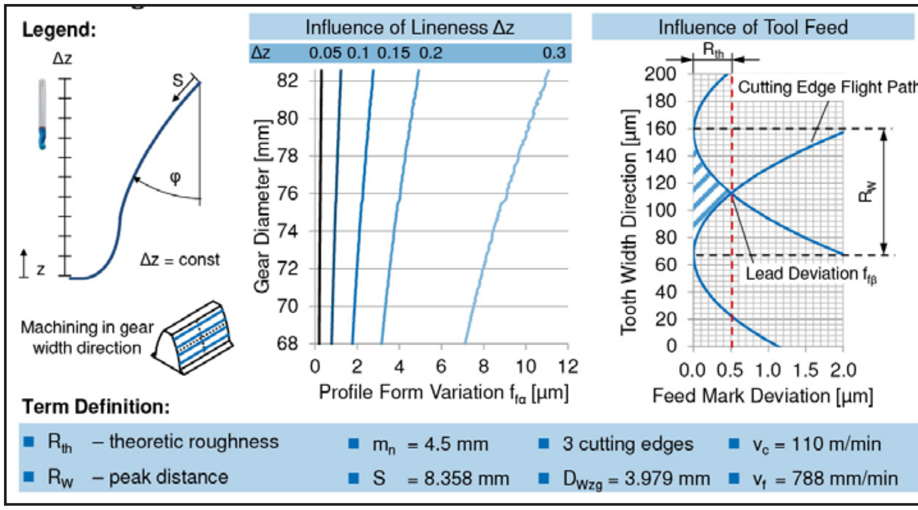

Figure 5 Influence of process parameters on kinematic surface roughness.

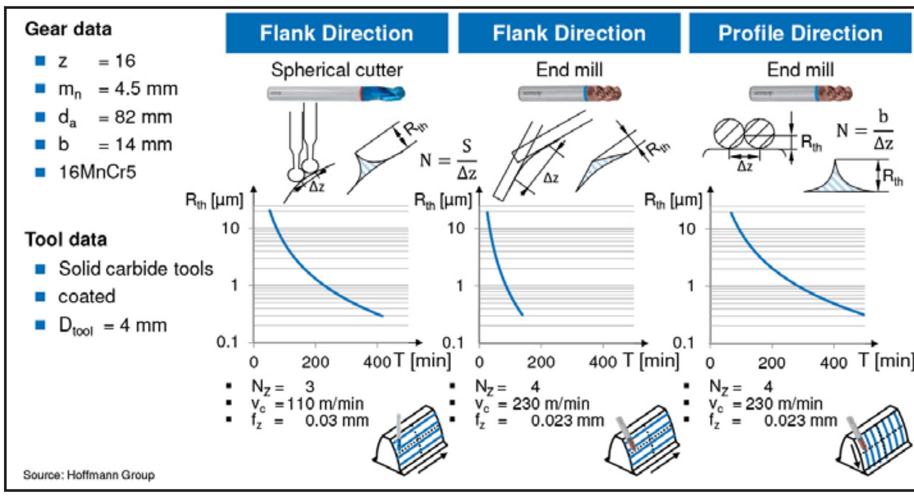

Figure 6 Machining time based on different milling strategies.

machining, so that the pitch deviation between first and last tooth are high.

During unsteady indexing, the gaps are machined in even distribution around the gear; errors are not accumulated in this case. The peak of pitch deviation can be avoided in this case. Machining time will be higher than with steady indexing, because more movements are necessary.

Process-specific surface structure. Lineness and trajectory directly influence the process-specific surface structure; the trajectory defines the orientation and the amount of lineness.

The free-form milling of gears has a high degree of freedom concerning different machinable surfaces, in comparison to conventional gear manufacturing. Similar to gear hobbing, the surface structure can be divided into feed marks (form tool blades) and generated cut marks (lineness). The theoretical roughness can be calculated — as well as determined — based on tool movement (Refs. 12–13). Dimensions of both deviations for one example gear are shown in Figure 5.

Profile deviation is increasing exponentially, with decreasing number of lines. Fifty lines lead to profile form deviation $f_{fα} << 2\,µm$, which is quality class one. In this example, the trajectory is oriented in gear width direction so that feed marks should be visible as tooth flank form deviation $f_{fβ}$. The diagram on the right-hand side shows the roughness R_{th} that occurred because of tool feed. For this purpose the flight path of the cutting blade is sketched in the diagram. Tool feed during one rotation of the tool is $f = 0.09$ mm, so that for this example theoretical roughness is $R_{th} = 0.50\,µm$ as a result of radial run-out of the tool.

In comparison to gear hobbing, the machining time for rough machining is much higher. This is related to two main aspects: the required surface roughness and the defined machining strategy.

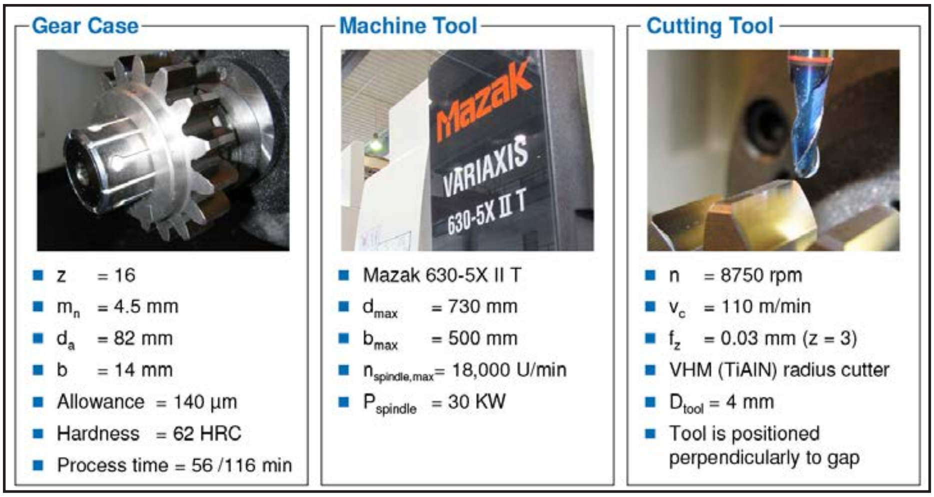

Figure 7 Gear case and machine tool.

