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GEAR INSPECTION

HEAT TREAT TRENDS

PLASTIC GEARS

ASK THE EXPERT
TOOTH THICKNESS TOLERANCE
P.50

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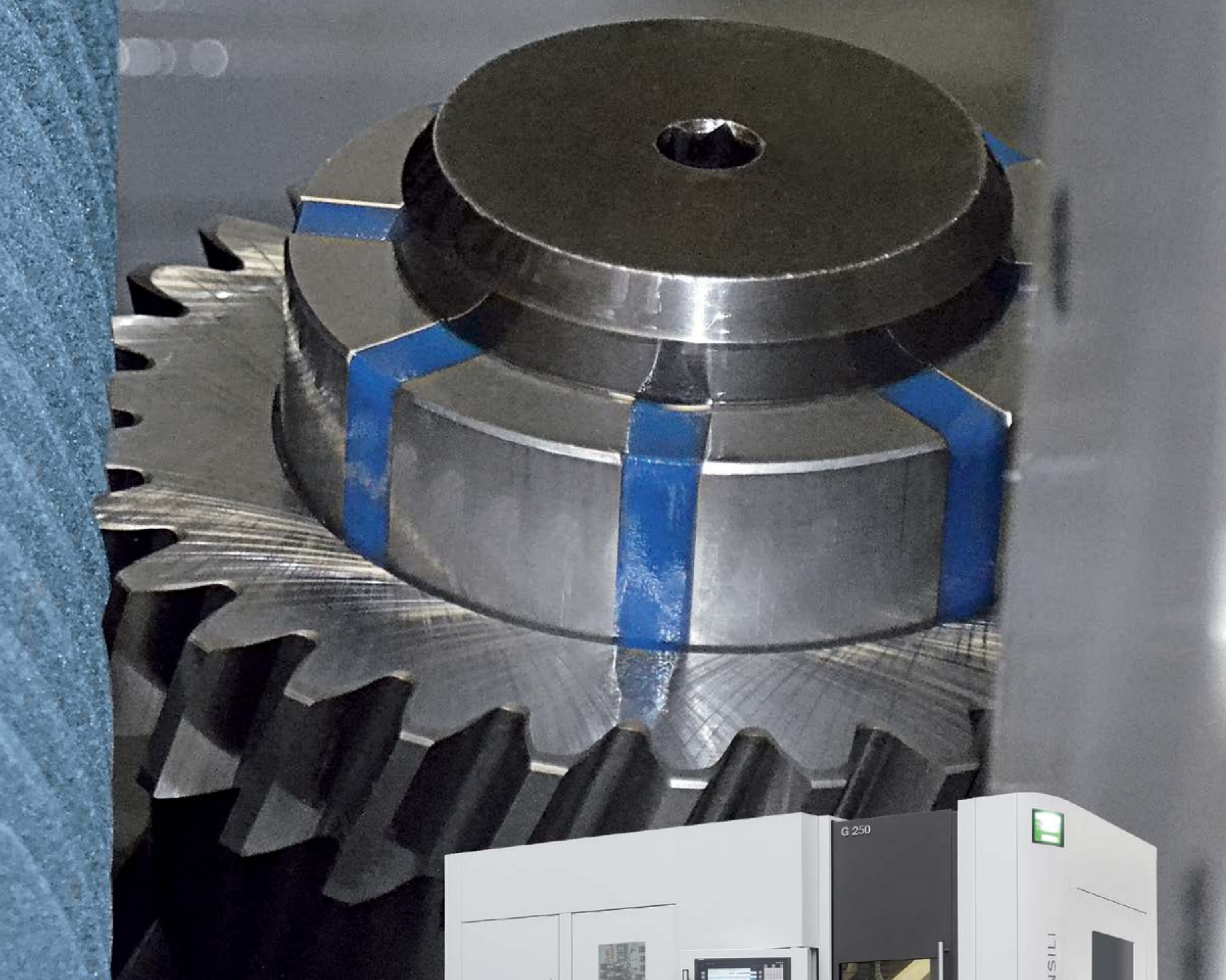

The G 250 / G 450 can be easily equipped with various automation solutions

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contents

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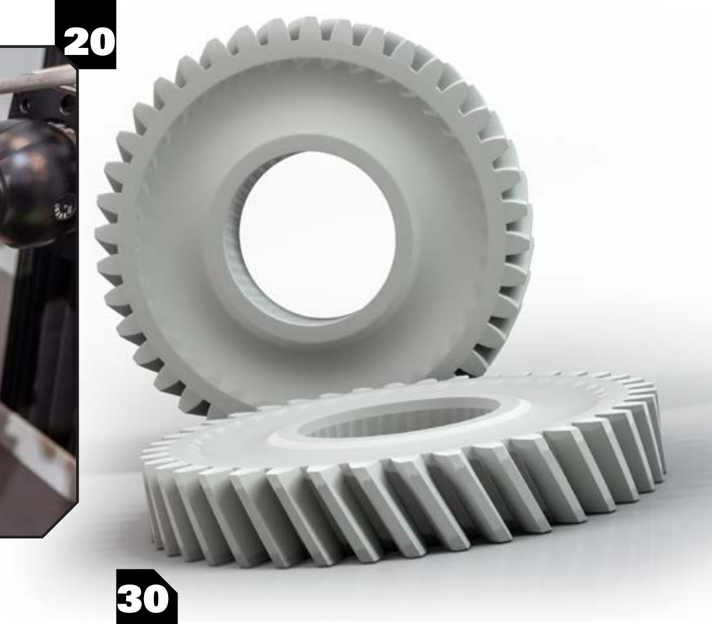
20



30

features

technical

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departments

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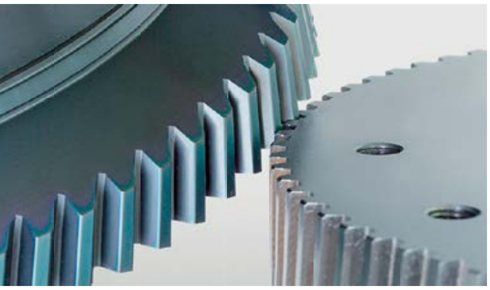

New gear skiving machine LK 300-500
Machine, tool and process from a single source

In the LK 300 and 500 gear skiving machines, process, tools and machine including tool changer and automation system come from a single source because in skiving^3 the delivery of an integrated solution for the customer is of primary interest. Skiving^3 is especially suited for internal gears of medium size and quantity, as it is much faster than shaping and more economical than broaching. The machine can be operated using the touch-based LHGe@rTec control system.

Machine
- Automation
- Deburring and tool changer
- Stiffness

Tool
- Design
- Manufacturing
- Reconditioning

Process
- Technology design
- Implementation
- Optimization

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Gleason Smart Manufacturing

Learn about Gleason's smart manufacturing systems with an emphasis on software, technology and services in this video:

www.geartechnology.com/videos/Gleason-Smart-Gear-Manufacturing-Systems-/

EMAG Collaborates with Humbel Gear Technology

Humbel Gear Technology is known for producing transmission components with the highest level of quality and precision (also for the motorsport industry). To accomplish this, Humbel chose EMAG vertical lathes.

www.geartechnology.com/videos/EMAG-at-Humbel-Gear-Technology-/

Gear Talk: Gear Origin Series

Our weekly blog has been featuring great stories about how many in the industry first became involved with gears. Read recent entries from Claude Gosselin, Rob Swiss and others here at *www.geartechnology.com/blog*. Be sure to send YOUR gear story to *publisher@geartechnology.com* to be included in future blog entries.

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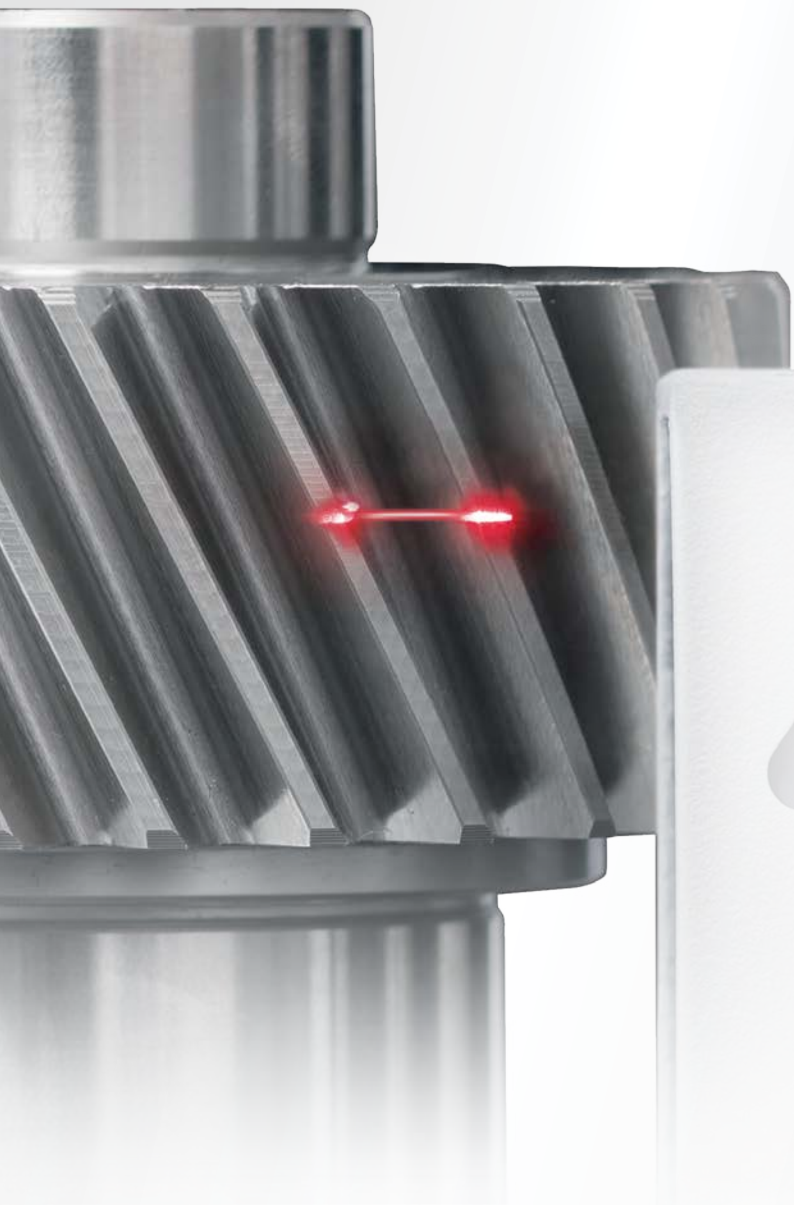


Knowledge is the Best Insurance

Matthew Croson
President of AGMA

If you were offered an opportunity to spend quality time with leading experts in your field, where in-depth discussions and dialogues occurred on subjects that directly impacted your business, would you do it?

If you knew of a meeting that was happening—where a decision that could mean the difference between meeting the needs of your customer, or not, was being made—and you had the opportunity to vote on that decision, would you do it?

AGMA holds 150+ meetings like this every single year through our Technical Division. These committee meetings have 250+ industry professionals participating in them. On a five-year rolling basis, AGMA updates 61 different standards and 39 different information sheets covering 23 different committees. These committees touch on every possible facet of gear design, nomenclature and manufacturing impacting 100%—that's right, 100%—of the products any gear company makes.

This isn't a free service—to participate your company must join AGMA, then join a committee in which you have specific interest. AGMA has two full time staff engineers and a full time publications manager who oversee this industry function—and the organization covers the cost for the Webex conference call system, the Higher Logic online information sharing portal and software, and covers the travel to attend a variety of ISO meetings that occur throughout the world.

Joining AGMA and a committee is an investment in making sure you and your team are up to speed on the latest math, science, strategy and execution of all facets of gear manufacturing and production. Without participation, you ***may*** be doing things in the most up-to-date way—but you would be **guessing**. Actively participating in the standards development process ***ENSURES*** you are current in process and with the latest information.

You may think your own internal team has all the answers, but by actively participating on a committee, you see and hear the vigorous debates members have on very in-depth topics. Through this process, your team learns what to focus on, what to consider, and what you may need to adjust within your own company.

And that knowledge is invaluable. Where else but AGMA can you leverage the opportunity to share knowledge with experts with 30–40+ years of experience, when the result can help you as a person, and your company as a whole?

Why not make committee participation a part of your team's human resource investment? Think of it as training that is done regularly, with the best teachers, and all you need to do is allow access via tele-conference.

Just more than 97% of the committee work AGMA does is done online via Webex. Gone are the days of considerable travel, and days on end meetings at hotels. The same conversations happen, but just about all of it is done online.

Without this technical knowledge, built over 103 years of standards development—which is why AGMA was created back in 1916—your company doesn't have the minimum technical requirements in order to do business in the U.S. or the world.

Think of it as technical insurance against your company's core product.

There isn't a serious customer in the world that isn't going to reference an AGMA, DIN or ISO standard when they put together the engineering specifications for their projects. So, without in-depth knowledge of these standards, through active participation in our technical committees, non-participating companies could be not current—perhaps leveraging decades old knowledge from the in-house engineering team. It could be right, or it could be very wrong. Is that knowledge gap a risk your company is willing to take? Is that the insurance you are comfortable with when it comes to your core product?

Now, more than ever, it's critical you and your company get involved.

Investing is all about managing risk—and for a reasonable cost along with about an hour each month on a WebEx–discussing important topics that directly impact your company—being an AGMA member is a good technical risk management technique.

In the past three years since I joined AGMA, I have had the honor of visiting 94 different AGMA members in the U.S., Canada, Germany, France, the Netherlands, and India—in every company I have visited, AGMA's standards have been talked about and discussed. If you are a current member, thanks for supporting our primary mission via your dues and your participation—and please consider investing in your people via active technical committee participation.

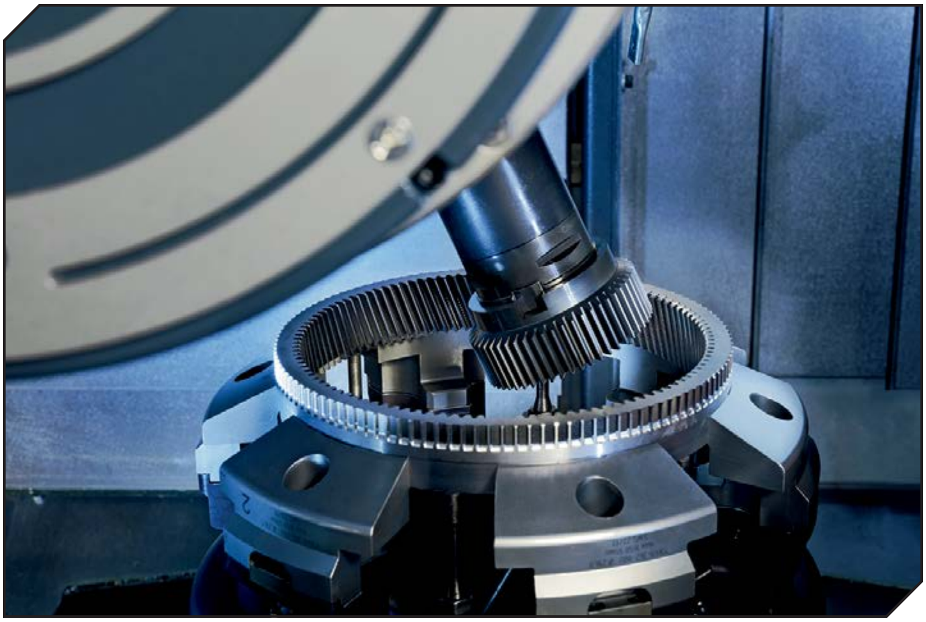
If you are not a member, consider joining AGMA and supporting our efforts to ensure both your people and your company have the most current technical standards to leverage as you innovate for your customers.

It's an investment in your people and your company—and I guarantee it will pay off—just like it does for 472 current AGMA member companies.

Working together, we have created a strong technical platform to ensure our industry is meeting the needs of its customers via standards and information sheets. To ensure we maintain this business insurance policy, we need more companies to get involved. Visit *www.agma.org* and see how we can connect your company to leaders and get you started.

Pittler

OFFERS COMPLETE MACHINING OF COMMERCIAL VEHICLE COMPONENTS WITH SKIVELINE



Planetary gears date back to the beginning of the 18th century when Scottish engineer William Murdoch invented them to improve the power gear ratio of a steam engine used to lower the groundwater level in a tin mine. Today's power transmission engineering is still relying greatly on planetary gear sets, whether on bicycles, in cars or commercial vehicles with their broad range of powertrains or in electric motors for mechanical engineering. Their compact build and the option of creating a positive locking link between various drives and generators in the same vehicle make them the ideal device for transmitting the torque in hybrid and all-electric vehicles. Manufacturers however face the particular challenge of making the internal and external geared wheel whose quality standards have increased massively over the past couple of years. Under a tier 1 order for the mass production of internal geared wheels, Pittler T&S used its SkiveLine machines to supply a trend-setting end-to-end solution for machining before hardening.

Both ring gears and planetary gear sets should be as compact, lightweight, powerful and accurate as possible. These requirements can be met only, if the sensitive component is made with highest precision and economic efficiency. Providing both attributes is particularly challenging, since the component walls are very thin and many processing steps are needed to produce grooves, oil bores or lubricant cavities on the inner and outer radius. A leading commercial vehicle manufacturer who contacted the DVS Technology Group member Pittler T&S with the task of making his existing production line much leaner and economically more efficient also confirmed this finding. In particular, the large number of six different process steps and set-ups had to be reduced significantly.

Six set-ups reduced to two

After a couple of successful trial runs on-site at the premises of the experienced manufacturer of turning and gear cutting machines based in Dietzenbach, Hesse, the combined process design had fully convinced the prospective customer. Based on the Pittler SkiveLine series of machines, an end-to-end production process was developed to cover everything from turning before hardening to gear cutting by means of the Pittler Skiving technology.

Process OP10 combines turning, gear cutting and drilling on the outside diameter. Use of the Pittler Skiving technology for internal gear cutting and all upstream lathing steps was integrated into process OP20. Thus, a component ready for installation was available after downstream nitrogen hardening. Having two SkiveLine machines plus automation unit take care of the entire machining process resulted in optimized cycle rates compared to the process being handled by separate machines and in a higher total productivity involving just two steps and set-ups. Another plus was that rigging and charging times could be kept very short although the actual machining times differed greatly.

Clamping system solution

An appropriate design of the clamping tools was essential to high-precision machining. This problem was solved in a joint effort between group business unit DVS Clamping and Pittler.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KAPP NILES KNe3P
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Installation and set-up in a blink!
The KNe3P comes with machine mounted electrical panel and is easily accessible. New KNgrind software graphically guides you through applications.
KAPP NILES
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"The first trial runs already suggested that the component walls were of greatest significance because they were very thin after all material had been removed," says Omar Sharif, Pittler's skiving technology product manager. "Conventional clamping would have deformed the component excessively in the machining process. A radial run-out of this magnitude would have made it almost impossible to achieve the specified final quality," he concludes.

Instead, a fixing spindle is used to clamp the component in the first operation (OP10). The spindle just centers the component from the inside by three fingers holding the workpiece axially at a force of 10,000 N. This special tool helped to reduce the deformation attributable to clamping to just 2 µm. The second operation yielded a similarly successful result. A six-web diaphragm chuck also designed by DVS Clamping picks up the component at its outer diameter after the automation cell has fed the component into the workspace in the correct orientation. Introducing the force through just two points of the chuck reduced the deformation to 4 µm plus tension forces released by the workpiece and imperfections from the actual machining process. The innovative clamping tools reduced the total radial run-out of the internal gearing to just 40 µm.

William Murdoch probably could have only dreamed of such a precise and efficient solution for the production of planetary gear set components. The commercial vehicle manufacturer enjoys numerous benefits from the new production line. Fewer machines, fewer set-ups and fewer persons are needed to produce larger quantities of more accurately machined internal geared wheels of improved concentricity.

For more information:

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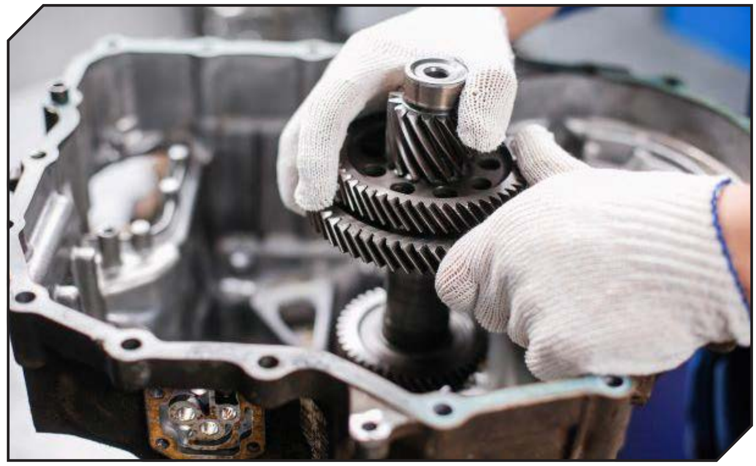
www.dvs-technology.com

Höganäs and Dontyne Gears

COLLABORATE WITH CAR MANUFACTURER ON PM SOLUTIONS



Lighter metal powder components with complex designs can bring substantial cost savings for car manufacturers and system suppliers in the automotive industry. Through a newly formed cooperation, Höganäs and Dontyne Gears offer a complete package of services with the aim to drastically improve driveline solutions.

Cutting weight both from electric and traditional internal combustion engine and driveline solution vehicles continues to be a major focus for the automotive industry. Getting more miles per gallon and increasing the range of plug-in vehicles to relieve range anxiety will be a key for carmakers to differentiate as the whole industry is being disrupted into the era of electrification.

"We help car manufacturers and system suppliers design, test and prototype new, light-weight powder metal driveline solutions that are a much better fit for the hybridization and electrification of the automotive industry," says Eckart Schneider, director powder metallurgy (PM) business development at Höganäs AB.

"As materials and production techniques continuously improve, there are many applications that benefit from being looked at again to find much simpler and more cost-efficient alternatives," says Mike Fish, CEO of Dontyne Gears Ltd.

The push towards light-weight materials brings new opportunities to create completely new solutions. In this context, the two companies' cooperation makes perfect sense. Höganäs has a deep and vast materials knowledge and experience of metal powder component applications for automotive driveline solutions, while Dontyne Gears is an expert in uniting gearing and system design, and manufacturing practices to reduce time and resources and promote efficient production in the gear industry.

"Our cooperation with Dontyne

Gears means we can become even better partners for our customers in developing and prototyping PM components in general and drivelines in particular," Schneider says.

Dontyne Gears contributes with system design analysis, manufacture of machined prototypes and bench-testing of gears with a very flexible test rig.

"Car manufacturers will benefit greatly when switching to components made out of PM instead of solid steel. We see a number of new applications where PM brings big advantages, such as weight and inertia as well as noise reduction," Fish says.

The two companies have started a joint concept development towards hybridizing a pick-up truck to take advantage of PM gearing and electrical motor solutions. So far, the project shows promising development and could potentially have a big impact on a large scale for design-optimized drivetrains based on powder metal solutions.

For more Information:
Höganäs
Phone: (814) 479-3500
www.hoganas.com

FVA-Workbench 5.5

OFFERS DETAILED TRANSMISSION CALCULATION RESULTS

FVA-Workbench Version 5.5 of the simulation platform for transmission systems, released in May, accelerates development processes and provides even more detailed calculation results.

This unique software includes the latest results from the FVA research network — new calculation methods for fast, precise results.

The new *FVA-Workbench* is significantly faster and easier to use. Individual gearbox components to complete systems can be developed in the shortest time possible. During the calculation process, built-in wizards automatically suggest suitable values which can then be adjusted manually.

Even complex planetary stages can now be modeled at lightning speed thanks to add-in wizards. Users can model very complex planetary gear designs (e.g., Ravigneaux and Wolfrom sets), from consideration of installation conditions to automatic calculation of dependent variables (such as center distances and addendum modifications), in the shortest time possible.

Values automatically assigned by wizards can be adapted to individual requirements at any time, so that symmetrical systems as well as planetary gears, in which the planets are distributed asymmetrically, can be calculated. Variations, such as bore tolerances for planet pins or stiffness-dependent load distribution, can also be considered.