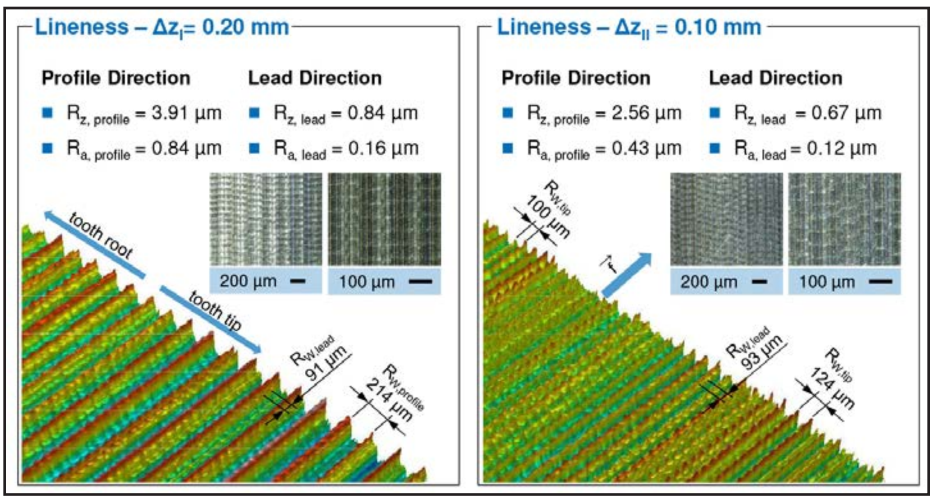

Figure 8 Analysis of process specific surface structure.

Figure 6 gives an overview of the influence of both aspects on machining time T per part.

The initial machining strategy on the left-hand side was arrived at with a radius cutter (Fig. 5); the tool is positioned perpendicularly to the tooth flank. The machined quality is directly related to deviations of tooth diameter and length. Surface roughness is directly defined by the penetration of tool radius. Quality class one ($R_{th} < 2\,\mu m$) requires a machining time of T = 160 min. The advantage of this strategy is that fewer axes are necessary for machining.

The second strategy in the middle of Figure 5 is using a shaft cutter. The tool is positioned tangential to the tooth flank. Note that deviation of tooth diameter is influencing tooth width — but not profile quality. The tool is cutting with the outer diameter so that a deviation of tool length has no influence on part quality. What is more, the tool can be shifted so that tool wear can be distributed equally over the entire length of the cutting blade. This strategy is much more efficient than the first one because fewer lines are necessary. Hence the machining time for $R_{th} < 2\,\mu m$ is T = 70 min.

The third machining strategy on the right-hand side of Figure 5 is using a trajectory in profile direction; tool and cutting parameters are equal to the second strategy. The tool is also positioned tangential to the tooth flank and is cutting with the outer diameter. In comparison to the other strategies, a high number of lines is required. In addition, complex movements of tool and part are necessary, which leads to a machining time of T = 200 min for $R_{th} < 2\,\mu m$.

Analyisis of Process Capability in Milling Trials

Process capability of free-form milling of gears with standard milling tools on universal cutting machines can be validated by hard-machining of parts after heat treatment. Hard-machining includes aspects of CAx process chain, as well as quality requirements of finished gears.

Gear geometry and machine tool. In order to analyze the process capability of the free-form milling of gears, a trial series with standard spur gears was carried out. Due to the smaller amount of influences, this simplification offers the opportunity for the basic research of fundamental process phenomena; the principles of process correction can be comprehended directly. Also, this gear type can be compared to various research projects with the same gear type.

For the milling trials the parts were soft-machined conventionally. Hard-machining tests were done after heat treatment (hardness 62 HRC). Thus the focus is on tooth flank quality. The tooth root was not hard-machined. Allowance for hard-machining was 140 µm to 150 µm. Radial and axial run-out were checked manually and less than 2 µm.

Experimental Set-Up and Overview

Cutting parameters were adopted from tool manufacturer data. Cutting velocity and tool feed were constant for all tests. Machining was done dry without cutting fluid.

The influence of lineness was analyzed; therefore two different feeds were compared. The first process had a feed of $\Delta_{zI} = 0.2$ mm (42 lines). The second process had a feed of $\Delta_{zII} = 0.1$ mm (84 lines). The trajectory was defined in tooth width direction. Tool feed was constant between two paths, so that tool positions were equidistant.

In the beginning of machining, the part was centered by measuring equipment of the machine. During indexing no additional centering step was applied. The indexing strategy was varied. Three different strategies were tested. Focus of the analysis was the process-specific surface structure of the flank and pitch deviation, as well as the tooth profile quality of the machined gears.

Surface analysis of gear flanks. Gear surface analysis was done by digital microscope as well as tactile measurement of 3D surface topology (4.8 mm × 4.8 mm); (Fig. 8).

Based on these measurements the influence of lineness on surface structure can be described. Therefore gears were manufactured with two different line spaces, i.e. — $\Delta_{zI} = 0.2$ mm and $\Delta_{zII} = 0.1$ mm. It can clearly be seen that the surface structure significantly depends on the defined lineness. The line space is clearly visible in the measured topologies. The line space also changes over the tooth profile — which was expected — because of the equidistant tool feed ($\Delta z = const$). So the line space increases at the tip of the tooth.

Pitch deviation. Since free-form milling of gears is a discontinuous indexing process, every gap is machined separately and the focus must be on pitch deviation of the manufactured gear. Therefore different trials with three indexing strategies were compared. For every trial a whole gear was machined using one single strategy. Individual and total pitch variation (f_p and F_p) as well as pitch error f_u were compared (Fig. 9).

The first trial on the left-hand side was carried out with steady indexing and without new positioning of machine axes (NNP). Most gaps show a small, single pitch deviation. Only between the last and the first tooth is there a high single pitch deviation of $f_p = 7.0$ µm (quality class 6); the total pitch deviation F_p has quality class 2.

The second trial, shown in the middle, was also carried out with steady indexing but with new positioning of all machine axes for each gap (NP). The total pitch deviation is similar to the trial on the left-hand side (quality class 2). The single pitch deviation was reduced to $f_p = 4.8$ µm (quality class 5) — within the quality requirements for this gear.

The third trial (on the right-hand side) shows mainly higher individual pitch deviations. Nevertheless the highest pitch error ($f_{u\,max} = 6.6$ µm) leads to quality class 4. Also, the maximum individual pitch deviation is $f_{p\,max} = 3.9$ µm (quality class 4), which is an additional improvement in quality in comparison to the other indexing strategies. *And*, the total deviation F_p has a better quality.

Form deviation of gear tooth. The tooth flank form deviation $f_{f\beta}$ has quality class 1 for all parts. The deviation of tooth flank angle $f_{H\beta}$ has quality class 2. This can be caused by deviation of the fixture of the part. In total, the results are very sufficient.

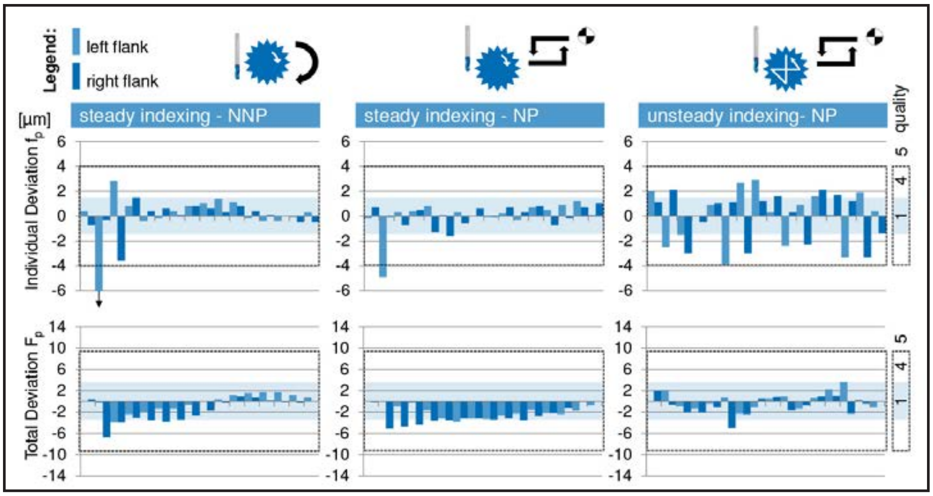

Figure 9 Pitch deviation depending on machining strategy.

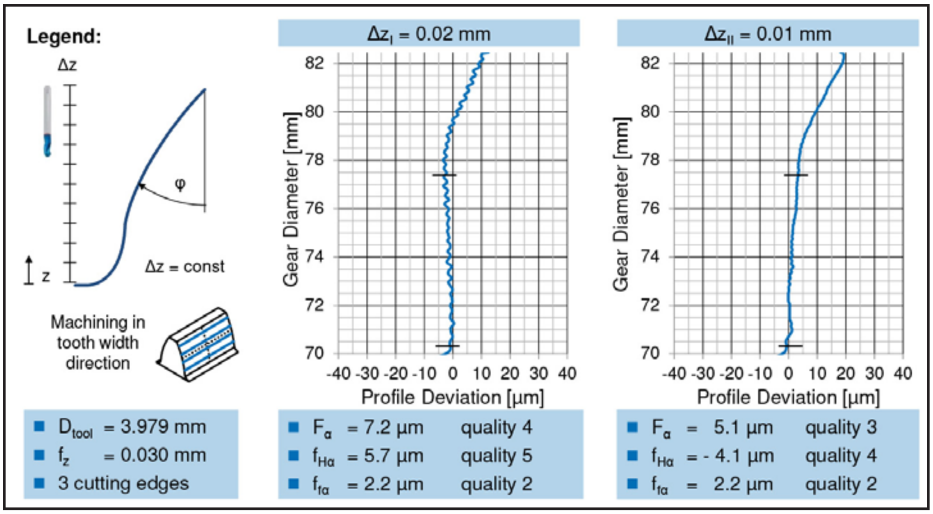

Figure 10 Profile deviation depending on lineness.