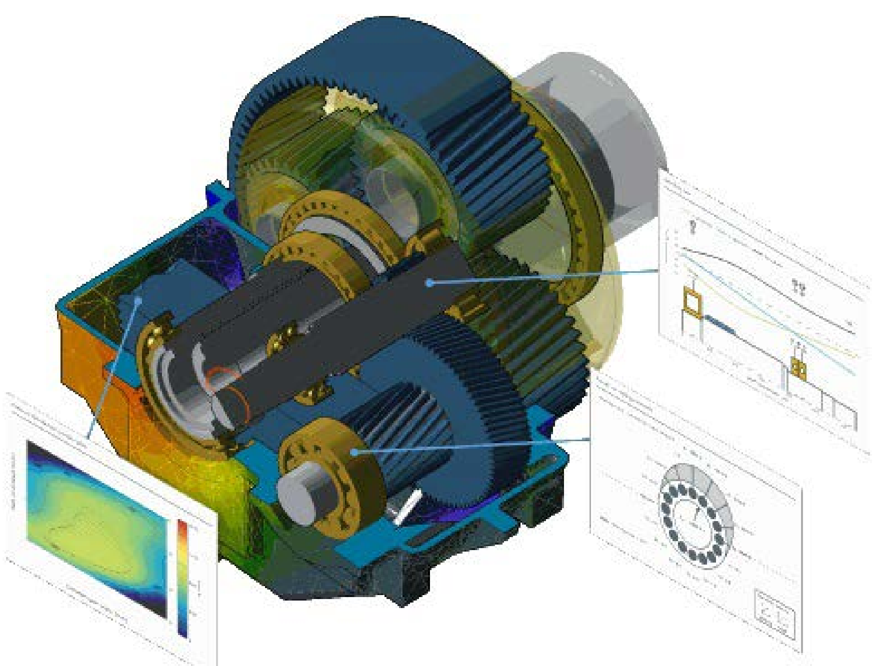
In the new version of the software, load spectra are considered in system-level calculations for the first time. Users can determine the service life of cylindrical and bevel gears as well as rolling bearings, enabling operationally stable gearbox designs.

In addition to planet carriers and gearbox casings, wheel bodies can now also be imported in many common CAD formats. First, the wheel body is automatically adapted to the FEM mesh of the gear. The FEM meshing as well as positioning and connection to the gear model are then performed in just a few seconds. Automation, interactive user navigation, and user-friendly assistants make these steps extremely simple.

"Efficient FE methods are indispensable for optimizing the power density of gear stages. For this reason, WZL has been working on the successful development and validation of FE-based tooth contact analysis for more than 30 years. With the release of *FVA-Workbench 5.5*, free wheel body geometries can also be considered in the FE tooth contact analysis feature. The wheel body is imported as a CAD model and automatically connected to the FE model of the gear. Thanks to FVA GmbH's exceptional cooperation with the Universität Bayreuth CAD research institutes and the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, software users can now easily and efficiently achieve weight saving potentials by adjustment of wheel body geometries," said Dr. Christoph Löpenhaus, chief engineer gear technology, Laboratory of Machine Tools(WZL) of RWTH Aachen.

Live demonstrations will be available during the Motion + Power Technology Expo 2019 in Detroit from October 15–17 at Booth #3737.

For more information:
FVA GmbH
Phone: +49 69 6603-1663
www.fva-service.de/en/home-en/



United Grinding

EXPANDS TWO-IN-ONE GRINDING CONCEPT

Based on a highly efficient and productive two-in-one concept, Walter Helitronic Vision Diamond 400 L, Helitronic Power Diamond 400 and Helitronic Diamond Evolution tool grinding machines, from United Grinding North America Inc., integrate both eroding and/or grinding capabilities into single grinding machine platforms. From a production standpoint, the two-in-one concept lets users completely erode tools (PCD) and completely grind tools (carbide) using the same machine to eliminate the time-consuming task of moving workpieces to a second machine.

The Walter two-in-one concept is especially beneficial in the production of modern PCD tools in which the tool's carbide blank already has soldered PCD. The ability to erode, grind or even do both operations in one clamping gives users an unparalleled level of flexibility and reliability for their tool production applications. The machines process any PCD tool, whether for the wood, automotive or aerospace industry sectors, in addition to special/custom applications.

With the ability to perform both eroding and grinding or combinations of the two processing methods on one machine, tool makers can also expand into the PCD tool-producing field to increase new business and growth without incurring additional risk or threatening cost effectiveness.

All Walter two-in-one machines feature the company's Fine Pulse Technology, which has set new standards in terms of achievable surface quality, cutting-edge toughness and process reliability for PCD tool production. A tool made with Fine Pulse Technology shines on its free surface, similar to a polished/ground tool. Even coarse-grained PCD types, which previously could not be fine finished, are effortlessly eroded with Fine Pulse Technology.

In some cases, entire steps in the production chain have been omitted because the eroded tools no longer require re-sharpening or polishing. And in addition to PCD tool productivity, the machines work with *Walter Helitronic Tool Studio*, a software solution that makes tool shaping even easier and clearer, especially for PCD tools.

For more information:
United Grinding North America
Phone: (937) 859-1975
Grinding.com

Star SU

ANNOUNCES HOBBING AND SHAPING MACHINE LINES FROM SAMPUTENSILI

Star SU LLC is pleased to announce it has expanded its comprehensive gear manufacturing product offering to include a line of horizontal hobbing and gear shaping machines available in the North American market.

Star SU technology partner, Samputensili, has recently signed an agreement between its Machine Tools Group and CLC, a reputable Italian producer of hobbing and shaping machines. The newly created company, Samputensili CLC S.r.l. can now offer new machines from its manufacturing plant located near Bologna, Italy.

The agreement helps complete Star SU's line of gear hobbing machines for shafts and long workpieces, as well as the addition of gear shaping, strengthening its position as a globally recognized leader of gear manufacturing solutions.

For more information:
Star SU
Phone: (847) 649-1450
www.star-su.com

Measurement Management

The secret to meeting today's inspection demands is influenced by the technology and those in charge of operating it.

Matthew Jaster, Senior Editor

Data-driven manufacturing is changing the shop floor in so many unique ways that it's only logical the technology and personnel need to follow suit. Many gear shops are manufacturing additional components in 2019 and many non-traditional job shops are starting to manufacture gears. This presents both a challenge and an opportunity when considering equipment for gear inspection. While we've discussed the merits of dedicated gear inspection equipment in this magazine on several occasions, there are also several inspection alternatives to consider. Many shop floors utilize dedicated gear inspection machines, CMMs, or a combination of both. The answer to your individual inspection needs will come down to cost, versatility, software and the operational benefits. Like a good college English essay, there's no right or wrong answer.

What's Out There?

Companies like Mitutoyo, Hexagon Manufacturing Intelligence and Involute Gear and Machine offer a diverse range of inspection capabilities for the gear market.

Hexagon Manufacturing Intelligence, for example, offers universal 3D coordinate measuring machines with ultra-high accuracy (in sub-micron range) for highly-specialized applications. The idea is to provide highly universal and flexible-to-use hardware and combine it with highly specialized software, which allows operation for different user levels.

"Here you'll find different options that help to individualize the system regarding the use of different sensors, palette measurement and 4-axis scans," said Svenja Schadek, product manager UHA for Hexagon. "Even the ultra-precise measurement of large ring gears is part of the Leitz standard portfolio as the maximum measurable gear size is only limited by the measurement volume of the machine."

Mitutoyo offers a diverse catalog for full gear inspection with a CMM equipped with *GEARPAK* software which is a module within the *MCOSMOS* software package. (*MCOSMOS* is Mitutoyo's internally developed CMM software package). According to Derek Sporleder, application engineer at Mitutoyo, *GEARPAK* has modules for the measurement of various gear types from spur and helical gears to bevel and hypoid gears to worm gears.

"The module guides the user through the input of the required gear parameters, tolerance classes, etc. and automatically generates a macro for the inspection and subsequent evaluation of the desired gear parameters with a detailed report showing graphical results for the tooth profile and lead evaluations, adjacent pitch, cumulative pitch, measurement over wires, and radial runout to name just a few," Sporleder said.

Mitutoyo also has many different accuracy classes of CMMs as well. This allows for a customer to select a CMM with an appropriate accuracy based on the tolerance classes of the gears they intend to inspect.

"The 3 standard classes of bridge type CMMs that Mitutoyo offers are the Crysta AS series which has an maximum permissible error (MPE) specification of 1.7+3L/1000 microns with an SP 25 probe, the Strato series which has an MPE specification of .7+2.5L/1000 microns with an SP 25 probe, and the Legex series which has an MPE specification of .28+L/1000 microns with Mitutoyo's MPP probe. Mitutoyo also offers several specifically designed inline CMM models as well," Sporleder said.

Involute Gear and Machine Company, located in Chesterfield, Michigan, distributes' gear measuring equipment from Osaka Seimitsu Kikai Co., Ltd., a pioneer in the development of CNC control gear surface measuring equipment.

The Leitz PMM-C combines highly accurate 3D metrology performance with well-proven gear measurement capabilities (photo courtesy of Hexagon Manufacturing Intelligence).

"We provide tooth form measurement of any kind of gear, including parallel axis gears, bevel gears and worm gears, etc.," said Ryohei Takeda, director, engineering, at Osaka Seimitsu Kikai. "We also provide geometry measurement of gear cutting tools, such as hob, shaper cutter and shaving cutter, etc. as well as 360 degree scanning measurement of gear teeth including tip and root, regardless of tooth form."

Much of this equipment is different from dedicated gear inspection equipment mainly in their versatility and cost.

"CMMs offer customers the ability to perform inspection of all characteristics that dedicated gear inspection equipment may not be able to evaluate such as geometric position of holes or keyways and perpendicularity or parallelism callouts to name a few," Sporleder said. "The gear measurement macro that is generated by *GEARPAK* is executed in a traditional measurement program in *MCOSMOS* so customers can evaluate all the necessary characteristics in one setup using one CMM measurement program not just the gear parameters themselves."

Sporleder also said that a dedicated gear system may not be justified for customers who produce a variety of parts where gears are only a portion of their work. "A CMM with a gear inspection software module is a much better alternative. Additionally, most dedicated gear inspection equipment is quite expensive," he added. "Additionally, CMMs have many options that can be added based upon the needs of the customer. While most gear inspection equipment has a size limit on the size of the gear that can be checked, CMMs can be built to almost any size specification so the range of part size can be much larger with CMMs.

Mitutoyo uses Renshaw probing systems for touch trigger systems and most scanning probe systems so the customer has many options when it comes to probing. Additionally, rotary tables can be integrated into the CMM to improve cycle time as well.

"This gives Mitutoyo the ability to offer a system much more tailored to the customer's needs such that a customer who wants spur gears and is comfortable with discreet touch points could be offered a CMM configuration with a fixed probe head and touch probe system whereas another customer that makes various types of spur, helical, straight bevel and spiral bevels gears may need an indexable probe head with a scanning probe system and a rotary table," Sporleder said.

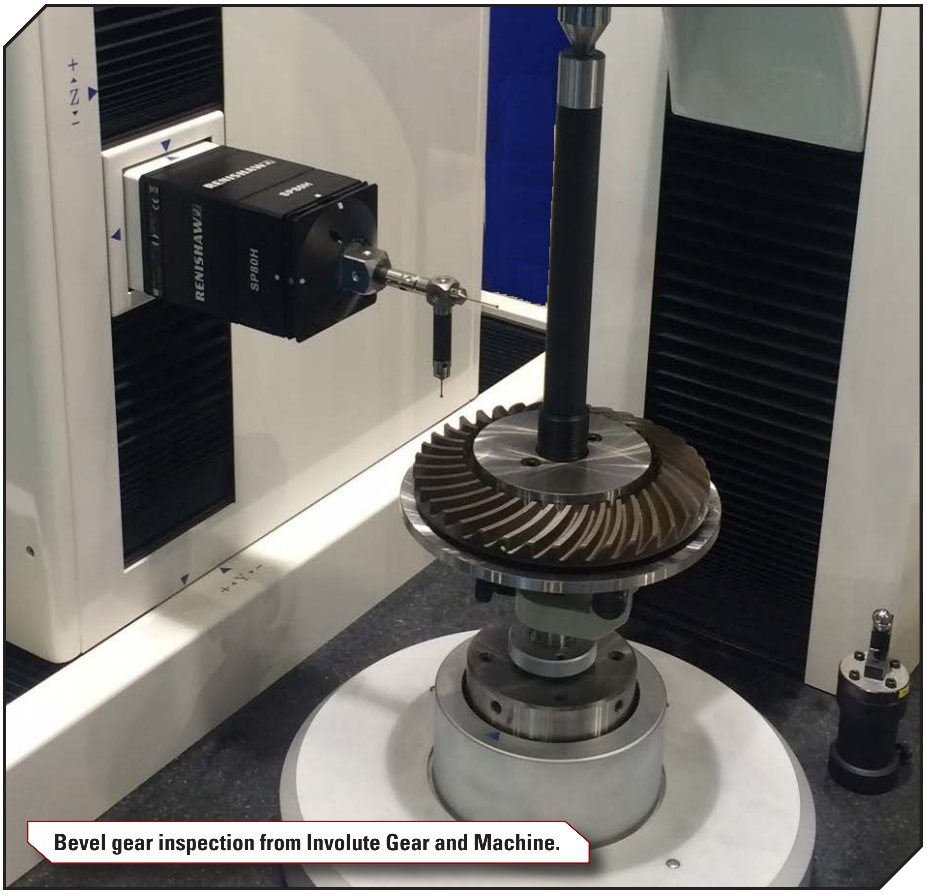
The most visual difference between Hexagon's products and dedicated gear inspection equipment is the machine design.

"A universal 3D CMM offers a rectangular shaped measurement volume, instead of a cylindrical. This set up is ideal to solve any measurement task," Schadek said. "The design of the machine and range software allows users to utilize Leitz CMMs not only for a dedicated solution but also for a wider variety of parts. This enables not only the measurement of gears but also of housings."

In addition, the independency from a rotary table also allows the physical alignment of parts in any position, not only in vertical but also in horizontal position. For example, long shafts can be measured horizontally and gear rack measurements can easily be carried out.

Flexible and automated equipment can go a long way in making the shop floor much more manageable. Flexibility and automation, in fact, are two of the most important market requirements and inspection trends today.

"The trend of flexibility is combined with the requirement to fulfil new and changed measurement tasks with a minimum effort and change of the existing metrological environment. Rotary tables can be used for 4-Axis scanning applications or easy part positioning, but at the same time the same CMM can be used for housings or pallet measurement," Schadek said.



Bevel gear inspection from Involute Gear and Machine.

Leitz CMMs enable users to add new sensors for new measurement approaches quickly and easily with the SENMATION sensor exchange interface. This is also supported by the measurement software *Quindos* that allows adding new modules for a wide range of special geometries with a simple integration procedure.

The trend of automation is closely linked to increasing throughput. This requires taking the whole measurement process into consideration. Automated part loading systems, automated or guided selection of measurement programs, automated evaluation and processing of measurement data all contribute to increased throughput. Hexagon created one particular solution that combines all these aspects which been realized with a German costumer who produces high precision gear racks.

Mitutoyo CMMs can easily be integrated into automated cells. Mitutoyo has a Solutions Group that is dedicated to designing custom fixtures, automation control boxes, and integration in automated cells. A standard package that includes an IO card and a custom designed control box based on the work cell requirements can be added to any CMM to begin the process of integrating it into a work cell. "They have a significant amount of experience setting up automated work cells with all types of robots in a multitude of industries and work with the local application personnel of Mitutoyo to provide a seamless integration process," Sporleder said.

None of these advancements would be possible without a user-friendly software package that can deliver the right inspection tools for machine operators of many different skill levels.

"The developers of the *GEARPAK* software have spent a lot of time developing a work flow that helps guide users through the setup of a gear inspection routine. There are various tool tips that give explanations for each input. The help files for a particular input can be easily accessed and are very informative as well," Sporleder said.

Mitutoyo also prides itself on the extensive support that is provided free of charge. "Mitutoyo doesn't have software maintenance agreements for *GEARPAK* or *MCOSMOS*. Free software support exists via phone or email for the life of the product. Training is included with the purchase of each software module as well so even inexperienced users have ample time to be trained and gain confidence using the software packages," he added.

Involute Gear gives basic gear dimensions so setup of automatic measurements can be done via its software. Additionally, gear quality can be analyzed according to DIN, ISO or AGMA standards.

Hexagon's *Quindos* software can be set up to serve purely as an execution tool. Measurement programs can be automatically loaded from a database, either be manually selecting a certain part by ID-number or picture or by integrating devices to automatically read part information e.g. from a data matrix code. This requires a minimum experience on gear manufacturing and metrology.

"A second level of user interaction can be seen in the setup of the measurement programs. Guided by intuitive user interfaces the gear parameters can be entered, evaluation standards defined and based on this information a measurement procedure is automatically created, ready to be executed," Schadek said.

"On a more advanced level of experience, user can even dig deeper into the creation of the measurement program and setting up evaluation routines. So, interfaces can be defined, and measurement procedures adapted to very individual requirements."

Furthermore, *Quindos* supports the Gear Data Exchange format GDE which allows data exchange in the whole manufacturing process from design to manufacturing to quality assurance. It includes all geometrical parameters, including modifications and tolerances.

Industry of Change

Sporleder said that the most noticeable changes in metrology divisions relate to automation and a reduced machine footprint. "Each year we work with more customers to develop automated work cells using all types of robots with integrated inspection equipment that not only seamlessly communicates with the robot but also can optionally provide measurement results back to the machine tools for offset calculations and/or part sorting," he said.

Mitutoyo offers an internally developed SPC software package named *Measurlink* that can be utilized to monitor the various process control indices in real time as well. The reduced machine footprint pattern has become much more prevalent in the last few years. As the economy has continued to strengthen many companies have been forced to increase production and floor space has become very important.

For several years now, Mitutoyo has offered a KOGAME CMM system which is a very small shop floor CMM that has a very high acceleration and measurement speed and can significantly increase throughput. The measurement volume for that system is 120 mm × 120 mm × 80 mm. The system doesn't require air and can be put in almost any environment as the temperature range for operation extends from 10 degrees Celsius to 35 degrees Celsius.

"These systems have gained in popularity recently as companies try to squeeze more equipment into existing space and realize that a traditional CMM may in some cases have a larger footprint than is needed. These systems in particular are often found in the work cell right next to the machine tools and can utilize manual part loading or can be integrated into robot fed cells. We also offer larger inline systems such as the MACH 3A which is a high speed horizontal arm CMM for shop floor inspection which can be built into a conveyor system or any other type work cell. A larger vertical inline machine, the Mach V, is also available as well," Sporleder said.

For Takeda at Osaka Seimitsu Kikai, the push for electric vehicles (EVs) in the automotive industry is definitely changing inspection needs.

"These EVs are getting very popular and the number of gears used is being reduced, but higher quality gears are necessary so there's a greater demand for precise inspection. In the case of robot applications, smaller sized gears with non-involute profiles are being used, so there's a higher demand for the measurement of those gears," Takeda said.

Three important factors can be noticed in inspection today, according to Schadek.

Leitz CMMs from Hexagon enable users to add new sensors for new gear measurement approaches.

"An increasing demand for higher throughput, the need for higher data density and the holistic use of data," she said.

A change of sensor technology is noticeable. Besides the well-established tactile scanning sensors, more and more optical sensors are used. They provide a higher data density that allows new and different views on gear measurement with a more surface oriented evaluation instead of a line (profile, flank) centered approach.

These sensors offer higher scanning speeds, so higher throughput can be generated. But still there is a high need for tactile solutions when it comes to the established parameter evaluation.

Another important trend is the use of data. A closer interaction of CMM and tooling machine as well as the design department will be needed. Even the use of measurement data for costumer focused spare part supply will be increasing.

All of these factors hint at a future where connectivity and smart manufacturing will increase the diversity and flexibility of the CMM. Takeda sees an inspection industry in the future where closed loop data communication between design, manufacturing and inspection exists.

Sporleder said that Renishaw will continue to develop new probing systems and so with the development of the 5-axis touch and scanning probes that have the ability to index to any angle like the PH20 and REVO systems, that should continue to help improve gear inspection and reduce cycle time as the cycle times when measuring parts with those systems are always considerably shorter than more traditional probing systems.

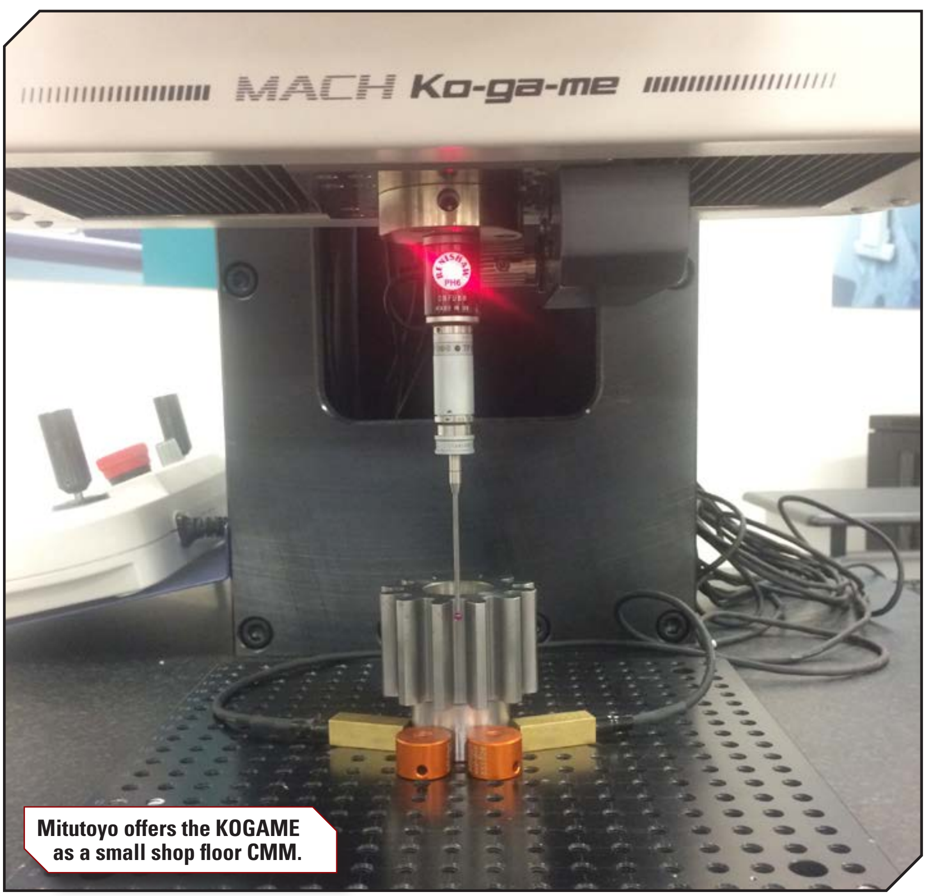
Additionally, measurement programs continue to get more automated. Mitutoyo currently has a software called *MiCAT Planner* that utilizes Product Manufacturing Information (PMI) which is machine readable tolerances that are imbedded in the 3D CAD model. "If these tolerance callouts are semantically referenced to the model, the software can read them in and automatically write an entire inspection program by analyzing all the available probe configurations on a particular CMM and choosing the best option for each feature automatically," he said.

Sporleder believes as the standards for this type of information continue to develop, undoubtedly gear inspection will fall into this category.

"I certainly can see a time in the somewhat near future where all of the information for the gear can be written into a CAD model of the part in a machine readable fashion such that it can be read into the software automatically and a measurement program generated even faster than can currently be achieved using the existing *GEARPAK* module," Sporleder added.

Schadek sees an increased demand for more universal CMMs with a wider variety of sensors to reduce the number of different inspection systems that can be found around the GMM, e.g. surface inspection. This follows the requirement for increased throughout. So, most inspections can be done with only one measurement system. This reduces handling times.

"In conjunction with this approach, data evaluation and processing will get a stronger focus. The feedback loop, not only to production (closed-loop), but also to the engineering department will get of more importance," Schadek said. "Furthermore, information that has been generated from gears that have been in use will be needed to be feedback to the information gathered during production to create a more holistic view."



Mitutoyo offers the KOGAME as a small shop floor CMM.

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Heat-Treat Trends

Coping with a Labor Shortage, Looking into 3D Printing

Joseph L. Hazelton, Contributing Editor

Jim Oakes and Tom Morrison agree: The U.S. heat-treat industry is in the middle of a labor shortage. Morrison sees a silver lining, though, a coming solution to the present problem.