The main focus is on the analysis of profile deviations $f_{H\alpha}$ and $f_{f\alpha}$. Lineness was varied from $\Delta_{zI} = 0.2$ mm to $\Delta_{zI} = 0.1$ mm; line space was equidistant. The results are shown in Figure 10.

The comparison of both results shows significant influence of lineness on profile form deviation $f_{f\alpha}$. For tool feed of $\Delta_{zI} = 0.2$ mm, maximum profile deviation is $f_{f\alpha} = 2.1$ to 2.6 µm. These values are very similar to the calculated values for kinematic surface roughness $R_{th} = 2.5$ µm.

For tool feed of $\Delta_{zI} = 0.1$ mm, the profile form is much smoother. Nevertheless the profile deviation is in the same range — $f_{f\alpha} = 1.2$ to 2.7 µm. This error cannot be based in kinematic surface roughness, which is $R_{th} = 0.63$ µm.

Summary and Outlook

Gear manufacturing with free-form milling has recently become more relevant for industrial use. The key reasons for that are high degrees of freedom, as usage of universal tool geometry and machine tool allows for the flexible machining of various gear types and sizes with one manufacturing system.

As "state-of-the-art" provides no sufficient description of this manufacturing process in any literature, terminology has been developed concerning the process characteristics of the free-form milling of gears. As such, machining strategy was fully defined in this paper. This definition includes the trajectory (path of tool movement during cutting process); lineness (number and distribution of trajectories); and the indexing strategy (machining order of gaps), as they are the three main components of the machining strategy. Additionally, process-specific surface characteristics were described and calculated, enabling immediate consideration of surface structure during process design for different machining strategies and tools.

Machining tests were conducted. Results show a direct link between process parameters (feed and lineness) and gear surface. Also, they validate the consideration of surface structure, as the correlation between test and calculation is sufficient. Gear geometry shows good results concerning pitch (quality 4) and tooth flank form deviation (quality 2). Furthermore, profile form variation is directly influenced by lineness.

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Regal Beloit

ACQUIRES POWER TRANSMISSION SOLUTIONS OF EMERSON ELECTRIC

Regal Beloit Corporation recently announced it entered into a definitive agreement to acquire the Power Transmission Solutions business (PTS) of Emerson Electric Co. for approximately $1.4 billion in cash plus $40 million of assumed liabilities.

"This acquisition will be transformational for Regal," said Regal Beloit Chairman and CEO Mark Gliebe. "PTS will broaden our portfolio, diversify our end market exposure and strengthen our global footprint. PTS brings complementary products and well-known brands, but more importantly a very talented team who are experts in their markets as well as very strong operators. We are excited to have PTS as part of the Regal family and we look forward to growing with them in our future."

PTS is a manufacturer of highly engineered power transmission products and solutions. The business manufactures, sells and services bearings, couplings, gearing, drive components, and conveyer systems under brands including Browning, Jaure, Kop-Flex, McGill, Morse, Rollway, Sealmaster and System Plast. With annual revenues of approximately $600 million, PTS has over 3,000 employees around the world. PTS will become part of Regal's newly-defined Power Transmission segment.

"PTS is a strong business with an outstanding management team and excellent brand recognition," said Emerson Chairman and Chief Executive Officer David N. Farr. "The business will benefit by joining Regal, who has a proven track record of success in building and growing businesses. Regal management estimates 2015 accretion between $0.40 and $0.60 per share including purchase accounting adjustments and closing costs, and 2016 accretion between $0.95 and $1.15 per share. Transaction synergies are estimated to be $30 million within a four year period."

The transaction, which is subject to customary closing conditions, is expected to close in the first quarter of 2015. Shareholder approvals are not required to complete the transaction. Robert W. Baird & Co. served as the exclusive financial advisor to Regal. White & Case LLP served as the legal advisor to Regal.

Star SU

FORMS ALLIANCE WITH PROFILATOR

Star SU LLC recently formed an alliance with Profilator to manufacture Scudding tools for the global market and in North America, in cooperation with GMTA in Ann Arbor, MI.

Scudding is an improvement on traditional power skiving technology for gear production. Often thought to be limited to internals only, Scudding is beginning to compete in shaping, broaching and other gear cutting applications for gears and splines.

"Star SU is using its vast experience of gear cutting tool technology for new tool development, as well as its tool service centers to support Profilator on this new technology process," said David Goodfellow, president of Star SU LLC. "We are looking forward to working with Profilator and GMTA and see this as mutually beneficial for each company."

H-D Advanced Manufacturing

ACQUIRES INTELLIFUSE TECHNOLOGIES LLC

H-D Advanced Manufacturing recently announced that it acquired Intellifuse Technologies LLC, the sixth acquisition completed by H-D in the two years since it was formed in December of 2012.

Intellifuse joins Overton Chicago Gear Corporation, a manufacturer of large, heavy duty gears and gearboxes; Innovative Mechanical Solutions (iMECH), a manufacturer of custom bearings for the downhole mud motor industry; Leading Edge Heat Treating Services Ltd., a provider of heat treating solutions; Sungear, a manufacturer of high precision gears and assemblies for the aerospace industry; and Crown, a manufacturer of specialty components used in hydraulic actuation systems for commercial aircraft.

Located in Houston, TX, Intellifuse manufactures radial bearings, pads and other wear products. The addition of radial bearings to the H-D product portfolio is expected to complement the existing thrust bearings currently offered by iMECH. Both of these products are incorporated into the downhole drilling motors used by oil and gas companies and will operate out of a new facility in Houston.

Intellifuse's cofounders, Mike Speckert and Majid Delpassand, will remain with the business. Speckert will be the manager of U.S. operations for the combined iMECH and Intellifuse business, while Delpassand will serve as an advisor to the company.

"Intellifuse's coated radial bearings are proven in the market and represent an outstanding, complementary line extension for iMECH," said H-D CEO Chris DiSantis. "Intellifuse and iMECH are both experts in the manufacture of downhole mud motor components. We will now be able to provide our customers with another durable solution that enhances drilling efficiency, reduces cost per circulating hour, and allows for higher asset utilization."

"H-D shares our vision for growth and can provide the resources required to invest in facilities, equipment and product development," added Speckert. "We're excited to partner with H-D and look forward to expanding our relationships with both new and existing customers."

H-D was formed in December 2012 by a partnership among Hicks Equity Partners, The Riverside Company and Weinberg Capital Group to acquire and develop manufacturers of mission-critical, precision engineered components.

Sylvia Wetzel

SPEAKS AT ANNUAL REGIONAL MEETING

On Monday Dec. 8, Bison Gear & Engineering Chief Learning Officer Sylvia Wetzel spoke at the National Fluid Power Association's (NFPA) annual regional meeting at Harper College (Palatine, IL). The meeting, which focused around workforce development, was geared toward helping a company address the challenge of finding and maintaining a skilled manufacturing workforce.

In addition to Wetzel, the meeting featured Dr. Maria H. Coons, vice president of Workforce and Strategic Alliances, who also spoke on the need for developing a maintainable skilled workforce.

Wetzel has implemented the National Association of Manufacturers (NAM) stackable credentials at Bison for all production personnel, improving productivity within the organization by 32%. She was also a leader on the state-wide STEM manufacturing program study in Illinois, and continues to lead the Skilled Workforce Initiative to create and implement solutions that can remedy the shortage of qualified entry level workers.

Tooling U-SME

MAKES COMPETENCY FRAMEWORK AVAILABLE

Tooling U-SME, a company specializing in manufacturing training and development, recently launched a new industry resource — Tooling U-SME's Competency Framework.

The Competency Framework offers a newly designed online tool allowing companies to implement it across their organizations. The Competency Framework helps companies combat the increasing talent shortage and achieve stronger performance from their workforce while providing development pathways and career growth opportunities for their employees. It features a series of competency models in nine manufacturing functional areas and is made up of more than 60 defined job role competency models, outlining knowledge and skill objectives for job roles in production, technician, and lead technician/technologist and engineer levels.

"While employers invest in equipment, tooling and materials, they often neglect to make similar investments in their employees," said Jeannine Kunz, managing director of workforce and education for SME. "Tied to business goals, a well-designed training program, including the Competency Framework, becomes the foundation for performance management, talent acquisition, and leadership development, which helps drive a company's competitiveness."

Created by a committee of experts from industry and academia, Tooling U-SME's Competency Framework is designed to complement other competency models in the marketplace. It can be used "as is" or customized to individual work practices at a company's facility. For an improved training and development process, knowledge objectives within the framework are mapped directly to Tooling U-SME's extensive training resources.

Dr. Sebastian Idler

WINS CTI YOUNG DRIVE EXPERTS AWARD

On December 10, the 6^{th} Annual CTI Young Drive Experts Award Ceremony was held at the 13th International CTI Symposium for Automotive Transmissions, HEV and EV Drives. The runner-up was Dr. Felix Töpler, while first place went to **Dr. Sebastian Idler**. The honorary speech was held by Prof. Dr. Ferit Küçükay of TU Braunschweig, who is a jury member and the chair of the Berlin Transmission Symposium.

Töpler won the award for his PhD thesis on “Predictive Energy Management for Plug-in Hybrid Vehicles.” In its statement, the jury explained that “Dr. Töpler added a prediction function to existing operating strategies of plug-in hybrid vehicles. In a realistic driving cycle, the parallel plug-in hybrid vehicle assessed consumed 5 percent less energy than a hybrid vehicle without the prediction function.” Dr. Töpler wrote his paper as a student at the RWTH Aachen. He currently works as a senior engineer in the field of drive systems at FKA: Forschungsgesellschaft Kraftfahrwesen mbh Aachen.

The title of Idler’s winning PhD thesis was “Scuffing Load Capacity of Continuously Variable Transmissions.”

In his honorary speech, Küçükay said “[Using Idler’s applied procedure] it is possible to optimize the pressure strategy in relation to temperature, and hence to prevent scuffing reliably during operation.”

Idler currently heads the E-Mobility Team at the Gear Research Centre (FZG) at Munich Technical University.

Koepfer America

SPONSORS ‘ITALIAN GEAR TECH TOUR’

Koepfer America sponsored a group of North American gear manufacturers on a technology-focused “Italian Gear Tech Tour.” The trip started Nov. 16 and ended Nov. 22, 2014, and covered the latest Italian gear products to be introduced to the North American market.

The group consisted of select representatives from the industry’s leading gear manufacturers who received a personal look into these companies as well as tours of several gear manufacturers, such as Corradini Giacomo Gears and OMIG Ingranaggi.

The tour took place in the northern region of Italy where the country’s heart of manufacturing is concentrated. A key stop was to CLC, one of Italy’s fastest growing gear machine tool manufacturers.

“It was a pleasure to host such a great group of gear manufacturers,” said Roberto Cervi, president of CLC. “We truly welcome the opportunity to share the latest technology being developed and implemented in our factory.”