For both men, a problem in the heat-treat industry is a real concern. Oakes is board president of the Heat Treating Society, an association located in Materials Park, OH. Oakes is also vice president of business development at Super Systems Inc., Cincinnati, OH, a company that makes products for the heat-treat industry.

Meanwhile, Morrison himself is chief executive officer of the Metal Treating Institute, also a heat treaters association, located in Jacksonville, FL.

Jim Oakes, board president of ASM Heat Treating Society. (Photo courtesy of ASM International)

Tom Morrison, chief executive officer of Metal Treating Institute. (Photo courtesy of MTI)

A Labor Shortage

"We're in the midst of an incredibly competitive labor market, where companies are feverishly looking for staff," Oakes says. He describes the staffing problem as affecting captive heat treaters (heat-treat departments inside larger companies) and affecting commercial heat treaters (companies that heat treat parts made by other companies).

Oakes adds that the problem isn't confined to the office or to the shop floor, it includes metallurgical engineers, equipment operators, and managers: "It's actually everywhere."

Accepting that there are few qualified workers to spare, companies still have to be mindful of workforce development. However, they also have to be mindful of how to work around the labor shortage.

"The problem of workforce development is an eight-year problem," Morrison says. He sees the shortage as an eight-year problem because he expects that's when it'll end. "In eight years, there's going to be about 30 million new millennials in the workforce, and they're going to be more experienced. So, there are going to be plenty of workers out there," he says. "We're going to have more qualified workers than there are jobs out there."

Given this outlook, there is a question for businesses. "What do you do between here and there to grow your company?" Morrison says. "Gear manufacturers and commercial heat treaters have to figure out how do they grow their throughput for the next eight years without a lot of new employees."

More Capacity Through Automation

A solution is automation. "The most effective heat treaters in the next 10 years are going to be those that can take gears in receiving and push them out shipping with the least amount of human touch," Morrison says.

Oakes agrees: "An alternative to labor, of course, is automation."

Now, automation may mean robots, like pick-and-place machines in a facility. However, it may also mean only that a company make greater, more effective use of production information by running the data through sophisticated analysis software.

To do that, a company wouldn't need robots, it would need sensors and software. The sensors would be attached to production machines to gather process data, and the software would analyze the data by using complex algorithms. The sensors and software would turn production machines into smart machines and production facilities into smart facilities.

Now, in this case, increased capacity could result from using the machine data and analysis software to achieve greater process optimization, which could lead to greater precision, which could lead to less rework and less scrap. "Specific to heat treating," Oakes says, "what people are trying to do is reduce or eliminate rework and scrap."

A company could also increase capacity by using the machine data and analysis software to automate preventive maintenance. Specifically, data and software could be used to monitor the machine itself, to monitor its operating conditions and how long it operates under those conditions in order to more precisely gauge when technicians should perform preventive maintenance. That greater precision could maximize machine uptime not just by streamlining preventive maintenance, but also by avoiding unexpected machine failure.

"Those all yield efficiencies when it comes to heat treating," Oakes says.

Training Workers: Education Courses

Now, when the labor shortage ends, companies will need to train their new employees.

Naturally, many of the new hires will arrive as metallurgical engineers fresh from universities, as heat-treat technicians fresh from trade schools, or as engineers and technicians who already have a few years of work experience. No matter the case, they'll need additional training during their careers, on-the-job training and career development.

"Training becomes a significant component of getting people up to speed and making sure that they understand what the heat-treating process is for and what they're trying to accomplish," Oakes says.

Two sources of career development courses are the Metal Treating Institute and the materials association ASM

International. ASM and the Heat Treating Society are affiliated organizations and are both located in Materials Park, OH.

ASM offers four types of educational courses: classroom and lab courses; online courses; certificate programs; and customized, on-site courses. MTI offers online courses that can be taken individually or can be taken within four certificate programs. Also, each association provides educational opportunities at its trade expo and technical conference. MTI did so at Furnaces North America 2018. ASM and HTS will do so at Heat Treat 19, which will be held Oct. 15–17 in Detroit, MI (see sidebar *Heat Treat 19* on page 28).

Bill Mahoney, chief executive officer of ASM International. (Photo courtesy of ASM International)

Back in Materials Park, among ASM's on-site offerings are classroom and lab courses on additive manufacturing, also called 3D printing. Specifically, the courses are about the materials used in 3D printing and designing for 3D printing.

Many companies are interested in 3D printing. Consequently, ASM knows it needs to provide information about additive manufacturing to contribute to industry's understanding and use of the manufacturing process, including the heat treating of 3D-printed parts.

"Heat treating for additive manufacturing—the requirements and capabilities to effectively execute heat treating for a part that's additively manufactured—that's still a developing capability in our market space," says Bill Mahoney, chief executive officer of ASM.

3D Printing: Mass Production?

Like Mahoney, Oakes and Morrison are also mindful of 3D printing and how it could affect the heat-treat industry.

In 3D printing, a part is made from a powdered material, a metal or plastic, and from a computerized, 3D design of a part. The powder and design are used by a 3D printer to build the three-dimensional part, the printer laying down small, successive amounts of material to make all of the part's aspects to their correct dimensions.

Now, 3D printing is a manufacturing process, not a heat-treating process. However, its effect on the heat-treat industry could be significant.

Right now, 3D printing can be useful in prototyping, when a company needs only one part or only a small number of them. In those cases, companies may save time by 3D printing. "Instead of going through the numerous manufacturing steps, they're 3D printing it to reduce the time," Oakes says.

3D printing can also be useful as a regular manufacturing process *if* a company needs to make only a small number of parts, especially a small number of complex parts. "Right now," Oakes says, "it's isolated to very sophisticated designs that may be higher in cost to produce and have multi-steps to actually make those parts, where it makes sense maybe to have those printed."

But, what if 3D printing were developed so it could be used in high-volume production? Then its effect on the heat-treat industry would likely be significant. Right now, there is research-and-development work being done on 3D printing to see if its potential includes high-volume production. "Is it a legitimate manufacturing process that can be utilized in high-volume applications," Oakes asks.

If, one day, the answer is yes, there could be noticeable shifts in the heat-treat industry. Morrison provides examples of two possible shifts. First, there's the really complicated component that consists of many smaller parts, an aerospace component, for example. If a company makes the parts and assembles and heat treats them to create the final component, that's fine. But, what if the company makes the parts, then sends them out to a heat-treat company?

If 3D printing were a mainstream manufacturing process, that really complicated component, a company may be able to make it as one whole thing, not as an assembly of many smaller parts. In that case, there would be only one component to heat treat, not many parts. A commercial heat treater would get less business. "That's millions of dollars that go away," Morrison says.

Moreover, he isn't describing a hypothetical situation. Morrison was touring an aerospace company, got a chance to see its additive manufacturing, and learned about the complicated component that the company was now making as one whole thing. Morrison adds that he asked the tour guide: "If you only had to manage one piece, would you think about buying furnaces and putting them in-house and just doing that heat treating in-house?"

Morrison says the guide's answer was: "That's part of the discussion."

If the heat-treating were done in-house, then a commercial heat treater would get no work from that component.

Another possible shift could lead to commercial heat treaters becoming manufacturers themselves. In this scenario, Morrison sees the possibility of companies deciding not to invest in 3D printers themselves, but to outsource that manufacturing. In that case, to make up for lost heat-treat work and to ensure against further loss, commercial heat treaters could buy 3D printers and offer that service to customers. That way, a company could outsource both 3D printing and heat treating to one outfit, a heat-treat company that's also a 3D-printing house.

Right now, though, 3D printing isn't an option for many high-volume applications, so the possible shifts in the heat-treat industry are only *possible* shifts.

However, Morrison says, "Gear manufacturers and commercial heat treaters need to be really opening their minds up and really checking into how their customers feel and how their markets feel about 3D printing of something like a gear."

Also, he cautions industry, manufacturers and heat treaters, against thinking that 3D printing will never become a high-volume manufacturing process. "It may never happen," he says, "but you can't say never 'cause if someone figures it out, you're behind the curve."

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Heat Treat 19

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30th HEAT TREATING SOCIETY CONFERENCE & EXPOSITION

When:	Oct. 15–17, 2019
Where:	Detroit, MI
Exhibitors:	More than 180
Technical sessions:	More than 100
Co-located with:	Motion + Power Technology Expo 2019 (previously Gear Expo), organized by the AGMA (American Gear Manufacturers Association)
Reason to attend:	"There's an opportunity to, in both the technical programming and the expo, to learn." — Jim Oakes, board president, ASM Heat Treating Society

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The Measure of a Gear

Plastic gears still have an entire frontier to explore, and how they measure up against their steel cousins is a question still being investigated.

Alex Cannella, Associate Editor

Any time someone takes a look at plastic materials for gears, the question inevitably comes up: How well can it compete with steel? Typically, the way it goes is that every year we check in, sit with bated breath to see if somebody came up with a plastic material capable of standing up to the same pressures as steel, and then the news we report is a more underwhelming "well, they're getting stronger, but not yet."

According to Stefan Beermann, CEO of *KISSsoft*, however, that's looking at the question the wrong way.

"It would be wrong to play plastic against steel, although the question is typically phrased that way," Beermann said. "There are typical plastic applications and typical steel applications. The question is what torque do we want to transmit and what is the cost structure."

Beermann views plastic gears instead as a product that have carved a niche of their own. There's no sitting around waiting for them to "compete" in this case. They're already here doing their own thing. The question of steel versus plastic isn't one of competency or technology, it's a question of priorities and what you need to get a job done.

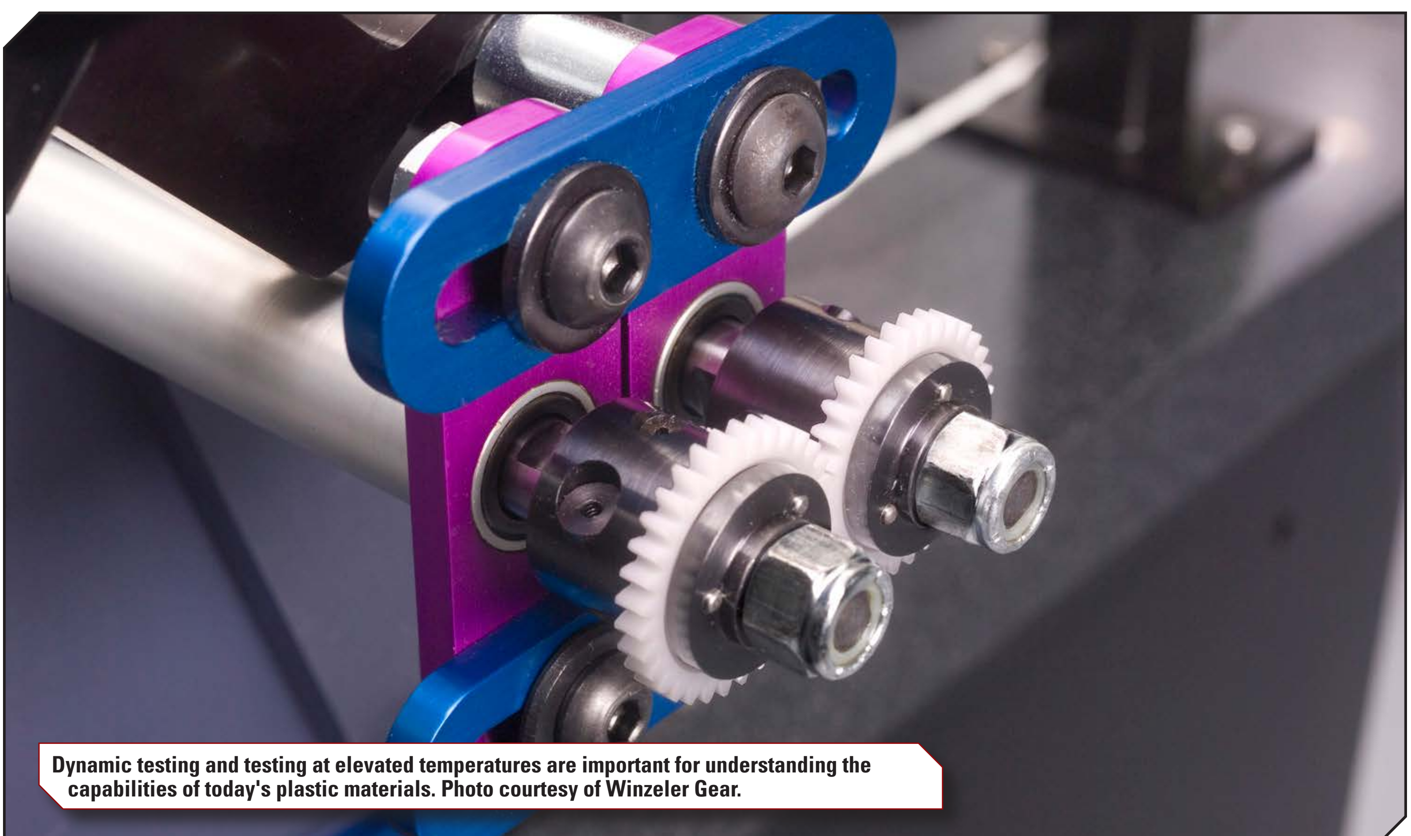
"Plastic gears are unbeatable in typical actuator applications with a large batch size," Beermann said. "On the other hand, in gearboxes, where large torque occurs and the size is somewhat limited, steel is the material of choice."

But that said, Beermann also noted that this perception is starting to shift. "What changed a lot in the last [few] years is that engineers now take plastic gears as a serious alternative. They started to treat them as 'real' gears."

As John Winzeler, president of Winzeler Gear, noted, one primary advantage some plastic gears hold is how many teeth can safely share loading, achieving some rather impressive contact ratios. In particular, he cited one material, Delrin, a proprietary material sold by partner business DuPont.

"The beauty of our favorite material [Delrin] is the fact that if you're designing with metal gears, and most gear designs, if you get more than a contact ratio much above 1, you probably have failure, because the teeth do not flex," Winzeler said. "The phenomenon we have with Delrin is that in highly loaded applications, up to 85 degrees Centigrade, we can have up to four teeth in contact and not have failure. So you have tremendous load sharing."

While in some cases, as with actuators, plastic gears are a clear choice, in others, it's more of a gray area. Take automotives, for example. According to Winzeler, one of the trends in the automotive space right now is to make everything more compact,



Dynamic testing and testing at elevated temperatures are important for understanding the capabilities of today's plastic materials. Photo courtesy of Winzeler Gear.

a trend that plastic gear manufacturers are adjusting to design around. Steel or reinforced plastics have a natural advantage here. As space grows tighter, plastic gears have a harder time keeping up with the stresses that come with an increased power ratio, not to mention their significantly lower melting point. And to muddy the waters even further, plastic gears can be reinforced with filler materials that will allow them to withstand higher temperatures, but in turn make the gears even stiffer and exhibit contact ratios more like their steel competitors. Often, it's a worthwhile tradeoff, but it's always a tradeoff.

"[Reinforcing plastic material] leads to higher stiffness and higher strength, especially for the root," Beermann said. "For housings and other non-gear parts, the story ends here. In case of gears, however, we have two opposing trends: the higher strength allows higher root stress. On the other hand, the higher stiffness reduces the contact ratio under load, thus increasing the root stress. Besides higher costs for the material and a more complicated molding procedure, fibers can also cause tribological problems: If significant wear occurs, at some point the fibers will come to the surface (more precisely, the surface comes to the fibers)."

But plastic gears also have an edge of their own. Due to being softer materials, they can reduce, though not single-handedly solve, gear noise, a primary and ever-growing focus for the increasingly electric-based automotive industry. As engines begin to ditch their gas motors, gears quickly become the loudest part of the machine, and the squeaky wheel gets the grease. In the case of gear noise, it's an almost literal saying. Sometimes, you can even take things one step further and mix rubber into the plastic, making the gear even softer and quieter.

But while plastic gears can help, Winzeler noted that ultimately the issue of gear noise is a system-wide problem that requires you to look at more than just a gear.

"Companies are coming to the plastic material suppliers and saying: 'make us quieter systems,' but it's really a system," Winzeler said. "The gears alone aren't going to do it."

Taking the Measure

For Winzeler, the primary division between steel and plastic gears is one of knowledge. As a new concept (at least relatively to steel gears), plastic materials just don't have the weight of as many years of research behind them. While the occasional conference headline touts a bold future of new plastic materials better than ever, Winzeler is instead digging deeper into the ones we already have.

"Plastics, unlike steel, there's still not the wealth of data for structural durability or design data to know as much as we need to know," Winzeler said. "And so the work that we're doing with our partner DuPont continues to be dynamic testing and doing testing at elevated temperatures to learn more about the materials we have today instead of the next generation material."

According to Winzeler, much of today's gear design either comes from tribal knowledge or historical data, but what Winzeler is pursuing, along with their partners Dupont, is more

Molded gears made from DuPont's Delrin material. Photo courtesy of Winzeler Gear.

dynamic testing under broader ranges of conditions.

"We have to know the limits of the materials," Winzeler said. "We have to know the limits of the processes we're using for those materials. We have to know are the parts designed or optimized for the process of the material, and the engineering tradeoffs that go into product design for gears and gear transmissions."

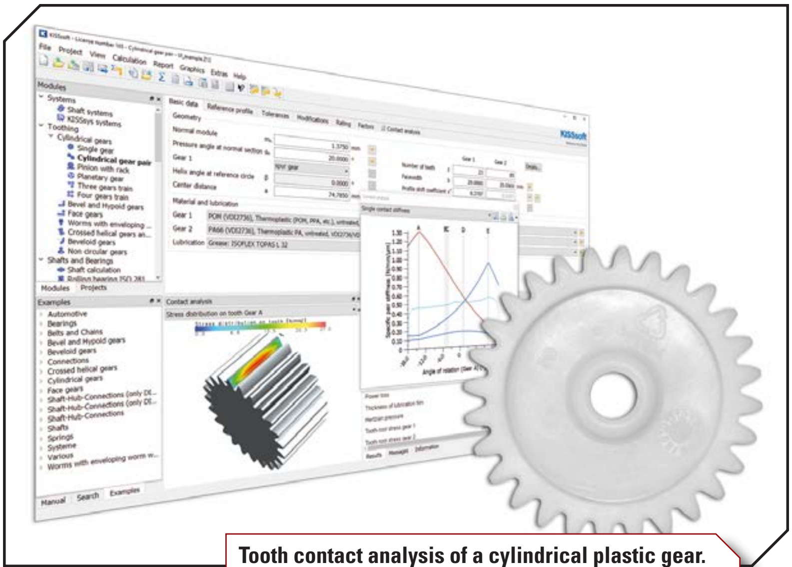
Brian P. Stringer agrees that more testing is needed to better understand the capabilities of plastic gears. Stringer is manager of sales and application engineering for *KISSsoft* in the United States and Canada. "Specifically, we need to gather root and flank fatigue data," Stringer says, "and we need to do this at *many* different temperatures, unlike steel."

One of the biggest challenges, Stringer says, is that there are no agreed-upon standards for how this testing should be done. "Very few companies are following the same testing procedures and using the same types of testing stands and set-ups to achieve apples-to-apples results, so it is difficult to trust any data you get unless you can confirm *how* it was gathered," Stringer says. Another significant challenge is the cost of prototypes. You can't just slap a gear blank on a machine, cut a test gear, and then proceed straight to manufacturing. For a plastic gear, you have to go through the more expensive process of developing a mold before you've even got a prototype. You basically have to spend just as much to prepare a test design as you do for a full mass production run.

For the most part, Winzeler isn't quite ready to fully discuss their ongoing research, but there is some fruit that it's borne. Most notably, they've been working to use their findings to design what Winzeler calls "new families of materials with low emission capabilities."

The ultimate goal here, however, is to reach the point where you can cut out that expensive testing phase with molds — to go straight from a computer simulation and right into production.

"That's the endgame…" Winzeler said. "That's where the world's headed. That's where it wants to go. Is that next year? 10 years from now? 20 years from now? I'm not sure. But because of the cost of product development and testing and everything that goes on, the more that can be done with computer simulation, the shorter the lead time and the lower the investment."



Tooth contact analysis of a cylindrical plastic gear. Image courtesy of KISSsoft.

Simulating Plastics

So speaking of, where are we at with plastic software? One of the more recent announcements in the field comes from *KISSsoft*, who have partnered with material supplier Lehvoss to expand their already considerable software suite.

First, the nitty gritty details. *KISSsoft* has added six new Luvocom materials from Lehvoss, high-performance materials designed to provide quality "mechanical properties" while still performing at temperatures above 200°C. This comes in addition to the 55 plastic materials that *KISSsoft* is already capable of simulating.

Currently, *KISSsoft* allows users to do both wear and static strength calculations for all six new materials, but in the future, the software suite is likely to expand those possibilities: At present, Lehvoss is working on fatigue strength testing.

According to Beermann, the partnership, as with many features with *KISSsoft*, primarily came about by customer request, and it's just one of a list of changes *KISSsoft* is slipping into their latest release. Alongside the new materials will be a new module the company's calling "KISSdesign," which expands their simulations of gearboxes, as well as quality of life improvements such as aysmmetric gear contact analysis (LTCA) and a partnership that allows the software to connect to SKF servers and use their calculations when needed.

Gleason in particular has been enjoying the benefits of *KISSsoft*'s software suite, making the software a part of their plastic gear manufacturing process, and perhaps becoming the software suite's own first anecdote to roll out.

"We have developed proprietary in-house mold bases, called our Quick Tooling, to limit the amount of expense and time needed to produce the molds," Stringer said. "The molds still offer the same quality as production style tooling, with the added benefits of less setup and changeover time, faster delivery, and lower overall cost."

According to Stringer, Gleason's managed to use these molds to produce up to AGMA 2000 Q11-quality molded gears in as little as four weeks while also applying the company's already existing No Weldline technology.

"We are sometimes able to run up to four different parts and materials in the same mold base and press in the same day," Stringer said.

Much in the same vein as what Winzeler Gear is doing, the primary benefits Gleason is seeing are speed and improved prototyping.

"*KISSsoft* helps us maximize gear design and system capabilities," Stringer said. "Our Quick Tooling helps us experiment with many different materials and tooth forms quickly to provide customers with as many options as possible to try during the testing phase, and our No Weldline Technology allows us to produce the most concentric and accurate gears in the market."

When taking the measure of a plastic gear, the question is increasingly not if it can outperform its steel counterpart, but when and where. Which isn't to say that metallic components are at risk of being overtaken or anything seismic like that, but rather that instead of combating them directly, plastic gears are finding their own comfortable niches where they excel. And as companies like Winzeler and *KISSsoft* keep working, they're only going to get better.

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CHAMFERING: Hard vs Soft Parts and Before vs After Heat-Treating

James Richards, James Engineering

For years, I have always told people who ask me that my machines pretty much don't care if a part is hard or soft. When I was asked to write on this topic, I stopped and thought and realized I have never really done anything to verify my beliefs directly.

Examining my sample shelves, I found several parts that had not been deburred yet. I chamfered one part as a baseline, which was *soft* (pre-heat treat). I then heated two parts up until the parts were non-magnetic and quickly water-quenched them — a very rudimentary form of heat treating. Filing on the parts showed they were significantly harder than the non-heated parts. Experience tells me they are in the mid-to-high 50's on the Rockwell C scale. The soft parts are probably in the low-to-mid 20's — also on the same C scale.

The exact hardness of the gears is not important for my test. I just need two hard gears and two soft gears; then, I'll run them on my machine using the same set-up with the same grinding wheel, working pressure, and speed. Afterward, I will measure the differences in the chamfers.

I had already run the control soft part first, so I ran the two hard parts and followed by running another test soft part. Visually, there was no difference between any of the parts. Using calipers and measuring the actual chamfer width I found no difference either. As a result, for this very simple test, the hard parts and soft parts had exactly the same size chamfer after being processed on a James 562 deburring machine using the same set-up for all parts.

This simple test verified what I have always believed, but now I have an actual back-to-back controlled procedure test to verify what I have been saying for years. This test confirmed that this specific alloy of steel had no effect on chamfering when the material was hard or soft.

What I am *not* saying is that all materials chamfer the same. Carbide gears are probably the slowest material on which to create a chamfer, and aluminum is the fastest, but not by much when compared to regular steel. Aluminum is a gummy material and plugs up abrasive medias, making it an elusive material to grind consistently. Hard and soft versions of each material type in my experience will have similar results, meaning there will be little measurable difference in chamfer size and depth after using the same deburring process. Again, different materials require different types of abrasive media to achieve proper grinding results.

We have yet to find a material that we cannot create a chamfer and/or edge finish on. As to whether we chamfer before or after heat-treating — that's a very different story.

Figure 1 The four parts referenced in the article; No. 1, on bottom of stack, is the first soft part; No. 2, just above and on top of No. 1, is the first heat treated part after processing; No. 3 is next and on top of No. 2, and is the second heat treated part after processing; and No. 4 is the last soft part on top of No. 3, having been processed last. (Photo James Engineering).

There are always exceptions to blanket statements, but in general, chamfering and edge-finishing before heat-treating is always best. On large gears the chamfer prevents the induction heat treating process (if used) from overheating and actually melting the tip and end of the gear profile. On these large gears a rather large chamfer is required for this very reason. In the heating, quenching, and cryo-processes of heat-treating, the sharp and rough edges of a gear tooth are at risk of forming stress cracks. Chamfering and edge-finishing dramatically neutralize or reduce this risk.

Often, after heat-treating, gears are ground to final size; this requires a bigger chamfer than the "blueprint" specifies should be applied; so, after grinding the material removed, the chamfer is brought back to the print specifications. The ideal process is to apply an abrasive brush to the gear edge and profile (both sides) after final grinding. This final process removes the sharp edge produced by the grinding process on the chamfered edge closest to the ground gear profile. Depending on the application and type of gear, this final chamfer size is more important as the gear flexing and stress levels increase in frequency and pressure.

We all know gears carry their loads — from one set of engaged teeth to the next set of engaged teeth — rapidly and seamlessly at staggering frequencies. When the loads are big and a gear's teeth are flexing with loading and unloading to a higher degree, edge chamfers and surface finishes matter with regard to gear life and safe operation. Such continuously rapid flexing can cause cracks to form on the gear edges, unless the chamfer is the right size and has the right surface finish. My job is to build machines that can achieve optimal results with the greatest efficiency, lowest operating cost, and highest quality of chamfer and surface finishes on every part.

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James Richards began his professional career in the world of automotive racing. In 1973 he joined the Kwik Mark marking company as vice president and co-owner. In 1980 Richards opened and has since operated his own manufacturing technology company — James Engineering.

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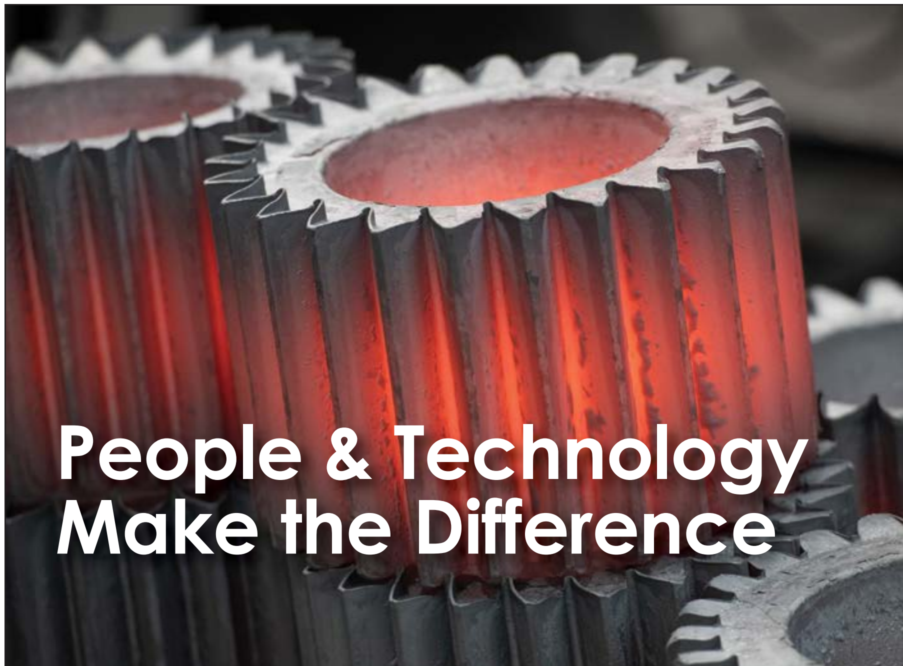
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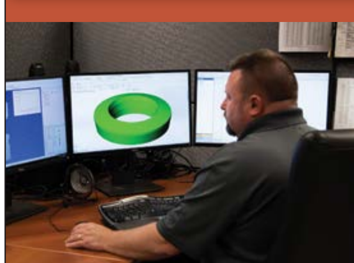


Gear Noise Analysis: Design and Manufacturing Challenges Drive New Solutions for Noise Reduction

Parag Wagaj and Douglas Beerck, Gleason Metrology Systems

Gear noise is among the issues of greatest concern in today's modern gearboxes. Significant research has resulted in the application of enhancements in all phases of gear manufacturing, and the work is ongoing. With the introduction of Electric Vehicles (EV), research and development in this area has surged in recent years. Most importantly, powerful new noise analysis solutions are fast becoming available.

Overview

Noise in a gearbox may be traced to various causes — to name a few:

- Gearbox design errors
- Gear pair transmission error
- Gear dimensional and surface quality
- Bearing and bearing journal quality
- Manufacturing and assembly variances
- External influences, such as radial and axial loads, and varying torques

In the design phase, proper kinematic and geometric gear design, along with mathematical modeling of gear systems, is done using state-of-the-art software tools to minimize gear noise at a later stage. In the manufacturing phase, tolerances of many gear characteristics such as index, lead and profile errors, along with other non-gear characteristics such as bearing surfaces and gearbox housing dimensions, are controlled to minimize noise.

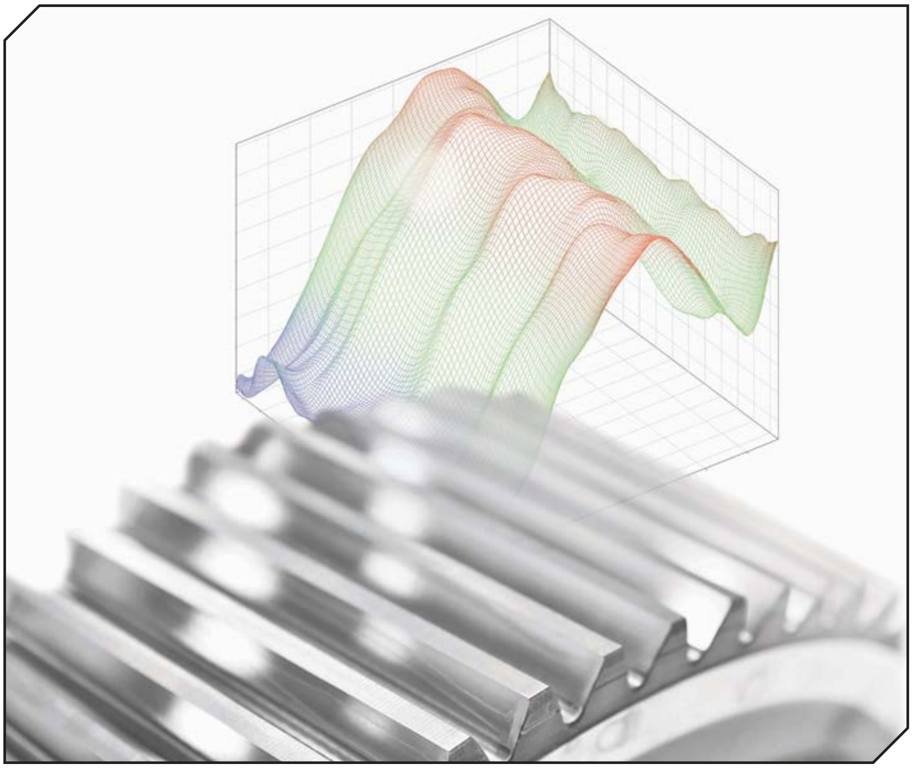
In the final testing phase, traditional methods have been widely used to measure and study gear noise such as single-flank testers to test subassemblies (mating gear pairs under varying loads and/or speeds) and dedicated test rigs to test entire gearbox assemblies. These end-of-line testing systems have helped the gear industry capture and control valuable noise-related data. However, the downside here is the final noise quality is determined at or near the end of the manufacturing process, with most of the manufacturing costs already incurred. Today's throughput targets require understanding what causes this phenomenon much earlier in the design and manufacturing process.

This article presents some of metrology tools Gleason has developed over the years to identify and control many of these noise sources. Its analytical machines (GMS, GMSP and GMSL series) provide a single platform from which users can measure, control and provide data to optimize gear manufacturing processes. All GMS series machines use Windows-based *GAMA* (Gleason Automated Measurement and Analysis) software. Many proven analysis tools are built into the *GAMA* software. Though the methods described in this article are mainly related to cylindrical gears, Gleason also provides similar solutions for bevel gears.

Traditional Methods and Analysis

Traditionally, gear measurement machines are used to inspect a few main characteristics on cylindrical gears: index, tooth size, lead and profile deviations. Many industry standards, such as ISO 1328, DIN 3960/62, China GB 10095, AGMA 2015 and JIS 1702, explain how to measure these characteristics, as well as providing tolerances based on the class of gears. Figure 1 and Figure 2 show typical chart output, displaying GMS *GAMA* measurement results with tolerances and gear class information.

These traditional measurements (index, lead and profile (involute)), assessed by comparison with published tolerances, provide quality information for a single gear. This is very useful in adjusting the manufacturing process for one gear type. In addition, they determine the quality class of a gear, which is required for commercial purposes in many cases.



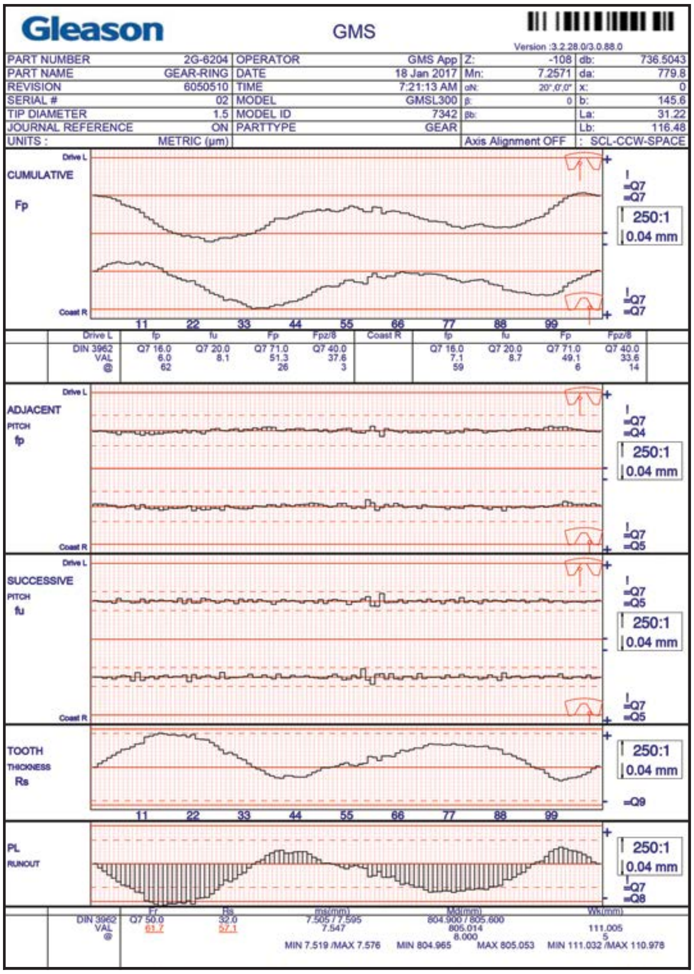


Figure 1 ISO 1328-2013 index analysis chart on GMS analytical machine.

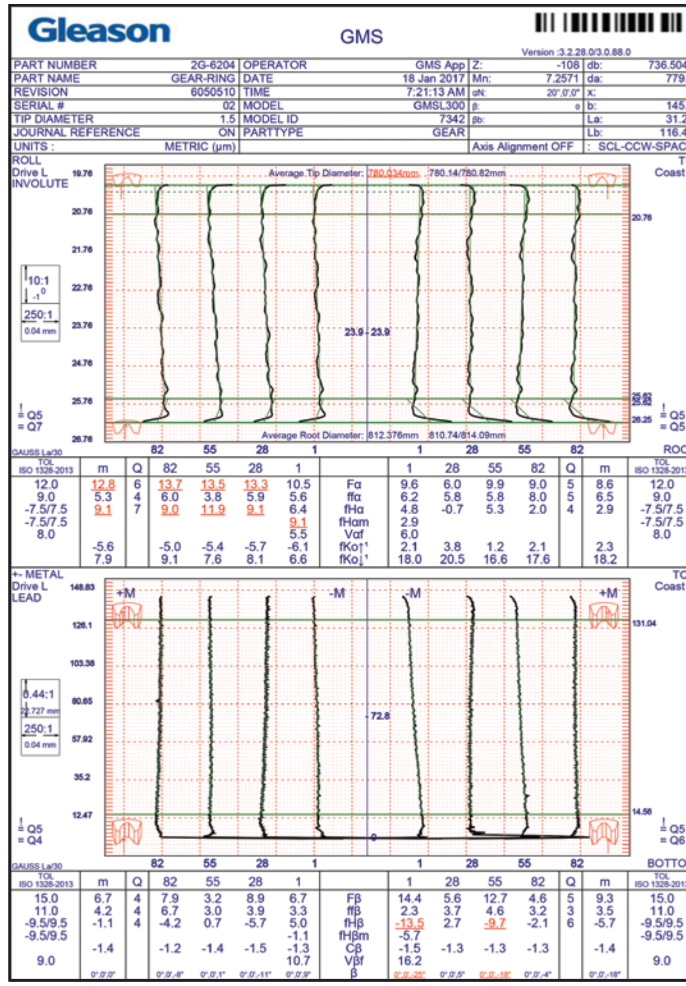


Figure 2 ISO 1328-2013 involute and lead analysis chart on GMS analytical machine.

While traditional measurements and analysis outputs are very useful in maintaining gear quality, they do not provide in-depth, easy-to-analyze data for noise analysis. For this reason, *GAMA* is equipped with multiple analysis tools to help identify the root cause of gear noise. The input to these tools is measurement data collected during the inspection of a gear. These tools are based on proven test results and save the *GAMA* user time with extremely user-friendly input requirements and mathematically optimized outputs for ease of interpretation. The output of many of these tools is correlated with noise signatures found during final testing of gearboxes or gear assemblies over the years.

New Analysis Tools

Several enhancements and additions have been made to these *GAMA* analysis tools, to take them to the next level, addressing the ever-changing needs of the gear industry and Gleason's customers. They include:

1. Fourier Analysis:
   - Waviness Analysis of Gear Measurements using Fourier transform technique
   - Waviness Analysis of Bearing Surfaces using Fourier transform technique
2. Tooth Contact Analysis
   - Transmission Error Plotting
   - Ease-Off Plotting
3. Surface Finish Analysis
4. *GAMA* and *KTEPS*
5. Loaded Contact Analysis with OSU *LDP* or Gleason *KISSsoft*

1. Fourier Analysis of Gear Measurements

Fourier analysis is the analysis of a complex waveform expressed as a series of sinusoidal functions, the frequencies of which form a harmonic series. Figure 3 shows Fourier analysis of index, lead and profile traces on the same gear pair shown in Figure 1. By studying the harmonic values of standard traces, the noise behavior of the same gear can be controlled. While Figure 1 qualifies the gear to pass traditional analysis, Figure 3 clearly shows significant issues with index harmonics. Amplitudes of lower harmonics (1st and 3rd) for index test are clearly beyond the tolerance curve. Comparing individual harmonics values of a production gear with a proven reference gear, the quality of produced gears is easily controlled. Such an analysis is combined with traditional gear inspection data already provided. This saves significant time, since no extra testing time is added, only analysis. By catching gears with higher harmonic values before any assembly takes place, significant cost savings is achieved.

Fourier Analysis of Bearing Surfaces

In recent years, Fourier analysis of bearing surface waviness has proven to be a very powerful tool in determining one of the main causes of low-frequency noise

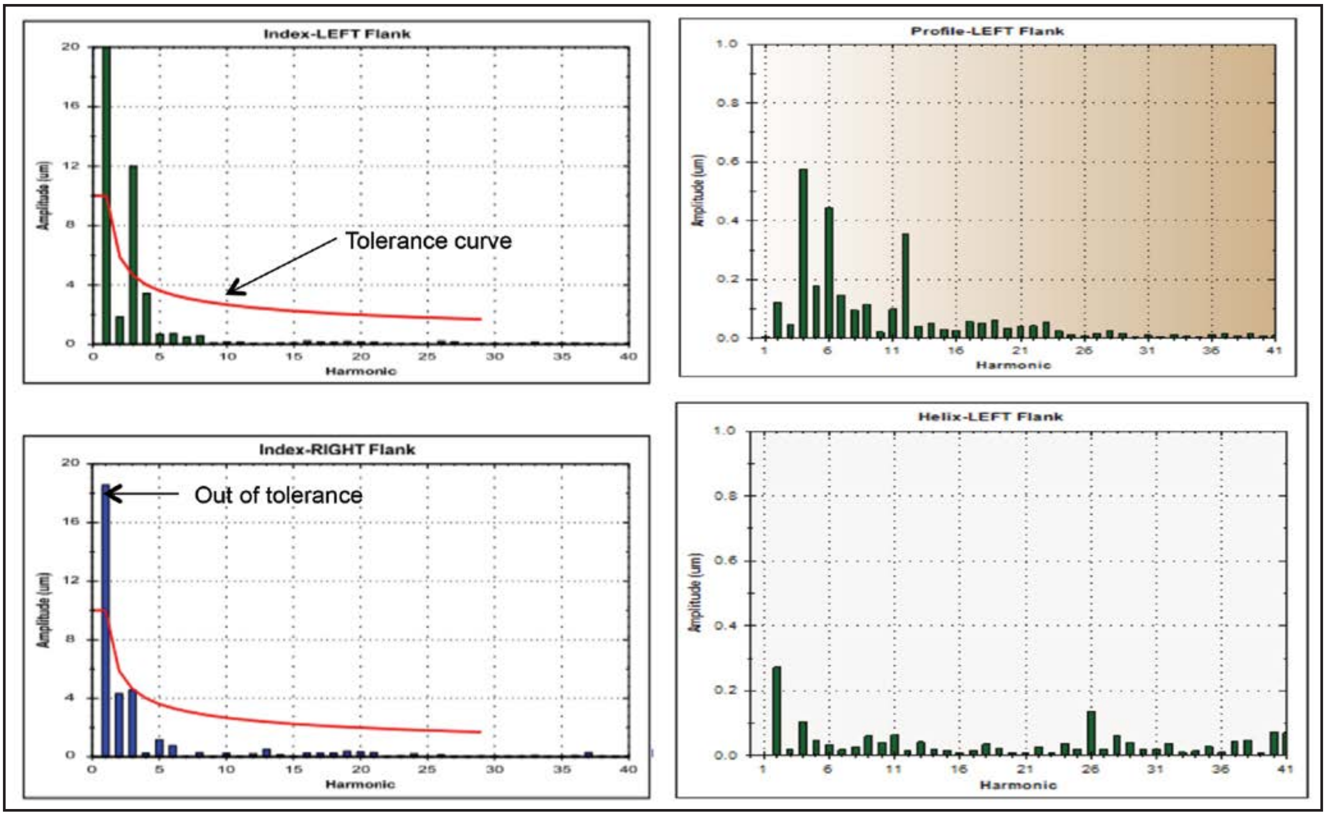


Figure 3 Fourier analysis of index, profile (involute) and helix (lead).

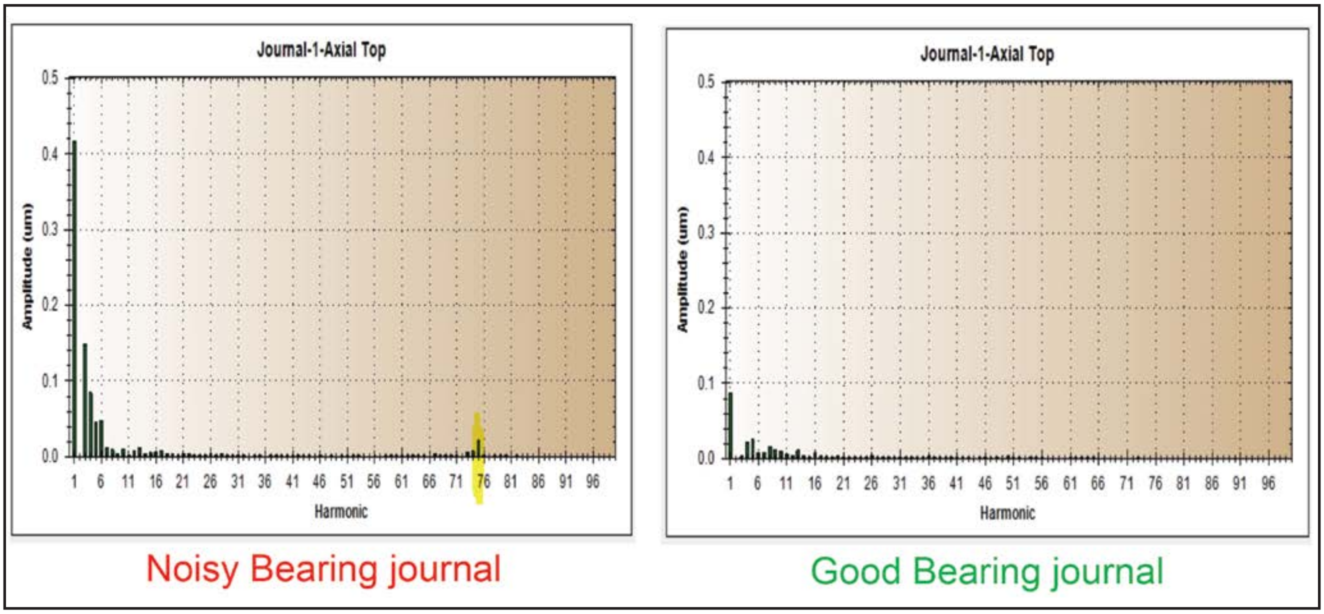


Figure 4 Fourier analysis of noisy and bad bearing journals.

in a gearbox. *GAMA* is equipped with Fourier analysis of bearing surfaces as well. Figure 4 compares Fourier analysis of a noisy and good journal measurement. This example shows that the 75th harmonic amplitude value is much higher on the first bearing journal. Upon careful analysis, it was found to be directly related to a manufacturing issue with the rotary table of the grinder used in the finishing operation of the measured bearing surface. Typically standard journal measurement charts can only assist with finding lower harmonic issues caused due to eccentricity. By applying Fourier analysis to measured journals, one can focus on higher harmonics as well. This example shows how *GAMA* can help control manufacturing of non-gear related features along with traditional gear features.

2. Tooth Contact Analysis

While waviness analyses as explained above are very useful for analyzing individual gears for quality control, in real life, gears are always meshed in pairs to transmit motion. The true performance of a gear is determined when it meshes with a pinion.

Over the years, many gear researchers

around the world have developed mathematical models to analyze the meshing of gear pairs. These models assist in the design phase of a gear pair, which is targeted to minimize transmission error and improve contact pattern on the gear surface. Transmission error is the difference between the actual position of the output gear and the position it would occupy if the gears were perfectly conjugate.

GAMA can also provide contact analysis. It provides valuable information to the user by mathematically meshing the surfaces of the gear and pinion, which is extremely useful in design as well as in all production phases of the gear. A topological inspection of the mating area of the gear and pinion is performed. This data is then input into the *GAMA* contact analysis software to compute transmission error along the meshing path and generate ease-off topographical charts. The software is capable of reviewing the effect of misalignments in the axial and radial directions. This allows design engineers to modify gear surface geometry such as amount and length of tip relief. The mathematical algorithms are optimized to give these results in a few seconds on GMS machines.

Figure 5 shows the interface for *GAMA Tooth Contact Analysis*. The user can select inspection data from a previously inspected gear and mating pinion, and analyze them with a single click.

Figure 6 shows transmission error plots with color codes. The user can see the distribution of transmission error over multiple mesh cycles and their overlap. Fourier analysis of these traces is available, which allows the user to perform harmonic analysis and determine the frequencies of higher amplitude.