Of particular interest to the group were CLC’s horizontal hobbing machines, which provide new options for the U.S. market. The tour highlighted these machines’ flexible customization that allows for the hobbing of long shaft-type parts up to 3 meters in length. CLC's gear shaping machines also presented a high-quality gear cutting solution that the group found intriguing.

Another featured stop on the Italian Gear Tour was to Fubri, one of Europe's premier gear cutting tool manufacturers. The tour included a close-up look at the many operations involved in manufacturing a gear cutting tool, such as relief grinding, gash milling, and final inspection and certification. The tour group learned about Europe's new high-speed steel, MC90, which features a specialized, high-quality heat treatment process that provides a material competitive with carbide.

"I enjoyed the opportunity to participate in the tour," said Simone Guarna, head of sales and marketing for Fubri. "I think the group valued the demonstration of our factory's wide range of capabilities in manufacturing high-quality, medium- and coarse-pitch gear cutting tools."

Artur Pajak

NAMED VICE PRESIDENT OF OPERATIONS FOR EFD INDUCTION GROUP

EFD Induction Group, a maker of induction-based industrial heating solutions, recently announced the appointment of **Artur Pająk** as vice president of operations.

"I'm of course excited to be joining EFD Induction" said Pająk. "The company has an enviable customer base and a global presence. That, plus the fact that we have superior applications knowledge and equipment technology means we are well positioned to become even more successful."

A Polish national, Pająk holds a Master and Engineering Degree from Radom University of Technology, as well as an Executive MBA from Warsaw University of Technology Business School. Pająk joins EFD Induction from Kongsberg Automotive, where he served as director of business line interior.

"I'd like to welcome Artur Pająk aboard," said CEO Bjørn Eldar Petersen. "He brings significant experience from the global automotive industry to EFD Induction, and he has keen insight and leadership that will prove invaluable to us as we work to safely and reliably deliver induction heating solutions to the world's leading manufacturing companies."

EOS and MTU

FORM JOINT STRATEGIC DEVELOPMENT OF THEIR TECHNOLOGIES

EOS, the global technology and quality leader for high-end additive manufacturing (AM) solutions, and MTU Aero Engines, Germany's leading engine manufacturer, are closely cooperating to develop quality assurance measures for metal engine components using additive manufacturing. The two companies have now signed a framework agreement for the joint strategic development of their technologies.

The first result of these joint endeavors is the optical tomography (OT) developed by MTU, a complement to the modular EOS monitoring portfolio. In addition to several sensors that monitor the general system status, the camera-based OT technology controls the exposure process and melting characteristics of the material at all times, to ensure optimum coating and exposure quality.

"MTU and EOS have been working intensively for several years, and this collaboration is now about to develop into an even closer, partner-based technological cooperation, centered on their quality assurance tool," said Dr. Adrian Keppler, head of sales and marketing (CMO) at EOS. "The OT solution enables us to perform an even more holistic quality control of the metal additive manufacturing process—layer by layer and part by part. A very large proportion of the quality control process that previously took place downstream can now be performed during the manufacturing process, with a considerable saving in quality assurance costs. This also allows us to satisfy a central customer requirement in the area of serial production."

Quality assurance is important in the field of serial production because it is vital both for ensuring repeatable high component quality and for continually reducing the quality control costs of components made using the technology, which ultimately serves to reduce unit costs. The system settings and process parameters are constantly monitored in the ongoing manufacturing process on EOS systems, to ensure that system and manufacturing process conditions are ideal for maximum component quality.

February 23-25 – MIM 2015 Sheraton Tampa Riverwalk, Tampa, FL. Metal injection molding, ceramic injection molding and cemented carbide injection molding have estimated sales of nearly $1.5 billion and could possibly double in a span of five years. With this continued growth and interest, the industry has realized major technological advances and overcome numerous business challenges. The objective of the conference is to explore these advances, assist in the transfer of technology, and investigate new developments in the field of injection molding of metals, ceramics, and carbides. The conference is targeted at product designers, engineers, consumers, manufacturers, researchers, educators, and students. All individuals with an interest in the application of powder injection molding will be encouraged to attend. For more information, visit *http://mpif.org/MIM/MIM2015/index.html*.

February 24-26 – Houstex 2015 George R. Brown Convention Center, Houston. Everything about Houstex 2015 is big, from the venue to the location to the opportunity. Exhibitors at Houstex 2015 can solidify their place in one of the nation's leading manufacturing regions, expand into new markets and industries, connect with decision-makers from diverse companies, demonstrate their products in a meaningful way, and network with the biggest thinkers and doers in Southern Manufacturing. Houstex 2015 is an immersive experience, featuring hundreds of exhibitors highlighting the latest manufacturing technologies and new interactive opportunities. Attendees will enjoy scores of new product demonstrations, hear experts share insights on industry trends and make connections that can take their company to the next level. For more information, visit *www.houstexonline.com*.

March 3-8 – TIMTOS 2015 Taipei City, Taiwan. It is estimated that over 1,000 exhibitors from 17 nations will be in attendance. The exhibit's 5,400 booths will make maximum use of the available 100,000 square meters of space spread out over the four venues. At the press conference held in November 2014, industrial journalists from Taiwan and abroad were present, paying close attention to the latest news on TIMTOS, Taiwan's machine tool exports and the domestic trade fair development. Officials answered any concerns and provided an abundance of information and analysis. In the end, people in the industry were invited to participate in the most concentrated machine tool show in Asia, TIMTOS 2015. For more information, visit *www.timtos.com.tw*.