Figure 7 shows an ease-off plot. Ease-off plots combine surface modifications (i.e. flank form corrections) from both gear and pinion. Lead crown, tip and root relief are some of the planned flank form corrections to keep contact in the desired region of the gear and pinion mating surface. A contact path is then plotted on this surface. As the figure shows, the contact pattern is shifted toward the root of the gear. It needs to be moved to the center of the gear, which can be done by increasing the tip relief amount of the mating pinion.

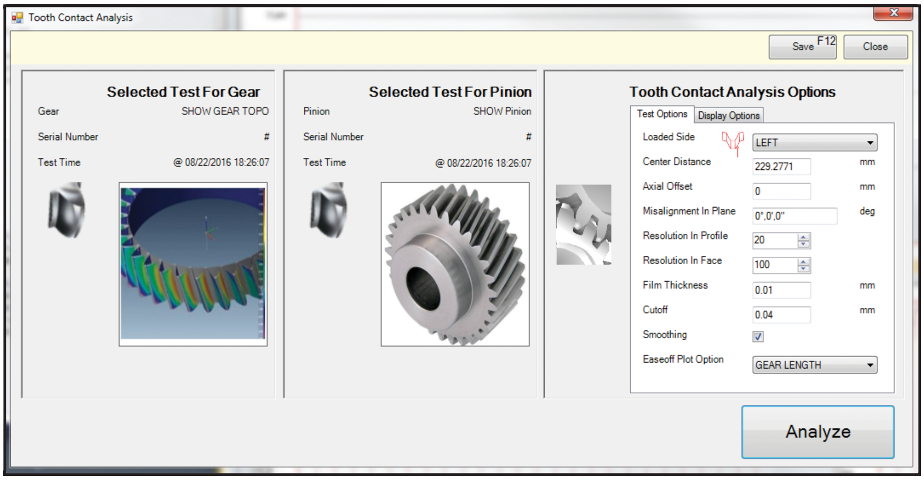


Figure 5 **GAMA Tooth Contact Analysis interface.**

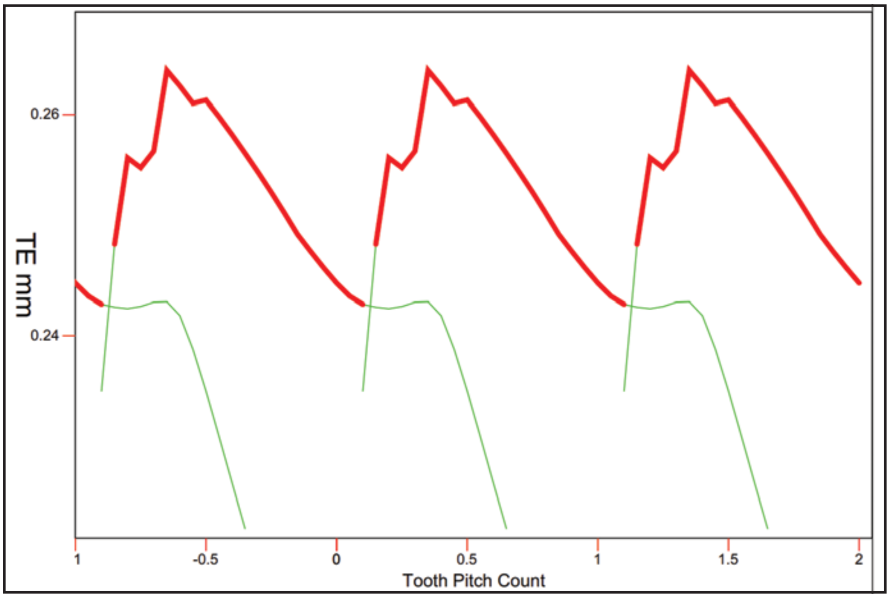


Figure 6 **Transmission error (TE) plot.**

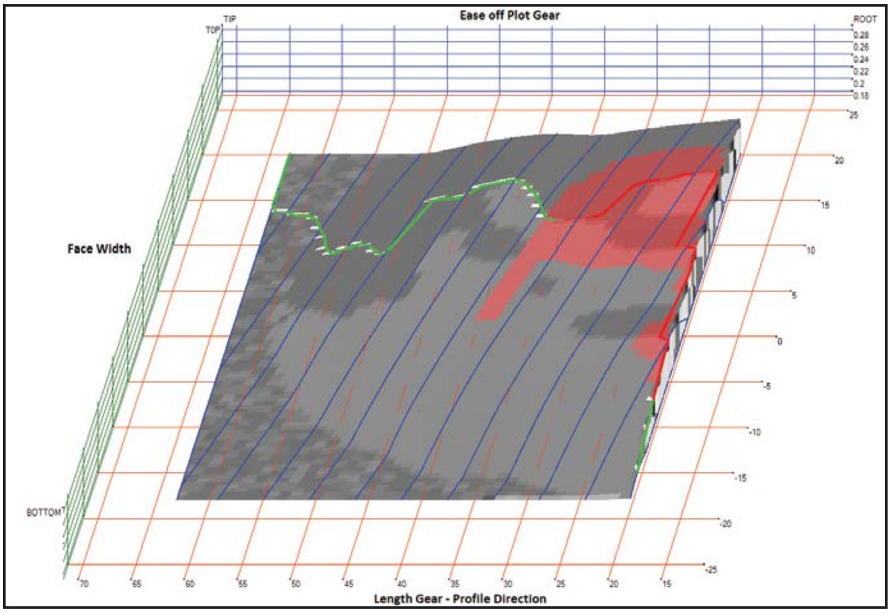


Figure 7 **Ease-off topographical charts.**

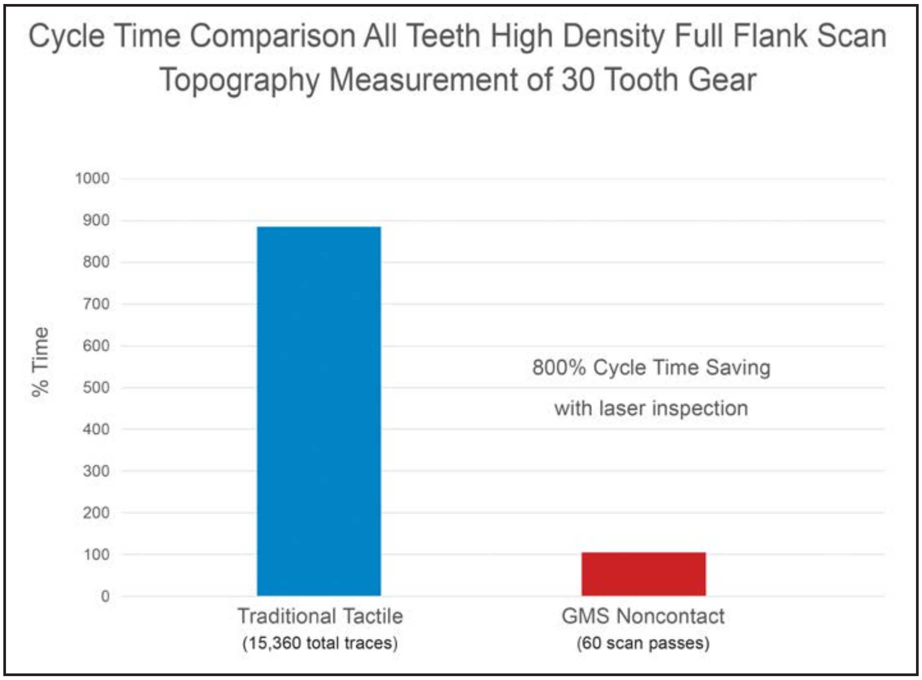


Figure 8 GMSL cycle time advantage.

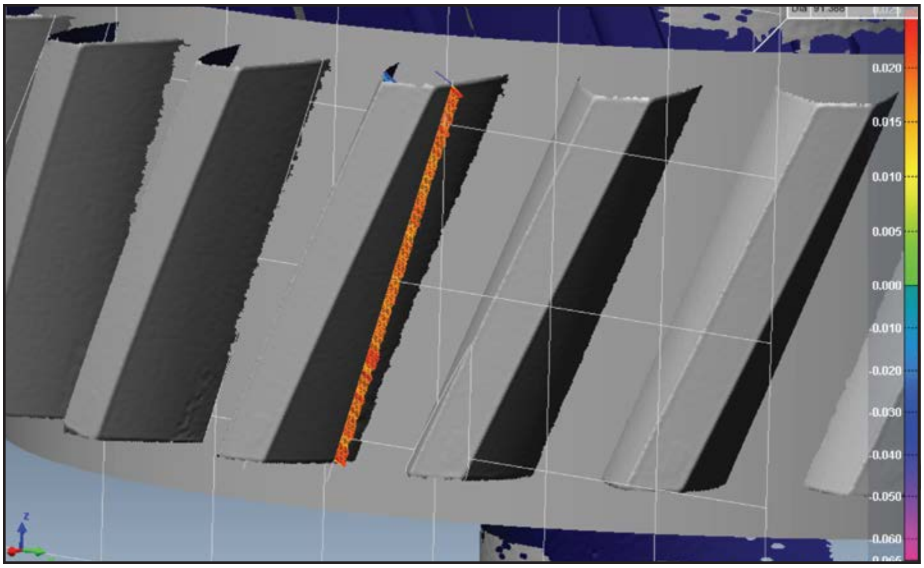


Figure 9 GMSL advantages – multiple sections from point cloud, including line of action.

The GMS, GMSP and GMSL series of machines are capable of performing contact analysis, since all use the same *GAMA* software. However, the GMSL series offers a significant advantage, due to the non-contact sensor's ability to capture high-density data at fast speeds, as explained below:

- Contact analysis of a gear pair requires significantly higher density points on gear flanks for accurate analysis. More data is better for accurate predictions and control.
- Collecting high-density data using a traditional contact probe is a very slow process. The contact probe simply cannot provide the high-density data that a non-contact probe can provide.
- Figure 8 shows an 800% cycle time reduction on a GMSL machine with laser sensor, compared to inspecting the same gear with a traditional touch probe.
- Figure 9 shows the ability to take multiple complex sections on a 3D point cloud generated by a non-contact sensor. *GAMA* can take these sections along the path of contact, and export them for transmission error analysis.

3. Surface Finish Analysis

While waviness and contact analysis are very useful in controlling gear pair-related noise issues, surface finish inspection has a direct impact on the higher frequency noise behavior of gear sets. Surface finish also has a proven impact on the life of a gear. Surface finish measurement of a gear on traditional, manual surface finish inspection machines is a very complex and time-consuming process. This has been made easier on GMS series machines with available integrated, surface finish, probing technologies and *GAMA* software. Figure 10 shows a surface finish chart produced by *GAMA*. Traditionally, Ra and Rz output is used to qualify the surface finish of gears. However, *GAMA* provides a powerful analysis package, which can measure up to 72 different surface finish characteristics with advanced filter methods to analyze high-frequency noise. The same software is available to measure the surface finish of non-gear features such as bearing surfaces.

4. GAMA and Kinematic Transmission Error Prediction Software (KTEPS).

KTEPS uses an analysis approach for determining and diagnosing gear noise especially related to ghost noise. Ghost noise in a gear pair is much more complex to analyze than mesh harmonic noise. The unique one-to-one correlation of gear performance in the time and frequency domains to the geometric and kinematic contributions to transmission error from the tooth face geometry of a single gear allows the software to break out tones and the harmonic nature of gear noise in ways that no other analyses can match. Simple error amplitude metrics do not correlate well with the noise generating properties of harmonic errors, but *KTEPS* is able to generate the unique error pattern on any portion of any gear tooth responsible for a particular noise harmonic, whether or not it is associated with a mesh harmonic.

The *GAMA* interface directly communicates with *KTEPS* in a much-simplified user interface as shown in Figure 11. All programmed geometrical and test data such as inspection locations are transferred automatically from *GAMA* to *KTEPS* at the end of test. *GAMA*'s ability to communicate with *KTEPS* in the background puts this interface at your fingertips on GMS machines.

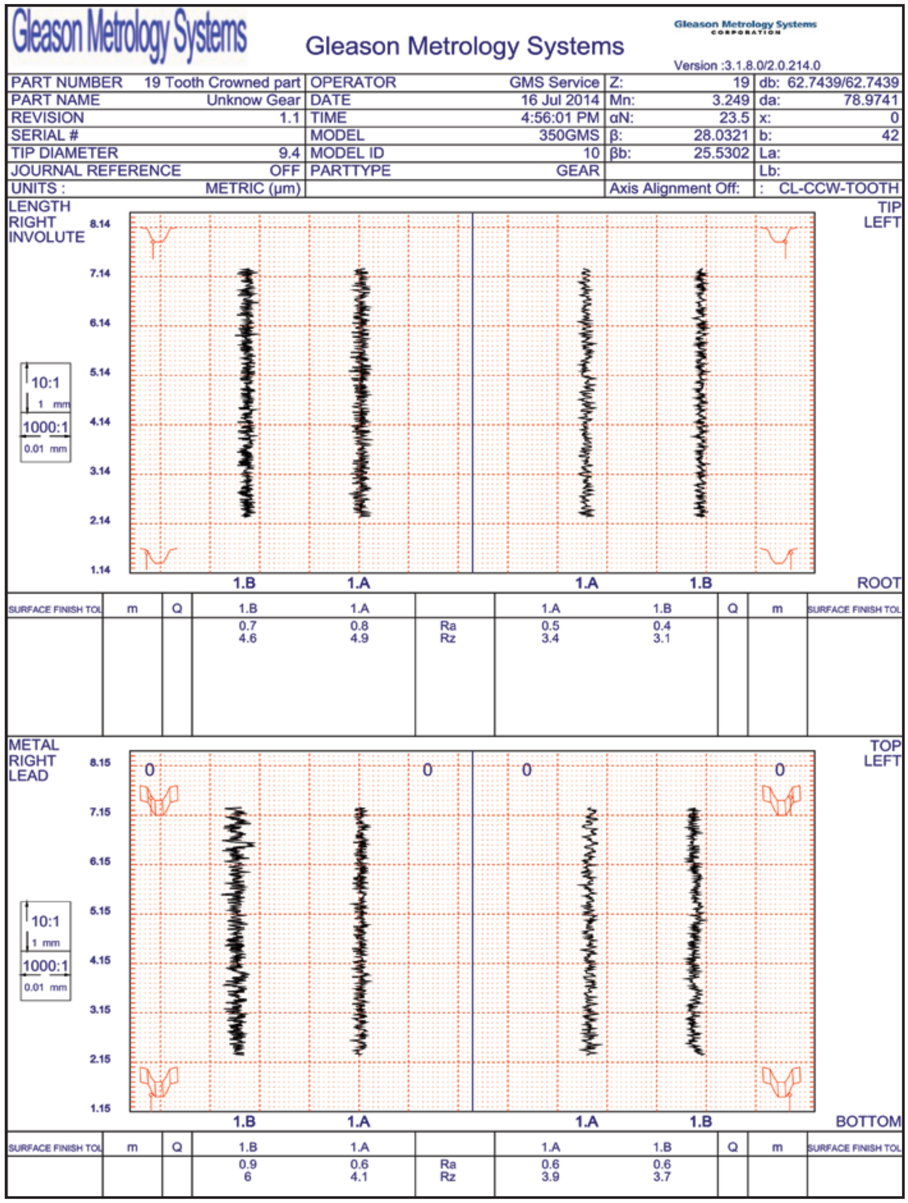


Figure 10 GAMA Surface Finish inspection chart.

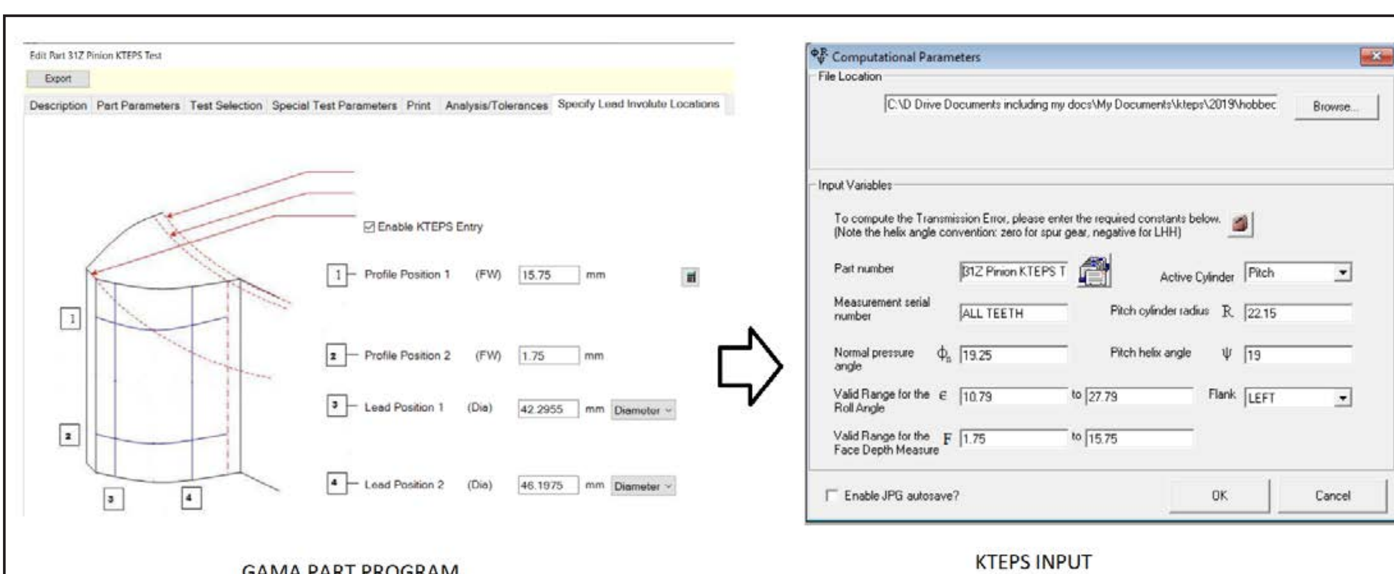


Figure 11 GAMA-KTEPS Integration.

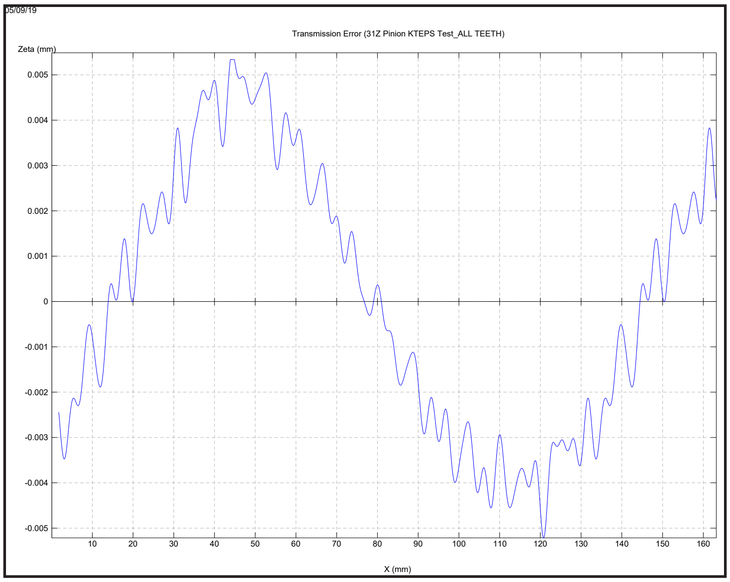


Figure 12 Transmission error of ALL teeth inspection.

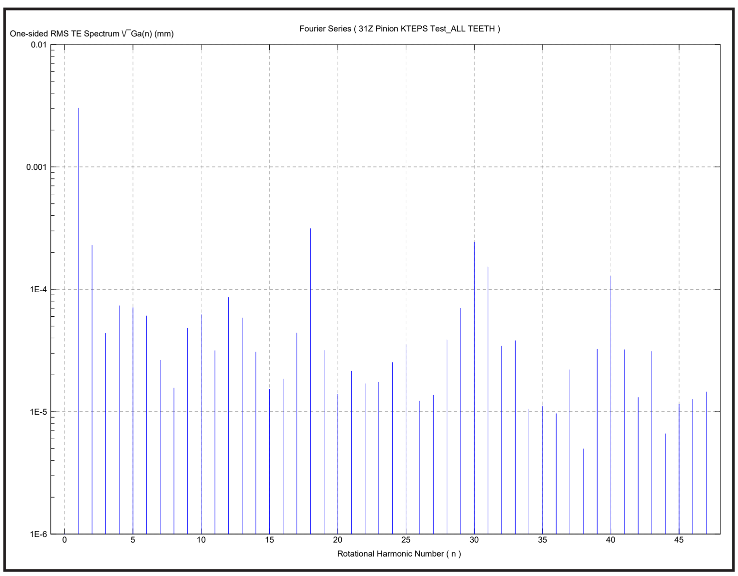


Figure 13 Fourier analysis of transmission error.

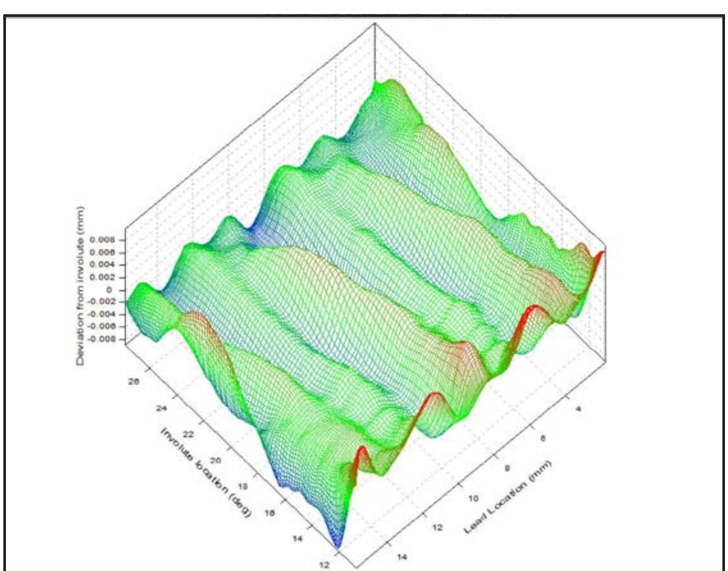


Figure 14a Reconstruction of tooth topological form for 1st harmonic.

Figures 12 to 14 show example analysis of a 31-tooth pinion in *KTEPS*. All teeth of the example gear are inspected at multiple lead and profile locations. Figure 12 shows transmission error analysis for one full rotation of the gear. Since the example gear has index error, the chart shows a large sinusoidal error for one full rotation of the gear. Each gear tooth shows varying transmission error as well. Figure 13 shows Fourier analysis of the transmission error for the same gear. Since this gear has 31 teeth, large transmission error amplitude is observed at the 31st rotational harmonic. The 1st rotational harmonic also shows large transmission error amplitude, which correlated with the large sinusoidal error generated due to index error shown in figure 12. The example gear has form error in the lead direction generated due to the hobbing operation. This has resulted in large errors around the 19th rotational harmonic. One of the major strengths of *KTEPS* is its ability to swap between spatial and time domains with no approximations. Figure 14 shows reconstruction of tooth tooth topological forms at different harmonics. Studying topographical charts at required rotational harmonics based on Fourier analysis gives users the ability to relate gear noise with topological errors.

KTEPS also has advanced analysis abilities such as programmable misalignment errors and ability to create transmission error induced audio clips at programmable RPM for analyzed gear sets.

5. Loaded Contact Analysis

For complete design, an engineer has to consider the effect of tooth bending under varying load. More research has been done to understand the behavior of a gear pair under varying torques or loaded conditions. This is also known as loaded contact analysis.

Both the *Loaded Distribution Package* (*LDP*) developed by Ohio State University as well as Gleason *KISSsoft* software have the ability to perform this analysis. *GAMA* is capable of writing gear inspection output files in a format that can be easily imported into OSU *LDP*. This is achieved by topographical inspection in *GAMA*, with a simple checkbox on the user interface. Using *GAMA*'s Gearnet ability, the user can control the storage location of such files for ease of use by a design expert at his offline workstation. *GAMA* is also capable of writing gear part parameters including tolerances and inspection test data in xml file format published by VDI/VDE 2610 GDE standard. This data then can be shared with *KISSsoft* for both gear and gearbox design optimization purposes.

As explained in this article, gear noise has multiple causes, and no one solution or analysis package can solve them all. It has been proven over the years that multiple areas of the gearbox assembly need to be controlled during the production phase. Gleason brings a significant advantage to its customers by combining multiple analysis tools on one platform. Figure 15 shows work flow using the *GAMA* interface. The single *GAMA* software interface can provide multiple analysis outputs.

For more information:
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Douglas Beerck is Vice President and General Manager of Gleason Metrology.

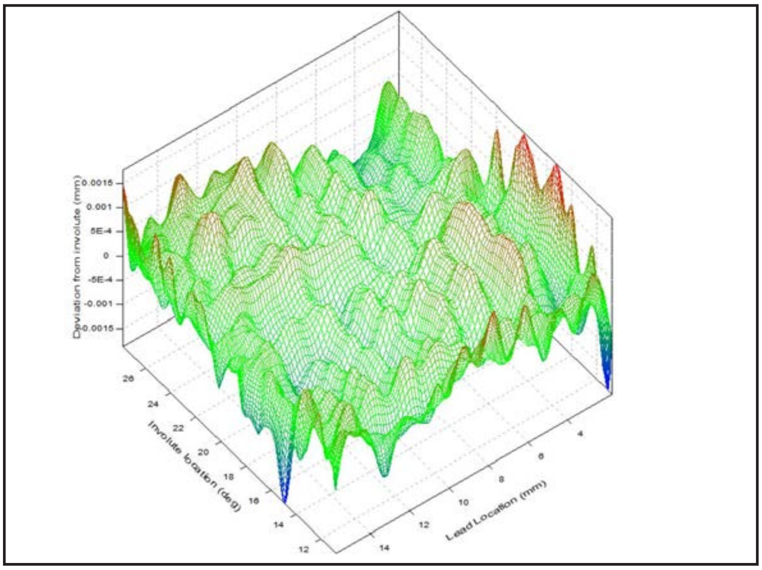


Figure 14b Reconstruction of tooth topological form for 19th harmonic.

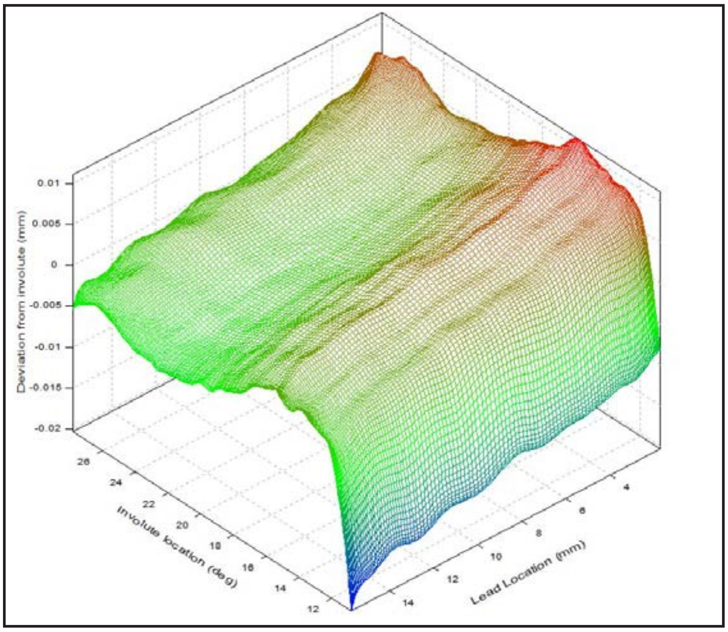


Figure 14c Reconstruction of tooth topological form for 31st harmonic.

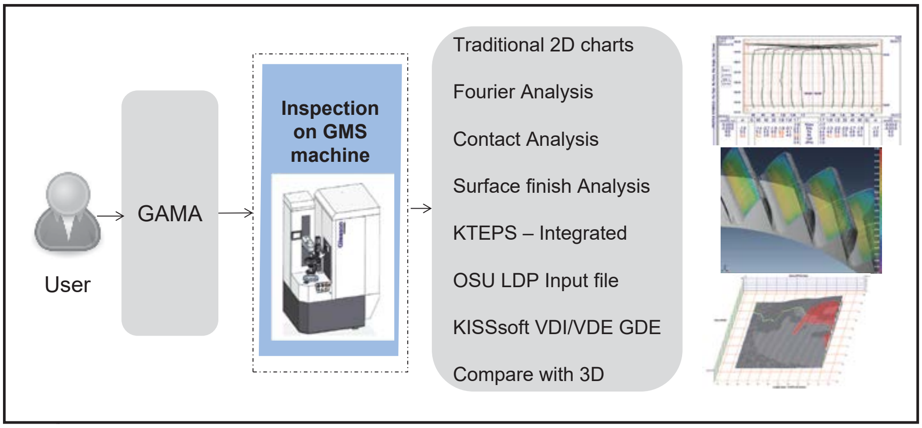


Figure 15 User interface – flow diagram.

AGMA STANDARD 2002-C16

Email your question—along with your name, job title and company name (if you wish to remain anonymous, no problem) to: *jmcguinn@geartechnology.com*; or submit your question by visiting *geartechnology.com*.

QUESTION

We are currently revising our gear standards and tolerances and a few questions with the new standard AGMA 2002-C16 have risen. Firstly, the way to calculate the tooth thickness tolerance seems to need a "manufacturing profile shift coefficient" that isn't specified in the standard; neither is another standard referred to for this coefficient. This tolerance on tooth thickness is needed later to calculate the span width as well as the pin diameter. Furthermore, there seems to be no tolerancing on the major and minor diameters of a gear.

Expert response provided by John M. Rinaldo, retired from Atlas Copco Comtec and AGMA Accuracy committee. AGMA 2002 is not a design guide; it does not specify or provide calculations to establish tolerances. It is a standard for the measurement of gears and provides methods for predicting backlash. Before using AGMA 2002-C16, the designer must select the tooth thickness and tolerance (or maximum and minimum tooth thickness) that is appropriate for the application. The designer must also select the tolerances for the major and minor diameters of the gear.

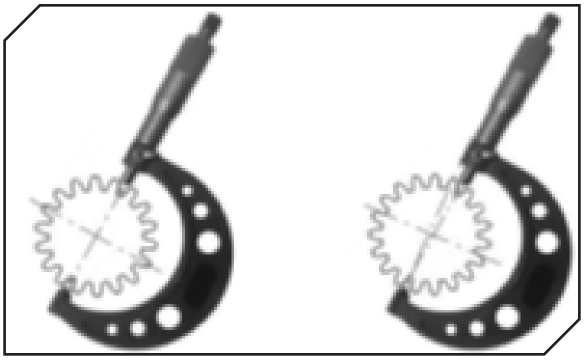


Figure 1 Measurement over balls.
From AGMA 2002-C16 Fig 10

There are two general methods used to establish tooth thickness. One uses profile shift coefficient, commonly referred to as the *x* factor. If the gears are designed using *x* factors, DIN 3967 provides a method for establishing appropriate values for x_e. This method is commonly used in Europe but is less common in the US. Another method is to just select the backlash and then distribute the remaining space on the operating pitch circle between the tooth thickness of the gears, annexes B and C give some guidance on this method.

Manufacturing profile shift coefficient is just one of many ways to specify the tooth thickness of a gear. It is not required by AGMA 2002-C16. If the manufacturing profile shift, x_e, is known, then in this standard it is only used to calculate the normal circular tooth thickness at the reference diameter. The standard provides methods to convert not only profile shift coefficients but almost any other specification of tooth thickness to other ways of specifying tooth thickness. For example, if the maximum and minimum transverse tooth thickness are specified at a given diameter, equations are provided to find the maximum and minimum normal circular tooth thickness at the reference diameter. Then the maximum and minimum acceptable measurement over balls or any of the other measurements covered can be calculated with the equations provided.

While AGMA 2002-C16 is focused on calculating measurement limits from a specified tooth thickness, it also provides methods to determine tooth thickness based on measurements that are indirect. For example, if a span measurement is taken, then the normal circular tooth thickness at the reference diameter can be found using equation 67. AGMA 2002 also provides information that can help those who take the measurements.

It should be noted that tooth thickness specifications may use either the nominal or functional system. The nominal system is more commonly used and allows measurement over pins or balls or with span. The functional system allows a more direct calculation of expected backlash but requires the tooth thickness to be measured in relation to the datum axis. Such measurements are typically performed on a double flank tester, a gear measuring machine, or from a datum surface to a single pin, ball, or block. Fully understanding the differences between the nominal and functional systems is essential to proper use of the standard.

Figure 2 Span measurement.
From AGMA 2002-C16 Fig 7

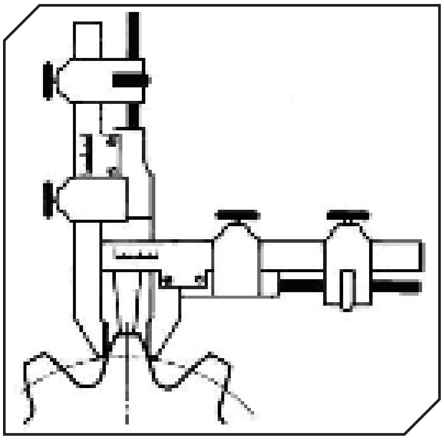


Figure 3 Chordal Measurement. From AGMA 2002-C16 Fig 21

Tooth thickness and backlash are intimately related, which is why AGMA 2002-C16 covers both topics in a single standard. In establishing tooth thickness, the goal generally is to ensure that the expected range of backlash will be appropriate for the application. In many applications, particularly when rotation is unidirectional, backlash is not particularly important. In these cases, allowing a wide range of backlash and hence a large tooth thickness tolerance will keep manufacturing costs down. When tight control of backlash is required, such as in indexing applications, then not only does the tooth thickness need to be tightly controlled but the other gear tolerances may also need to be tighter to allow the tooth thickness tolerance to be met. The gear tooth thickness measuring method may also need to be carefully chosen, since the method selected can affect both the ability to tightly control the tooth thickness and the manufacturing cost. For example, for a large gear a chordal tooth thickness measurement can provide a quick and inexpensive measurement, but unless the radius to the outside diameter has been accurately determined from the datum surfaces, there will be a considerable uncertainty in the calculation of functional tooth thickness. Measurement of pitch on a gear measurement machine will give a direct measurement of functional tooth thickness, but at a high cost. Double flank measurement can be used to quickly measure the functional tooth thickness of all the teeth on a gear, but generally is only applicable to small gears produced in high volumes.

The selection of the appropriate range of tooth thickness is similar to the selection of any of the myriad other choices the designer faces, such as selecting the appropriate numbers of teeth, the module, the helix angle, the face width, the material and heat treatment and the elemental or composite tolerances.

In summary, while AGMA 2002 can indirectly aid in the design phase to verify that the specified range of tooth thickness will result in the desired range of backlash, it is not intended to guide the basic design of the gears. But once the design is set, it provides equations to calculate test limits for the tooth thickness. *Editor's note:* ***Robert Errichello*** *assisted in presenting the above response.*

Fully Automated Roughness Measurement on Gears — Even on the Shop Floor

An Optimized System for Precision Measuring Centers

Georg Mies

Significance of Surface Roughness

For flawless operation of geared components in a transmission — not only the component geometry, but also the surface quality of the functional surfaces — plays a decisive role. Precise inspection of the geometry has been state-of-the-art for decades, and has since undergone further development; by contrast, insights regarding the effects of surface quality are still relatively recent. Just a few years ago, this aspect was not such a central topic for series production of standard transmissions, but thanks to new or improved machining technologies, smooth surfaces or defined surfaces can now be produced cost-effectively — even in large-scale production. Also, special manufacturing processes such as polish-grinding and chemical methods of polishing have made a contribution in this respect.

Surface properties defined with maximum precision are a key variable, and are frequently also the prerequisite for valuable improvements in drive engineering. Especially in the automotive industry, and particularly in the electric mobility area, the surface quality of the gearing components is essential. In combination with electric drives, extremely high rotation speeds are transmitted, resulting in new challenges in transmission and gearing design. But even in conventional drives with a combustion engine, smoother gearing can make a significant contribution to the running properties. The production of surfaces with an *Rz* value of less than 1 µm are now possible in series production.

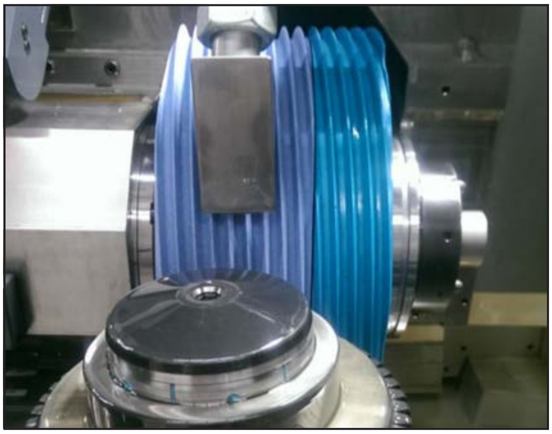


Figure 1 Polish-grinding with a combined grinding-polishing worm.

Figure 2 Reference plane scanning system.

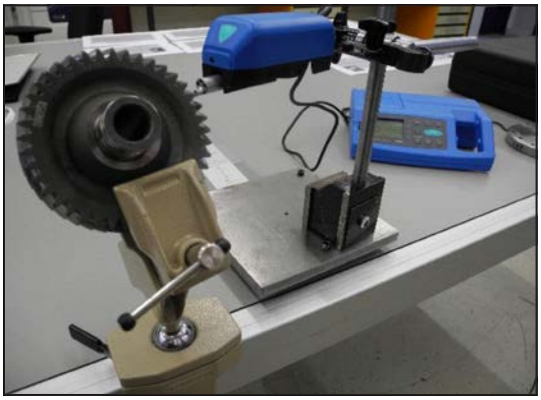


Figure 3 Skid scanning system.

Conventional Roughness Measurement Methods

As a result, the importance of roughness measurement of gearing has grown significantly. Although roughness can be measured on tooth flanks with the common roughness measurement systems, these systems are not entirely suitable for serial measurements. They are difficult to operate and they require trained technicians; measurements must be carried out in large part manually. Quite a bit of skill is required to even conduct such measurements with standard feed systems, as the component alignment also plays an important part. The setup procedure is particularly challenging with reference plane scanning systems. Due to the involute bend of the tooth contour, a curve is traced with the diamond needle. Because the feed unit executes a linear motion, the alignment must be selected so that this curve remains in the measuring range of the probe; a suitably larger measuring range is required. In addition, the diamond needle changes its alignment with respect to the surface during the motion.

When using a feed unit with a skid probe, the measuring range of the probe needle can be significantly smaller and the resolution correspondingly higher. The sensitive probe needle is protected by the skid. This makes the system quite robust. This provides advantages in handling, since it prevents needle damage when setting up the probe needle in the tooth space. Figures 2 and 3 show two linear feed systems measuring roughness on a gear. Regardless of the sensor technology, however, the above-described disadvantages apply to both systems; therefore the gear industry demanded an automated solution.

Figures 4 and 5 Roughness sensor mounted on the 3-D probe:

In addition to the roughness sensor technology, a precision swivel device is also integrated into the extremely compact roughness sensor. The roughness probe can therefore be operated on the adapter plate like the tactile styluses and can be changed automatically. An especially convenient feature of this is the automatic plug-in (right picture).

A Solution Optimized for Gears

In order to realize an automated solution, it is obvious to use a gear measuring machine and to adapt a roughness sensor system. In this context the question arises, i.e. — which sensor technology is the most suitable for this combination of a gear measuring machine and roughness sensor?

Automatic measuring cylcles, which can be done in combination with the gear measurement, require a robust system in which the sensitive probe needle cannot be damaged. This was the main reason for the decision to use a skid system.

But the skid system has a well-known disadvantage, i.e. — the signal corruption due to elevations on the surface. This causes the skid to rise at a different time with respect to the needle during the measured value logging process. The measurement signal detects a recess that does not actually exist.

But on high-quality ground or polished tooth surfaces of gears, this effect is very low. This is a positive precondition that favors the use of a skid scanning system for gear measurement.

Figures 4 and 5 show how the roughness probe that was especially developed for use on gearing components is adapted on a gear measuring machine. The roughness probe can be mounted directly on the standard adapter plate of the 3-D tracer head. In order to scan in different directions, the roughness probe is equipped with an integrated swivel axis. The adaption is possible because the combination of roughness probe and swivel axis has been miniaturized very much.

Due to this arrangement, the skid of the roughness sensor behaves like the ball of a tactile stylus mounted on the 3-D tracer head. As the point of contact of the skid is only a cut-out of a ball, the swivel axis rotates the skid with the point of contact perpendicular to the surface; the diamond needle is also twisted in the same direction. To understand this function, Figure 6 shows the front

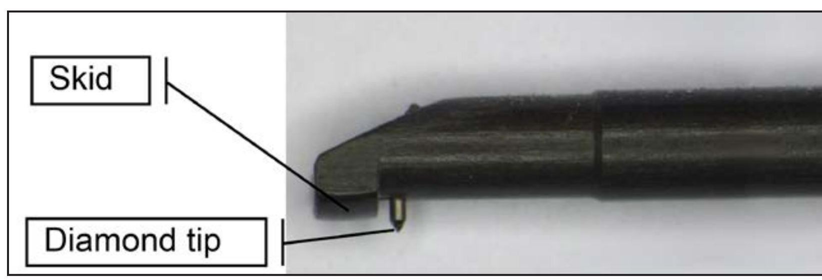
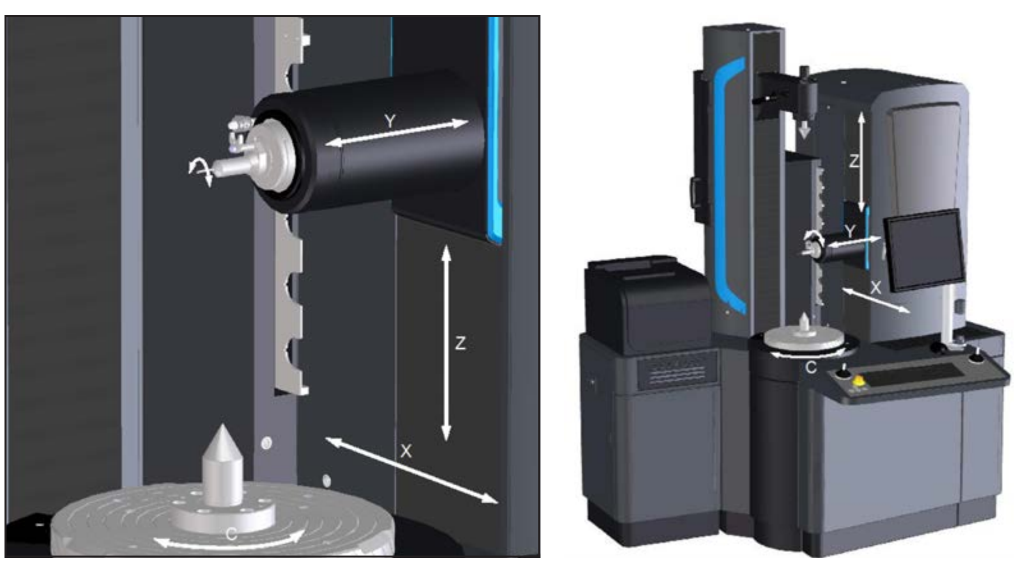


Figure 6 The front end of the roughness sensor shows the arrangement of the skid and the diamond tip. The probing force of the diamond tip is less than 0.5 mN.



Figures 7 and 8 The arrangement of the roughness sensor on the gear measuring machine and the assignment of the machine axes. The rotation direction of the sensor swivel axis is also marked. The gear measuring machine complies with class 1 of VDI/VDE 2612 and 2613. The roughness measuring system fulfills the requirements according to DIN/ISO 3274.

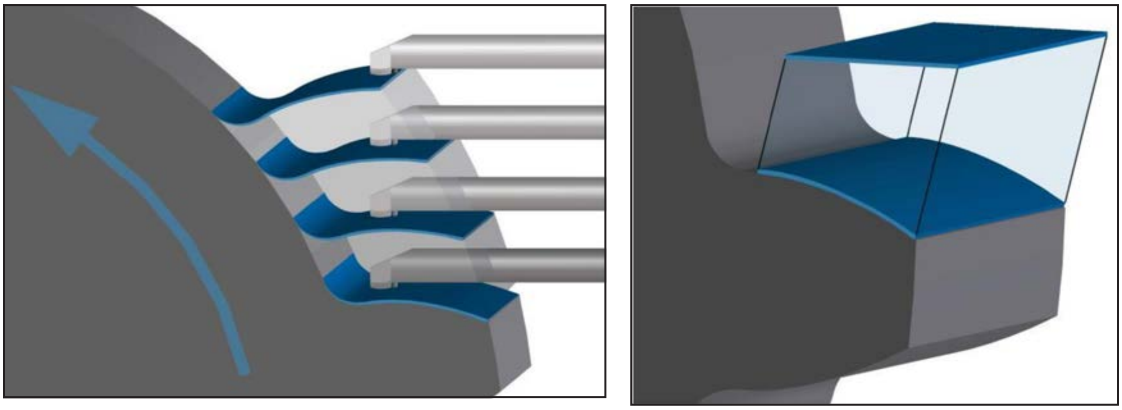
end of the roughness sensor.

Since the roughness system is optimized for recording roughness parameters specifically on gears, the same measuring cycles can be used for roughness measurement as for gear measurement — thus ensuring optimal tracing conditions. The tactile stylus and the roughness sensor can be exchanged automatically within the measuring process to have a fully automated measurement cycle — including gear measurement, size, form and position measurement — as well as roughness measurement in a single clamping.

Thanks to this integrated solution and a fully automated measurement cycle, serial measurements can be performed even by untrained staff. This requires a particularly robust system that can also be used in a production environment. This requirement is met through the arrangement of the roughness sensor with the skid. The diamond needle is actively protected from damage in cases of a collision. In addition, by using a skid system the roughness measurement is extremely insensitive to vibrations.

Figure 9 **Gear measuring machines have for years been used directly in the production area. By adapting the roughness sensor on these machines, this is now also practiced for roughness measurement.**

This is an important prerequisite for using the setup directly in production. For gear measurement this is already state-of-the-art. Numerous user examples have confirmed that it also works with the shown system for the roughness measurement.



Figures 10 and 11 **Owing to the optimized measurement and tracing strategies of the skid probing system, the curved surface behaves like an ideal plane relative to the roughness probe; illustrated here with a sample profile measurement on involute gearing.**

Another advantage of an integrated system is the chance to use the possibilities of a four-axis coordinate measuring machine with rotational axis. It allows keeping the diamond needle always exactly in normal direction to the surface, though it is an involute curvature. The curvature is fully compensated by the generative measuring movement, resulting in almost complete linearization of the scan on the gear surface (Figs. 10–11).

From the perspective of the roughness probe, the curved surface behaves like an ideal plane. The diamond needle records only the surface roughness and can therefore use an extremely small measuring range with a correspondingly high resolution. This prevents errors filtering the long-undulation curvature.