March 4-7 – The MFG Meeting Orlando World Center Marriott, Orlando, FL. The MFG Meeting brings together the manufacturing industry for a conference experience that provides educational and networking opportunities. Engage with the industry's thought leaders and discuss business solutions with peers – all in one place. One of the highlights of this year's conference will be a training session with Michael Hoffman, president of Igniting Performance, a company that specializes in sales, leadership and building customer loyalty. His innovative program, "Secrets of the 1%ers," taps into the methods and the motivations of the best of the best – showing how they became influential – and how to replicate their success. For more information, visit *www.themfgmeeting.com*.

April 20-23 – AeroDef Manufacturing Hilton Anatole, Dallas, TX. New in 2015, AeroDef Manufacturing will take place in Texas, one of the top manufacturing states in the country. The new location offers opportunities to reach a promising new audience for any company. The leading aerospace and defense OEMs have come together to provide direction for AeroDef have and lend insight on what they need from suppliers, discuss their current and future technology investments and plan for developing a skilled workforce. AeroDef attracts high-level attendees with exclusive content developed – and presented – by the leading aerospace and defense OEMs. Speakers, panel discussions and the technical conference are carefully selected to address issues and technologies of strategic importance to the industry. Networking events are held on the floor to encourage meaningful collaboration among presenters, attendees and exhibitors. For more information, visit *www.aerodefevent.com*.

May 12-14 - EASTEC Eastern States Exposition, West Springfield, MA. With more than 500 exhibitors, complimentary conference sessions, industry keynotes and much more, EASTEC is an event dedicated to keeping northeast manufacturers competitive. It's where manufacturing ideas, processes and products that make an impact in the northeast region are highlighted through exhibits, education and networking events. The event offers a unique chance to connect with resources that can solve any company's most pressing problems, improve productivity and increase profits. It's clear why so many business owners, engineers, designers, production managers and purchasing executives attend EASTEC to keep their operations current. EASTEC brings human ingenuity and manufacturing brilliance together. For more information, visit *www.easteconline.com*.

June 9-11 – Parts2Clean Stuttgart/Hannover, Germany. Cleaning parts and surfaces costs money – just how much money depends on the required result. Whether the job is simple degreasing or cleaning to meet strict technical requirements, achieving the necessary quality quickly, reliably and economically involves factors that go beyond the cleaning method used and include the selection of the proper cleaning medium and containers and subjects like bath maintenance and packaging of the cleaned parts. You can explore all these aspects at Parts2Clean, the only trade fair in the world focusing exclusively on industrial parts and surface cleaning. Parts2Clean not only reflects today's market in its entirety, but also offers lots of added value in terms of its unparalleled three-day forum. For more information, visit *www.parts2clean.com*.

June 17 – Western Manufacturing Technology Show Edmonton EXPO Centre, Edmonton, Alberta. True to its name, WMTS targets the specific needs of manufacturers in Western Canada. Ever-evolving technology, unique economic challenges, and the heavy influence of the oil and gas industry present a diverse mix of circumstances — and WMTS is up to the task of meeting them. A showcase of top solution providers, the WMTS has the answers attendees are searching for. Walk the show floor and meet face-to-face with the experts who can explain how applying new methods and advanced technology can improve operations and margins. Leading-edge machine tools, tooling and accessories, fabrication, design, automation, process control, and plant maintenance equipment — it's everything businesses need all under one-roof. For more information, visit *www.wmts.ca*.

gear TECHNOLOGY

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4 What is your primary JOB FUNCTION (check ONLY one)

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- ❑ Manufacturing Engineering Department (F)
- ❑ Product Design, R&D Management (H)
- ❑ Product Design, R&D Department (I)
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- ❑ Quality Control Management (P)
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- ❑ Other (Please describe) (N)

____

5 My company's principal product or service is:______________________

6 How are YOU involved with gears (check all that apply)?

- ☐ My company MAKES gears (20)
- ☐ My company BUYS gears (22)
- ☐ I DESIGN gears (23)
- ☐ I am a SUPPLIER to the GEAR INDUSTRY (please specify product or service) (24)