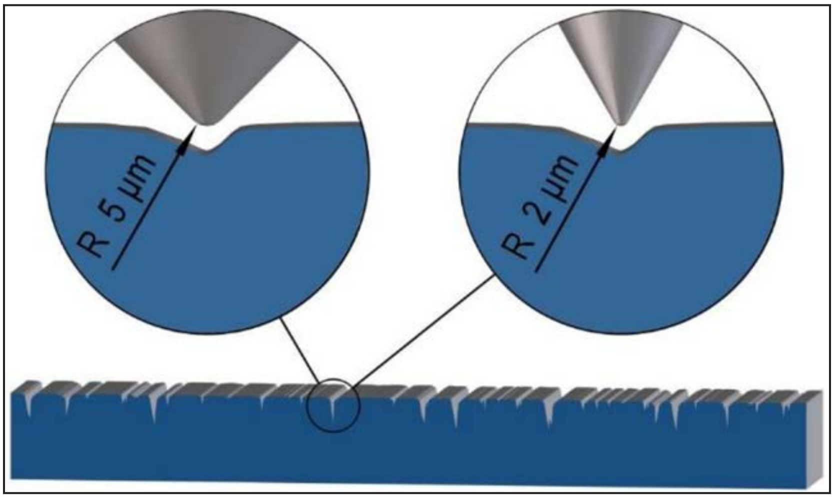


Figure 12 **Graphic with the same magnification factor in all directions shows the correct relation of the diamond tip to the deepest stria. The typical roughness profile presentation has strong vertical scaling. The gaps appear much tighter than they are.**

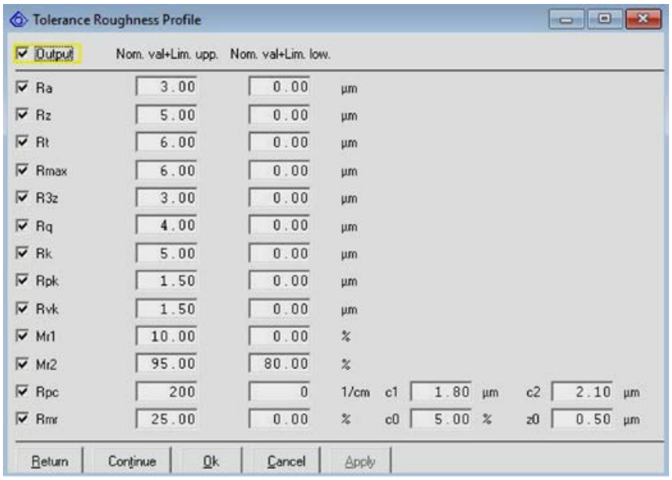


Figure 13 **Input menu for roughness parameters and tolerances.**

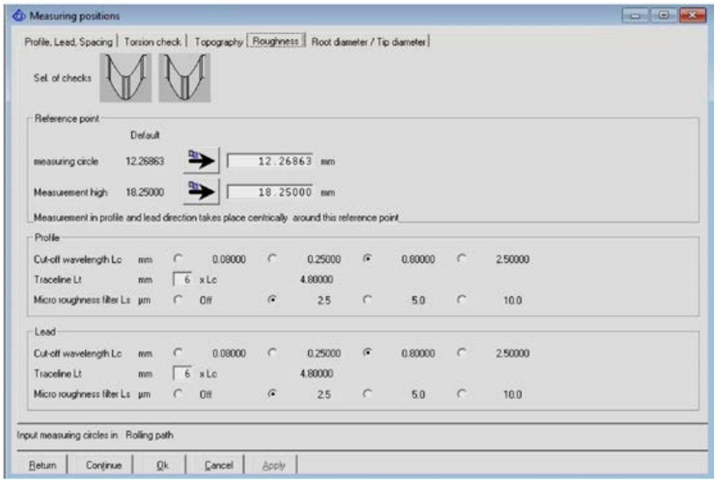


Figure 14 **Input menu for measuring length and filter parameters.**

Influence of the Tip Radius

The DIN/ISO 3274 standard specifies under which conditions a probe tip with 5 µm tip radius or with 2 µm tip radius is to be used; in both cases the radii are very small. In order to get a better understanding of the influence of the probe tip radius to the surface, the relation to each other must be made clear.

Due to the radius of 2 µm, very fine stria can be measured better. To illustrate this, it is advantageous to represent the relation between the surface in the longitudinal and vertical directions with the same magnification.

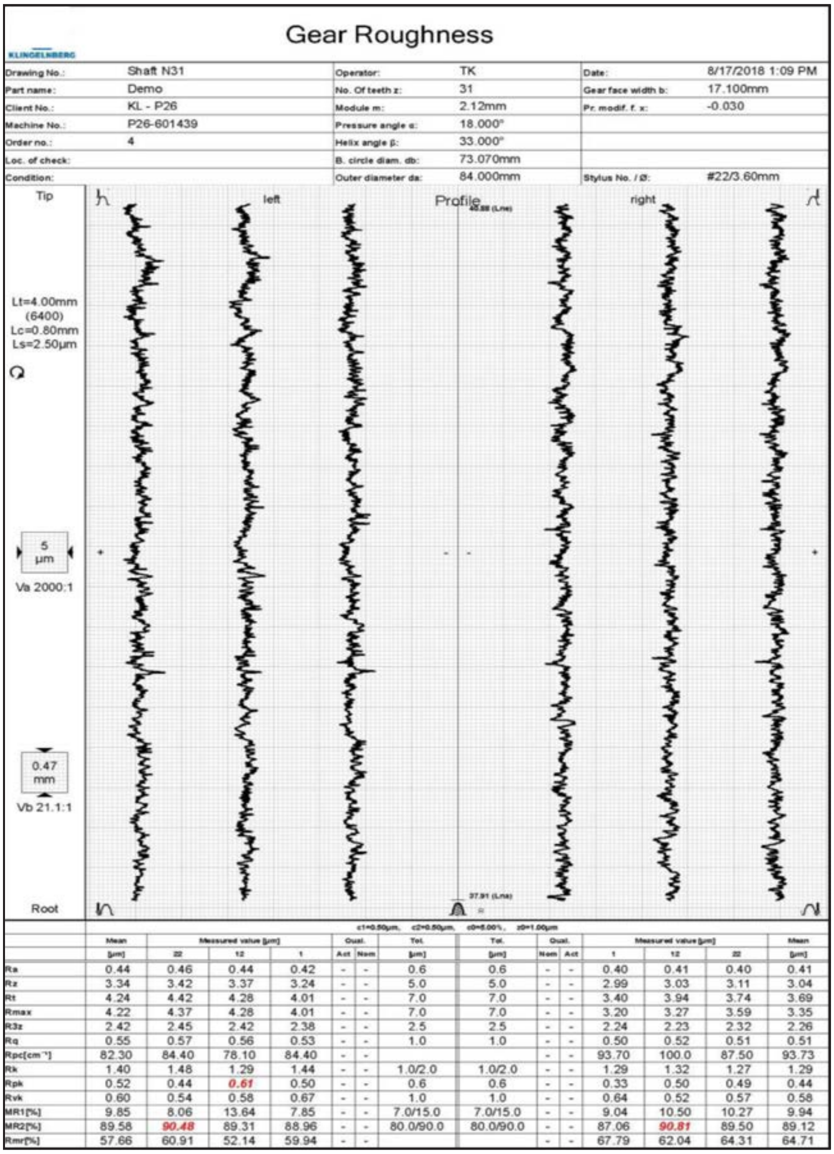
In typical roughness profile charts a very strong vertical scaling relative to the surface is used. This makes stria that are just 0.5–1.5 µm deep appear very narrow and seemingly impossible to measure using a 90° or 60° diamond tip. By showing the actual relation through the same magnification in the lengthwise and vertical directions, the actual appearance of the seemingly narrow compared with the tip becomes apparent. In this case, the stria could be measured with both — the 2 µm and the 5 µm tip. In a case of even narrower gaps, the 5 µm tip would not reach the bottom, so that the 2 µm tip is needed; Figure 11 shows the influence of the magnification.

Measuring Results

The evaluation and output of the roughness measurement results are analogous to the toothing evaluation. The roughness curves are shown in corresponding diagrams. The calculated parameters are listed under the diagrams in tabular form.

The roughness measuring system fulfills the requirements of DIN/ISO 3274. The filters work in accordance with DIN/ISO 166110-21. The parameters are calculated according to DIN/ISO 4287.

The desired roughness parameters, the measuring lengths, the filter settings and the upper and lower tolerances can be selected in the software;



	Mean [µm]	Measured value [µm] 22	12	1	Qual. Act	Qual. Nom	Tol. [µm]	Tol. [µm]	Qual. Nom	Qual. Act	Measured value [µm] 1	12	22	Mean [µm]
Ra	0.44	0.46	0.44	0.42	-	-	0.6	0.6	-	-	0.40	0.41	0.40	0.41
Rz	3.34	3.42	3.37	3.24	-	-	5.0	5.0	-	-	2.99	3.03	3.11	3.04
Rt	4.24	4.42	4.28	4.01	-	-	7.0	7.0	-	-	3.40	3.94	3.74	3.69
Rmax	4.22	4.37	4.28	4.01	-	-	7.0	7.0	-	-	3.20	3.27	3.59	3.35
R3z	2.42	2.45	2.42	2.38	-	-	2.5	2.5	-	-	2.24	2.23	2.32	2.26
Rq	0.55	0.57	0.56	0.53	-	-	1.0	1.0	-	-	0.50	0.52	0.51	0.51
Rpc[cm⁻¹]	82.30	84.40	78.10	84.40	-	-			-	-	93.70	100.0	87.50	93.73
Rk	1.40	1.48	1.29	1.44	-	-	1.0/2.0	1.0/2.0	-	-	1.29	1.32	1.27	1.29
Rpk	0.52	0.44	0.61	0.50	-	-	0.6	0.6	-	-	0.33	0.50	0.49	0.44
Rvk	0.60	0.54	0.58	0.67	-	-	1.0	1.0	-	-	0.64	0.52	0.57	0.58
MR1[%]	9.85	8.06	13.64	7.85	-	-	7.0/15.0	7.0/15.0	-	-	9.04	10.50	10.27	9.94
MR2[%]	89.58	90.48	89.31	88.96	-	-	80.0/90.0	80.0/90.0	-	-	87.06	90.81	89.50	89.12
Rmr[%]	57.66	60.91	52.14	59.94	-	-			-	-	67.79	62.04	64.31	64.71

Figure 15 **The picture shows the diagrams of the roughness measurement curves and the measured parameters. If tolerances are entered, the parameters are printed in red when the tolerance is exceeded.**

the corresponding input menus are shown (Figs. 13–14).

To ensure that the measurement results agree with the results of other measuring instruments a number of comparative measurements were carried out with reference measuring systems. The difficulty is to measure exactly at the same position. Such measurements have been done several times by customers; an example is shown (Fig. 16.) What is interesting is the correspondence of the diagram, if you actually hit the same spot.

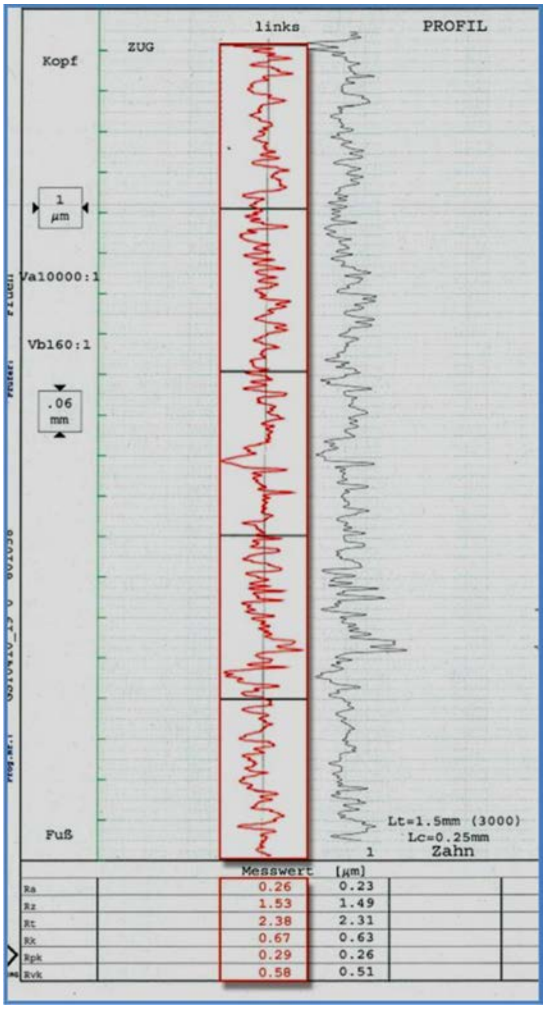
Material Ratio Evaluation

Over the years, standards committees have continually redefined new roughness parameters in order to express the surface characteristics in key values. Nevertheless an evaluation of the parameters *Ra* and *Rz*, which are very easy to describe, is still commonly used. However, this does not reveal the surface characteristic. Surfaces can have extremely different detailed structures — even though they have the same value for *Ra* or *Rz* — but in most cases different structures also mean different characteristics.

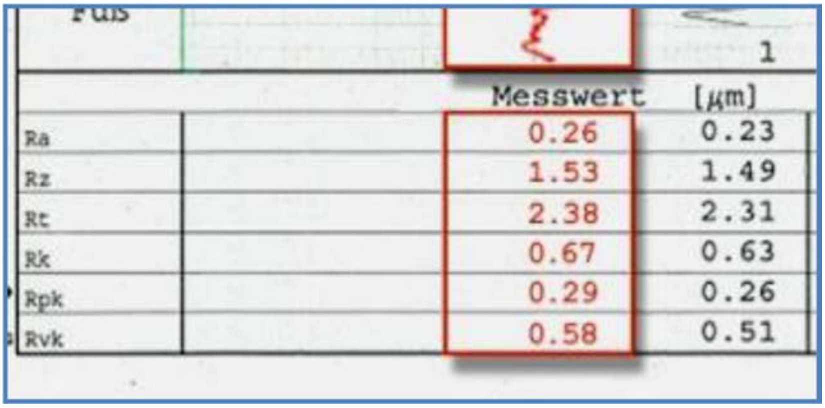
In addition to conventional evaluation of the roughness measurement curve via individual measuring sections, material ratio evaluation is now being used increasingly. This provides additional, useful parameters for evaluating the surface properties to be determined.

This evaluation generates cross-sections along the height of the recorded measurement curve,

Figure 16 This example comparative measurement conducted on a ground gear shows the correspondence between the measurement performed using a reference measurement system (in red) and using the gear measuring machine (in black). This is true not only for the parameters, but also for the characteristic of the two measurement curves.



In this older diagram format the measuring length of Lt = 1.5 mm and the filter Lc = 0.25 mm are printed beside the diagram.



	Messwert	[µm]
Ra	0.26	0.23
Rz	1.53	1.49
Rt	2.38	2.31
Rk	0.67	0.63
Rpk	0.29	0.26
Rvk	0.58	0.51

Please note that the differences are in nanometer range. However, due to the small roughness values, the percentage deviations appear large.

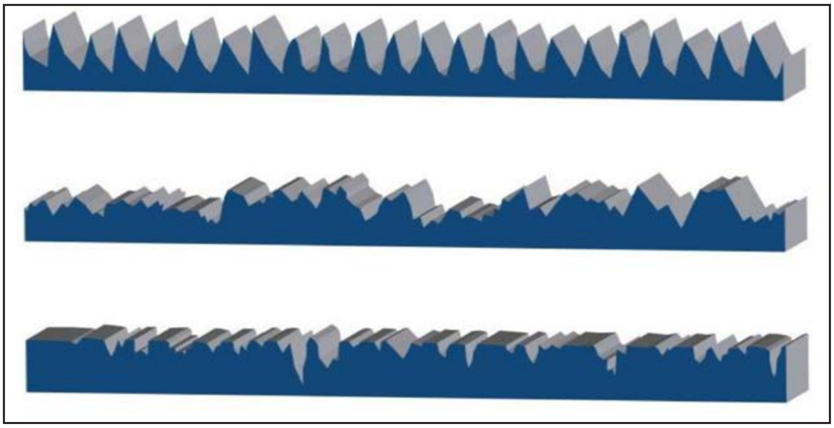


Figure 17 These three surface profiles illustrate the importance of the material ratio evaluation: although the characteristics of the surfaces are completely different because of the different production processes, the same Ra value was determined in all three cases.

in which the material ratio is calculated as a percentage value. Based on this, a so-called Abbott-Firestone curve is generated and is evaluated according to a special method.

The advantage of the material ratio evaluation is that it provides clear parameters resulting from the varying material density over the height profile — from the uppermost point on the surface to the transition into the solid material. Since gear manufacturers want to achieve very specific structures on the gear surface, this evaluation is helpful. Characteristics such as high peaks with broad plateaus, or broad plateaus with narrow grooves, are described via the material ratio parameters *Rk*, *Rvk* and *Rpk*, as well as MR1 and MR2. Accordingly, these parameters would differ significantly for the surfaces shown in Figure 16.

The parameters are calculated according to DIN/ISO 13565; this standard describes the meaning and the derivation of these parameters in detail.

Gears with Small Modules

The roughness probe design shown in Figure 6 cannot be used in combination with extremely small tooth spaces, as it does not fit in the small gaps. For this reason another roughness probe was developed with a special skid design and a parallel arrangement of the diamond needle for use on gearing as small as module 0.9 mm; the special design is shown (Fig. 19).

Because of the short distance between the tooth ground and the tooth tip, the parallel design of the needle and the skid was necessary. This design ensures that the biggest possible proportion of the short measuring section that is available with small gearing can be recorded. Because of the extremely compact design (Fig. 20), a ratio of 1:1000 was achieved between the probe tip radius (2 µm) and the skid radius (2 mm). The distance between the skid and the needle was also further reduced.

The small stylus tip radius shown (Fig. 20) is not a prerequisite for the measurement of small modules; the radius of the tip to be used is specified in the standard ISO 3274. That's why the roughness probes are optionally available with 2 µm and 5 µm tip radius.

Internal Gears

Measuring internal gears represents another challenge in that the use of reference plane scanning systems is even more complicated in the case of internal gears than for external gears.

Thanks to the highly compact roughness probe with integrated swivel device, it was possible to develop an overall system that can also be used in an automated setting. Combined with the

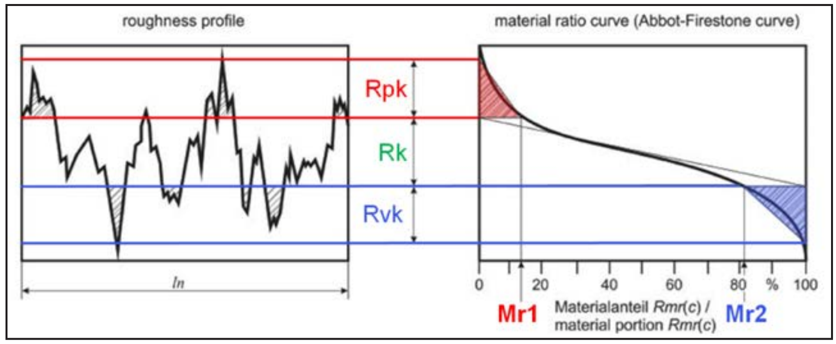


Figure 18 **Generation of an Abbott-Firestone curve used for surface characterization.**

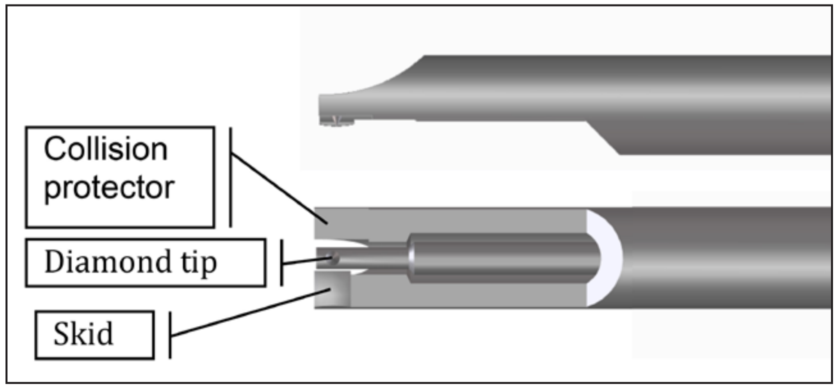


Figure 19 **The front end of the roughness probe shows the arrangement of the skid and the diamond tip. The position of the skid is beside the diamond tip. On the other side there is a collision protector to protect the tip.**

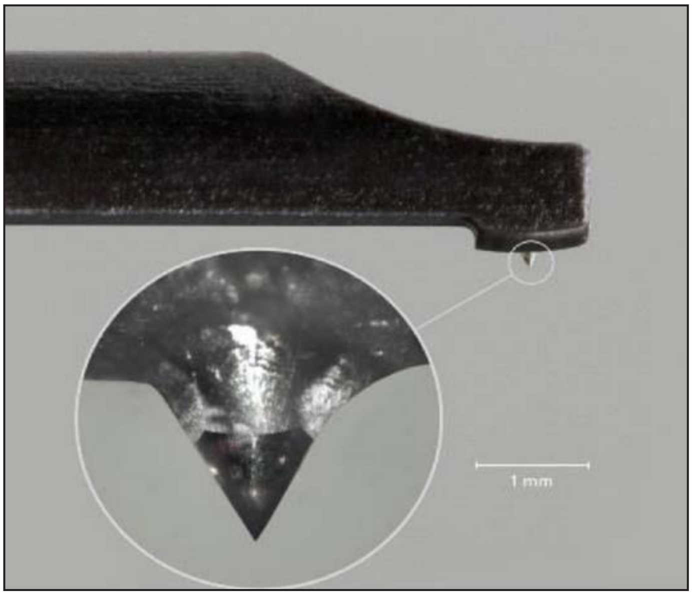


Figure 20 **A close-up image of the roughness probe for gearing starting at module 0.9 mm shows the skid in relation to the diamond tip. Because of the extremely small dimensions of the overall system, a ratio of 1:1000 was achieved between the tip radius and the skid radius. This roughness probe comes equipped with the 2 µm/60° diamond tip as standard.**

Figures 21 and 22 Roughness measurement of internal gears.

roughness probe for external gears starting with module 0.9 mm, the typical internal gears in complex passenger cars with automatic transmissions can also be measured. Figures 21 and 22 show the design of the system for roughness measurement of internal gearing and internal gears.

Due to the special scanning conditions, the usage of a skidded probe with a parallel arrangement of skid and diamond needle is advantageous. In this way, shaft collisions can be avoided through a significantly greater degree of freedom in the scanning angles. Also, a much larger measuring range can be executed relative to the tooth depth.

The probe rods with the roughness probe for internal gears can also be changed automatically. The electrical connection via the plug is also plugged in automatically, as with the other roughness probes.

Summary

The properties of the gear transmission can be improved by reducing the surface roughness of gears or by producing optimized surfaces. Among other things, this has a positive effect on the efficiency, power density, wear and running behavior. With modern manufacturing processes, such surfaces can be produced economically and reliably. In order to control the results of machining the surfaces, roughness measurement of gears gains importance.

With the known roughness measuring devices, these measurements are very time-consuming and require trained personnel. For series surveillance, the presented fully automatic system is better suited.

Since this system is based on a gear measuring machine, all measuring tasks of the gear measurement can be used. The developed roughness sensor with skid system is highly miniaturized so that the sensor can be adapted on the 3-D touch probe. In this case the roughness sensor is used instead of the tactile stylus. The skid and the diamond needle can be automatically rotated perpendicular to the tooth surface by means of a swivel axis integrated in the roughness sensor; the roughness sensor system complies with the DIN/ISO 3274 standard.

The use of the skid system protects the sensitive diamond needle of the roughness sensor against collision during the measurement. This makes the system very robust. The gear measuring machine is suitable for use in production. The combination with the robust roughness sensor and the automatic measuring sequences analogous to the gear measurements now makes the roughness measurement possible in the production area.

Due to the automatic change between the tactile stylus and the roughness sensor, measurements with automated processes and the combination with geometrical measurements are possible with this system. The programming of the measuring processes can be carried out by the operator of the gear measuring machine analogous to the gearing measurement.

For the measurement of gears with small modules, an additional roughness probe with a special skid design has been developed. This makes measurements from module 0.9 mm possible.

The roughness of internal gears can now also be measured with the same ease. In addition to the conventional evaluation of *Ra*, *Rz*, *Rt* and *Rmax*, etc. contact ratio parameters such as *Rk*, *Rpk*, *Rvk*, MR1 and MR2 can also be evaluated. The contact ratio parameters are evaluated according to the DIN/ISO 13565 standard. The roughness parameters are evaluated according to DIN/ISO 4287.

For more information. Comments or questions regarding this paper? Contact Georg Mies at *g.mies@klingelnberg.com*.

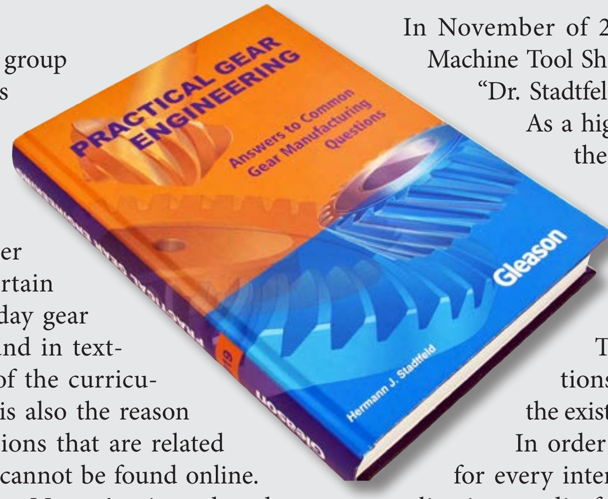
Dipl. Ing. Georg Mies is Head of Research and Development Precision Measuring Centers. Since his 1985 Graduation as Dipl.-Ing. in Electrical Engineering and Automation Technology, he has worked at Klingelnberg in the development of measuring machines. His fields of development are CNC-controller, sensor technology, machine concepts and compensation methods for improving accuracy. Mies is the inventor of over 30 national and international Klingelnberg patents and is considered the "father" of the well-known P26 measuring machine and all Klingelnberg touch probes.