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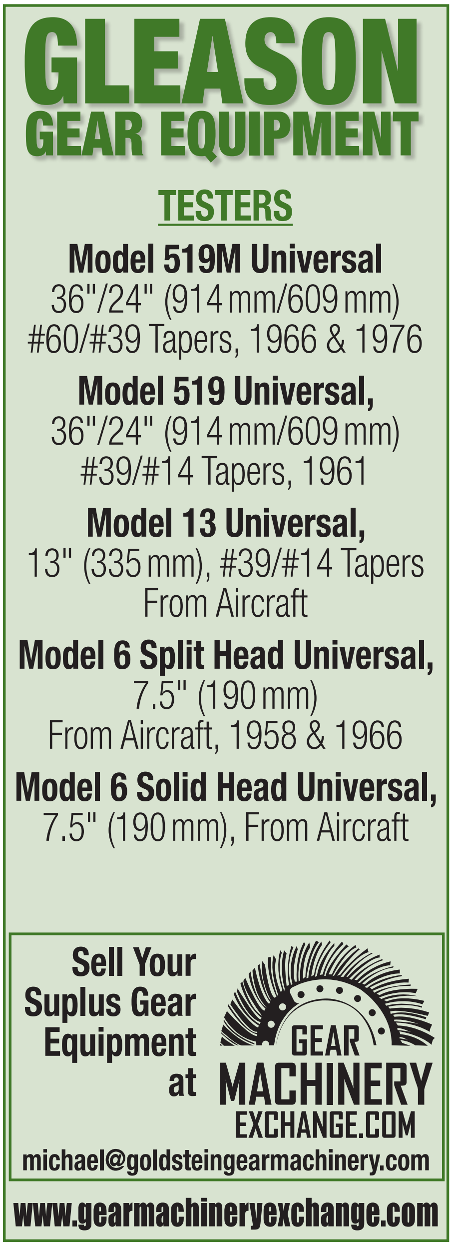
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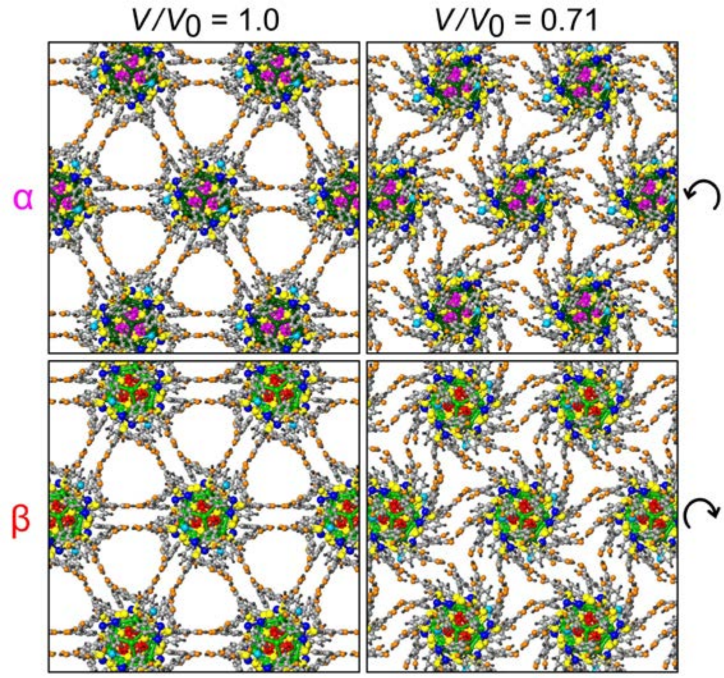
Little Gears, Big Picture

Georgia Tech professor discovers gear-like structures in superlattices

Erik Schmidt, Assistant Editor



If there wasn't such a thing as air (seriously, who even needs it?), gears might stand alone as the most ever-present entities on earth.

They are literally everywhere you turn — a universal, inescapable part of the world we live in, sort of like Justin Bieber but with less hair gel and electronic synthesizers.

Unlike the Biebs, however, gears hardly ever wind up in the tabloids, so they tend to exist in invisible space despite being right in front of your eyes.

Still, whether you acknowledge their handiwork or not, the fact remains that gears are what keep the world churning forward. Cars, bicycles, motors, clocks — you see, without gears we would literally become unstuck in time. And those are just the obvious apparatuses that contain them. Look closer, like through a microscope for instance, and you might find a Lilliputian landscape powered by teeny, tiny cogwheels.

That's what computational scientist Uzi Landman did, anyway.

The Fuller E. Callaway Professor of Computational Materials Science at the Georgia Institute of Technology, Landman recently conducted an experimental study of self-assembled, silver-based, crystallite structures known as superlattices.

And — surprise, surprise — deep down in even these smallest of forms, there were gears running the show.

Landman, an award-winner in the realm of physics who — despite sharing his name with a death-wreaking Israeli submachine gun — speaks with the kind of soothing, exotic voice that conjures up images of fuzzy woodland critters and religious figures draped in elegant white robes, was ecstatic with the fascinating discovery:

"We started to ask the question of what would happen if you actually take the solids that you can form from these little crystallites when you compress them," Landman said. "To our tremendous surprise, the process that accompanies the compression of these solids is very, very peculiar and unusual.

"In other words, the more you compress them, the easier it becomes to press on. Normally when you compress something there becomes a limit where you cannot compress any further. Think about a spring — you start and it's easy, but the more you compress, the more it resists the compression. These solids have something that is called negative pressure derivative; in other words, the more you press on it, the easier it becomes, which is very anomalous.

"What we found was that the individual crystallites that are neighboring each other, in response to applied pressure, instead of just moving and crowding together, they at some point start to rotate. They rotate in respect to each other very much like gears. The rotation is like the sawtooth of one gear moving the sawtooth of a corresponding gear.

"There is something very cooperative about this motion. It's like a huge array of thousands — of millions — of gears."

These gear-like structures, according to Landman, help to create a molecular machine with some of the smallest moving elements ever observed.

The smallest machine ever? Now that's big — figuratively speaking, of course.

The movement of these silver nanocrystallites could allow the superlattice material studied by Landman to serve as an energy-absorbing structure, converting force to mechanical motion. Think Kevlar on steroids after downing a crate of Mountain Dew.

"I'm not sure if it would be used for bulletproof vests, but it could be a material that will serve like a shield," Landman said. "It could also be used for the landing of a spacecraft, as it can absorb a tremendous amount of impact. If you have this material lined in certain areas of the craft it could be a way to protect from damage."

So yes, gears shoulder some massive responsibilities in our robust, metallic utopia in the sky. They are, in effect, the lifeblood of a sprawling civilization dependent on giant machines to keep pace with our oversized lives.

And yet it seems so fitting that, on a microscopic level, we have these quaint little gears churning and rotating like their bigger cousins — with the added benefit of absorbing damage done by bullets and other deadly impacts.

Big, small, it hardly matters. Gears will just keeping on quietly moving us forward, whether we notice or not.

Justin Bieber, eat your heart out.


Gearing your past
to power your future.