Practical Gear Engineering Answers to Common Gear Manufacturing Questions

By Dr. Hermann J. Stadtfeld

New book from Gleason's Vice President Bevel Gear Technology will be exclusively excerpted in Gear Technology magazine, starting with the article beginning on page 61.

Foreword



Gear engineers, just like any other group of our society, like to find answers online if they have a technical question. Those professional experts mainly look for answers to either quite uncommon complex problems, or they are younger Engineers who haven't faced a certain task yet. Many solutions to everyday gear engineering problems are not found in textbooks and are not typically part of the curriculum in engineering colleges. This is also the reason why most of the answers to questions that are related to gear design and manufacturing cannot be found online. To fill this void, ***Gear Technology Magazine*** introduced a series which is called "Ask the Expert." Gear engineers and gear manufacturing technicians from all over the world post the question on their website. Unlike posting a question in an online forum and receiving some answers over several days, *Gear Technology Magazine* searches in their files of experts in different aspects of gear design and manufacturing, and asks one or several of their contacts to provide an answer to a specific question. If the topic seems relevant for a larger audience, then the answer(s) are published in their next printed and online issue. This also means that if the same or a similar question is asked online, the search engine will find the answer in the online issue of *Gear Technology Magazine (geartechnology.com)*. After some time, a library of frequently asked questions is available for the benefit of gear experts in manufacturing and academia.

I have been asked frequently by the magazine to provide answers for the "Ask the Expert" column, which made me think about how useful it would be if also some of the answers to the questions which I am asked daily by engineers worldwide would be available as a PowerPoint presentation or as a mini paper. Until now those answers only exist in the email responses — often with hand-drawn graphics — supporting the written explanations. About three years ago, I began to copy questions and my answers to all topics which might be relevant for a broader audience in a special folder. When a question was repeated, then I copied the text in a Word document and I created a "mini paper" addressing the topic. As this library of answers reached a volume of several hundred pages, the idea was born to compile all of the collected mini papers in a book with the title *Practical Gear Engineering*. An interesting aspect to this book idea was the fact that the topics would cover practical answers and guidelines for cylindrical and bevel gear technology questions.

In November of 2018, at the Japanese International Machine Tool Show JIMTOF in Tokyo, the traditional "Dr. Stadtfeld Day" was held for the fourth time. As a highlight of the seminar, a prototype of the new book was distributed as a preprint to all attendees of the seminar. The questions were asked to the audience "Do you find such a book useful?" and "Do you like to see additional topic to be covered?" The result was a list of 10 more questions whose answers had been added to the existing volume.

In order to make this book readily available for every interested gear engineer, the main publication media format is as an e-book. The e-book is available for purchase online. However, it is also possible to obtain the answers to specific questions on the Gleason website. For those with a fondness for having a bound book as reference on their office book shelf, a hard cover version of this book is available as well.

Practical Gear Engineering covers 41 topics on 395 pages, and has 325 figures — which provide a better understanding and easier memorization of the covered material. The chapters are not organized by cylindrical and bevel gears, but rather by general topic. The content is divided in 5 parts:

Part 1 — Gear Design and Drawings
Part 2 — Manufacturing of Gears
Part 3 — Optimization
Part 4 — Measurement & Testing
Part 5 — Prototyping

I would like to thank Mr. John J. Perrotti, President and CEO of the Gleason Corporation, for the support during the realization of this project. I am also thankful to the Publisher and the Editors of *Gear Technology Magazine* for inspiring this book.

For the support during the realization of this book with many discussions and valuable suggestions to the different technologies covered, I like to thank my team of experts in Research & Development at The Gleason Works.

My special thanks go to the people who acted as editors of this book. My wife Hedy K. Stadtfeld; Mr. Theodore J. Krenzer, Ret. Director Gear Theory; Mr. Robert L. McDowell, Senior Patent Agent; and Dr. Haris Ligata, Manager Process Development, who spent many hours to improve the clarity and readability of the book with painstaking attention to facts and details.

Dr. Hermann J. Stadtfeld
Vice President Bevel Gear Technology
Gleason Corporation

Bevel Gear Blank Drawing Procedure

Dr. Hermann J. Stadtfeld

*With this first installment — "***Bevel Gear Blank Drawing Procedure***" — we begin a series of randomly excerpted chapters from Dr. Hermann J. Stadtfeld's new book —* **Practical Gear Engineering.** *The foreword, found on p. 60, will tell you everything you need to know about it, i.e. — what it's about, why it was written, and where you can buy it.*

How to Create a Correct Blank Drawing

In the following sections, a five step procedure is presented, which can be helpful for Design Engineers in the generation of a customary blank drawings for bevel pinions and ring gears. In many cases, the missing background information results in drawings which show the members of a bevel gearset from the view point of the transmission designer, however they often fail to include several information which are required for cutting, grinding and coordinate measurement of pinions and gears.

The Bevel Gear Dimension Sheet

The Dimension Sheet of a Gleason bevel gear design includes all required design parameters. Gleason defines as the origin of pinion and gear blank the crossing point of the axes of both mating members. The crossing point generally doesn't match any of the cone apex points. However, the crossing point is the most important reference point for all calculations, for the manufacturing and the CMM inspection.

In order to define the axial location of the turned blank relative to the crossing point it is important to define an axial location datum. The distance in axial direction from this datum to the crossing point is called the "Mounting Distance". The mounting distance is required for the manufacturing machine because the CNC has to relate the tool position to the crossing point. The step by step guidance in the following section begins with a coordinate origin, located at the crossing point on the axis of each member.

There are five major design steps which each require two numbers from the Dimension Sheet. The two connected numbers for one step have the same color in Figures 1 & 2. The Dimension Sheet numbers marked 1 through 6 in Figure 1 locate the cone apexes relative to the crossing point. The numbers marked 7 and 8 in Figure 2 locate the inner and the outer boundary of the tooth.

Dimension Sheet - Second Page

		PINION	GEAR	
PITCH APEX BEYOND CROSS PT .		54.25	-6.19	← 5
FACE APEX BEYOND CROSS PT. .		41.92	-6.19	← 1
ROOT APEX BEYOND CROSS PT. .		50.89	-6.21	← 3
CROWN TO CROSSING POINT. . .		77.32	29.77	
FACE ANG JUNCT TO CROSS PT .				
FRONT CROWN TO CROSS. POINT.		41.00	22.66	
MEAN NORMAL TOPLAND.		1.91	3.45	
PITCH ANGLE.		13.70	73.55	← 6
FACE ANGLE OF BLANK.		18.64	74.53	← 2
INNER FACE ANGLE OF BLANK. .				
ROOT ANGLE		12.85	67.88	← 4
OUTER SPIRAL ANGLE		50.94	20.74	
MEAN SPIRAL ANGLE.		49.99	15.94	
INNER SPIRAL ANGLE		55.68	9.60	
HAND OF SPIRAL		LH	RH	
DRIVING MEMBER		PIN		
DIRECTION OF ROTATION-DRIVER		REV		
BACKLASH	MIN	.13	MAX .18	
GEAR TYPE.			NON-GENERATED	
DEPTHWISE TOOTH TAPER. . . .		DPLX		
FACE WIDTH IN PCT CONE DIST.			30.172	
DEPTH FACTOR - K				
PROFILE SHIFT - X2			-.497	
OFFSET ANGLE		9.309	33.724	

Figure 1 Second page of Dimension Sheet with cone angles and apexes.

Dimension Sheet - First Page

		PINION	GEAR	
NUMBER OF TEETH.		9	35	
PART NUMBER.		# 1HFT	GLEASON	
FACE MODULE.			4.843	
NORMAL MODULE AT CENTER. . .			3.954	
FACE WIDTH		38.19	26.66	← 8
PINION OFFSET.	BC	44.45		
PRESSURE ANGLE - PIN CONCAVE		29.35		
PRESSURE ANGLE - PIN CONVEX.		8.65		
LIMIT PRESSURE ANGLE		10.35		
SHAFT ANGLE.		90.00		
TRANSVERSE CONTACT RATIO . .		.970		
FACE CONTACT RATIO		2.768		
MODIFIED CONTACT RATIO . . .		2.933		
OUTER CONE DISTANCE.		137.35	88.36	← 7
MEAN CONE DISTANCE		118.26	75.03	
PITCH DIAMETER		65.04	169.49	
ADDENDUM		7.93	1.51	
DEDENDUM - THEORETICAL . . .		2.77	8.78	
WORKING DEPTH.		9.44	9.44	
WHOLE DEPTH.		10.70	10.29	
OUTSIDE DIAMETER		80.45	170.35	

Figure 2 First of Dimension Sheet with outer cone distances and face widths.

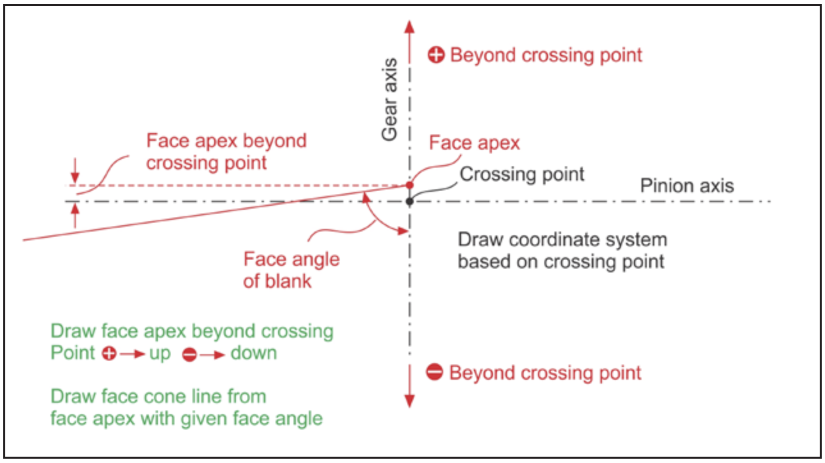


Figure 3 **Draw face cone line.**

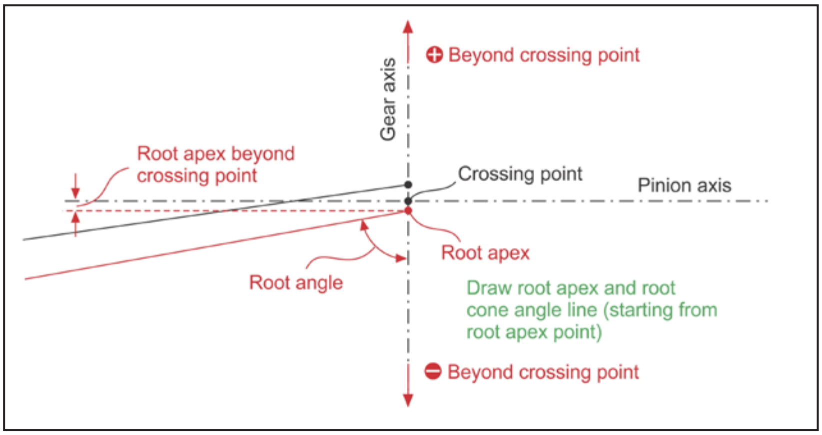


Figure 4 **Draw root cone line.**

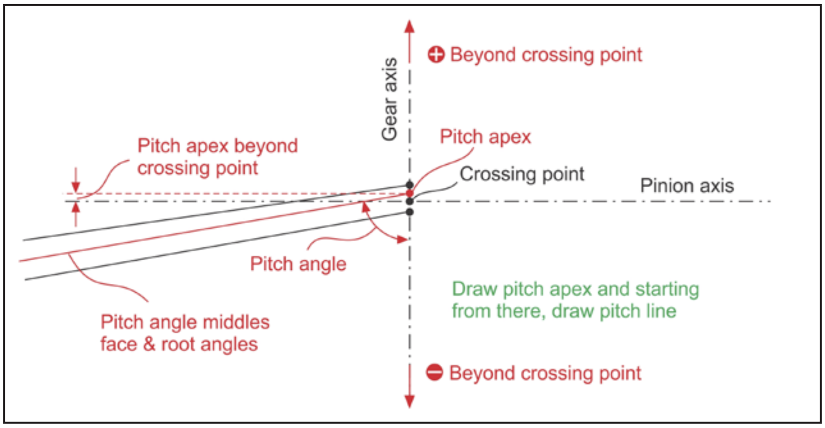


Figure 5 **Draw pitch cone line.**

Step-by-Step Explanations to Create a Blank Drawing

Begin the CAD drawing with a horizontal pinion axis and a vertical gear axis as shown in Figure 3. The crossing point is in the center of the screen. According to the value and the sign in the Dimension Sheet (Figure 1, item 1), mark the “Face Apex Beyond Crossing Point” of the gear at -6.19 mm (negative direction). Then draw the face cone line starting at the Face Apex point with an angle of 74.53° relative to the lower, negative part of the gear axis (Face Angle of Blank, item2).

Now mark the “Root Apex Beyond Crossing Point” at -6.21 mm (item 3) as shown in Figure 4. Then draw the root cone line starting at the Root Apex point with an angle of 67.88° versus the lower, negative part of the gear axis (Root Angle, item 4).

The next step is to draw the pitch line. The pitch line is not a required information in the blank drawing but it gives a more complete information about the bevel gear. Mark the “Pitch Apex Beyond Crossing Point” at -6.19 mm (item 5) as shown in Figure 5. Then draw the pitch cone line starting at the Pitch Apex point with an angle of 73.55° versus the lower, negative part of the gear axis (Pitch Angle, item 6).

In the following step, the Outer Cone Distance (Item 7 in Figure 2) is drawn along the pitch line as shown in Figure 6 which gives the location of the tooth heel border. The toe border is found by marking the Face Width (item 8 in Figure 2) from the outer cone distance towards the center of the gear (in direction of the pitch line), which marks the location of the tooth toe border.

The last step is devoted to fit the tooth boundaries together with face, pitch and root lines as well as the crossing point (labeled as such in the drawing) with the part of the blank dimensions which come from the gearbox design. The mounting shoulder of the ring gear (or the axial seating surface on a pinion shaft) is now used to define the mounting distance. The mounting distance as shown in Figure 7 is the distance from the crossing point to the mounting shoulder or seating surface of the bevel gear.

The example in Figures 3 through 7 demonstrated the creation of a ring gear blank drawing. The pinion blank drawing is done in analogy to the gear by following the exact same steps. The pinion blank values are found in the Dimension Sheet in the column left to the gear values (see Figures 1 & 2).

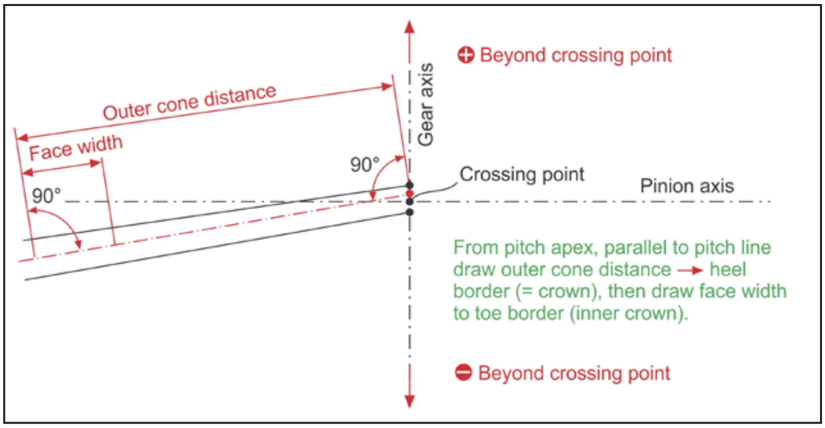


Figure 6 Draw outer cone distance and face width.

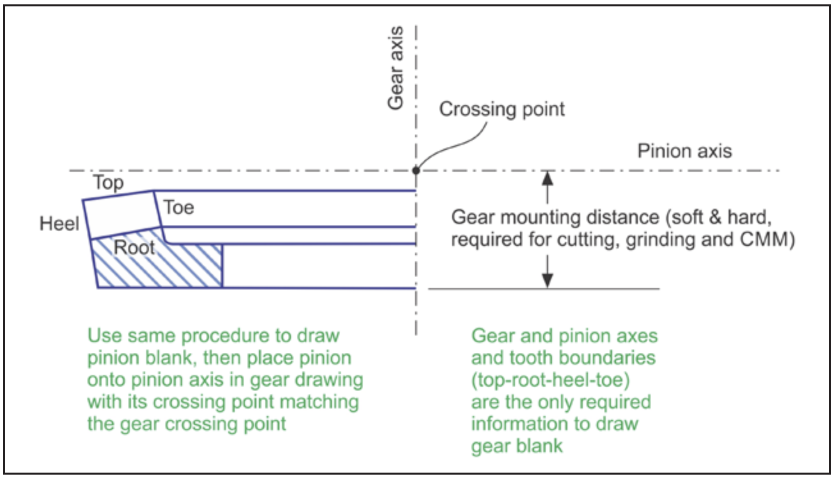


Figure 7 Fit the tooth and the gear or pinion body and define the mounting distance.

Summary

After the first draft of a gearbox the major boundary conditions for drawing the correct pinion and gear blanks are given. This chapter explains where the additional bevel gear design related numbers can be found and how those numbers are used in 5 easy steps in order to generate precise pinion and gear blank drawings, which include all required values for turning the blanks as well as for manufacturing and measurement.

Literature

1. N.N. Gear Dimension Sheet Explanations Company Publication, The Gleason Works, Rochester, New York, June 1978

For more information.

Questions or comments regarding this paper? Contact Dr. Hermann J. Stadtfeld at *hstadtfeld@gleason.com*.

Dr. Hermann J. Stadtfeld is the Vice President of Bevel Gear Technology and R&D at the Gleason Corporation and Professor of the Technical University of Ilmenau, Germany. As one of the world's most respected experts in Bevel Gear Technology, he has published more than 300 technical papers and 10 books in this field. Likewise, he has filed international patent applications for more than 60 inventions based upon new gearing systems, gear manufacturing methods as well as cutting tools and gear manufacturing machines. Under his leadership and guidance, the world of bevel gear cutting has converted to, environmentally friendly, dry machining of gears with significantly increased power density due to non-linear machine motions and new processes. Those developments also lower the noise emission level and reduce the degree of energy consumption.

Over a span of over 35 years, Dr. Stadtfeld has had a remarkable career within the field of Bevel Gear Technology. Having received his Ph.D. with summa cum laude in 1987 at the Technical University in Aachen, Germany, he became the Head of Development & Engineering at Oerlikon-Bührle in Switzerland. Dr. Stadtfeld held a Professor position at the Rochester Institute of Technology in Rochester, New York From 1992 to 1994. In 2000 as Vice President R&D he received in the name of The Gleason Works two Automotive Pace Awards, one for his high speed dry cutting development and one for the successful development and implementation of the Universal Motion Concept (UMC). The UMC brought the conventional bevel gear geometry and its physical properties to a new level. In 2015, the Rochester Intellectual UC Property Law Association elected Dr. Stadtfeld the "Distinguished Inventor of the Year." Between 2015 and 2016 CNN-Networks featured him as "Tech Hero" in a Website dedicated to technical innovators for his accomplishments regarding environmentally friendly gear manufacturing and technical advancements in gear efficiency.

Currently, he continues next to his Senior Management position at Gleason Corporation to mentor and advice graduate level Gleason employees, and he supervises Gleason sponsored Master Thesis programs as Professor of the Technical University of Ilmenau, helping to shape the future of Gear Technology.

Experimental and Numerical Study of a Loaded Cylindrical Glass Fiber-Reinforced PA6 Gear

J. Cathelin, M. Guingand, JP. de Vaujany and F. Ville

Introduction

Polymer gears find increasing applications in the automotive industry, office machines, food machinery, and home appliances. The main reason for this success is their low cost. Their low weight, quietness of operation, and meshing without lubricant are also interesting. However, they have poor heat resistance and are limited to rotational transmission. In order to improve the gears' behavior, glass fiber is added, where their lower cost and higher strength — compared to un-reinforced polymers — offers a potential increase in the gears' performance (Refs. 1–2).

Most of the literature on fiber-reinforced plastic gears is based on experimental studies. These last cover various aspects of plastic-reinforced gear pairings, including several studies on wear behavior (Refs. 3–4), working temperature (Refs. 5–6), failure modes (Refs. 2 and 7), and fiber orientation and its influence on gear metrology (Ref. 8).

In order to reduce the development costs, and particular to reduce validations testing under actual conditions, numerical models are developed. Due to the relative complexity of plastic material, very few numerical models exist. In fact, polymer behavior is viscoelastic (Ref. 9), which means that it depends on loading duration, temperature, and, for some polymers such as polyamide — on humidity. Moreover, fiber-reinforced gears have an anisotropic behavior.

Tsai and Tsai (Ref. 10) realized the first computing studies on static transmission errors as a result of an elastic multi-tooth contact FEM (Finite Element Method) analysis. More recently, Lin and Kuang (Ref. 11) developed a dynamical model for the case of Polyamide 6.6 and POM plastic gears. Their approach is based on a full FEM that incorporates the effects of position-varying tooth mesh stiffness, damping ratio, load sharing, tooth profile wear, and temperature on dynamic contact load. However, the accuracy of the results given by such an approach is largely counterbalanced by very time-consuming calculations.

To estimate the load sharing, the LaMCoS laboratory has developed an approach that consists in solving the displacement compatibility equation. The quasi-static model uses the influence coefficients method, which requires low computational time. This method has been applied on cylindrical gears (Ref. 12), face gears (Ref. 13) and spiral bevel gears (Ref. 14) of elastic materials. Recently, Hiltcher et al. (Ref. 15) adapted the method developed by LaMCoS for metal worm gears to the case of a plastic wheel and steel worm. Then in 2009, Letzelter et al. (Ref. 16) have developed a quasi-static load sharing model in the case of Polyamide 6.6 cylindrical gears. This method takes into account the viscoelastic behavior with a generalized Kelvin-Voigt model, and provides contact pressure, stress in the tooth roots and transmission error. This method has the advantage of being much less time-consuming, while also taking into account temperature and rotational speed effects. Following these developments, this study presents a similar method adapted for fiber-reinforced polyamide gears.

The work presents the thermal behavior of polyamide 6+30% glass fiber and the validation of the numerical model by measuring the loaded transmission error; which can be expressed as the phase difference of the driven gear compared to its theoretical position given by the transmission ratio. This is one result that is global enough to validate the three steps of the model: geometry, kinematics and load sharing. The measurements are carried out on a test bench developed at the LaMCoS laboratory (Ref. 17) using optical encoders to measure the angular positions of the pinion and the gear and an infrared thermal camera to measure the working temperature.

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Generality on PA6+30%GF Gears

Gear geometry and molding conditions. Reinforced polyamide 6 with 30% glass fiber granules was used to mold the gears. Polyamide 6 has a semi-crystalline structure, a glass temperature transition of 60°C, and a fusion temperature of 220°C at 0% relative humidity. Table 1 presents the gear's data.

In this study, a disc gating solution (Fig. 1) is used that has the best filling and fiber orientation regularity. The cavity geometry, molding conditions, and cooling conditions are obtained thanks to standard commercial molding process simulation software.

Fiber orientation. The fiber orientation and distribution in an injection-molded part is a function of component geometry; molding conditions (gating, temperature, pressure and holding time); matrix material; polymer melt viscosity; and fiber type (aspect ratio, density and volume fraction) (Ref. 18). Fiber orientation is obtained through molding process simulations and tomography microscopy observations (Ref. 19). Comparisons between quantitative, simulated fiber orientation predictions and the qualitative tomography observations show similar trends. Three main fiber organization areas were defined; each section is represented in Figure 2.

On the flank area, fibers tend to be parallel to the surface. In the core zone, they are more vertical, and near the tooth root, the orientation is more anisotropic. This model, taking into account the real fiber orientation, was later implemented in standard FEM simulation software.

Gear metrology. In real conditions, mold shrinkage varies with part thickness, mold layout, processing conditions and mold temperature (Ref. 20). During injection molding of fiber-reinforced polymers, the incorporation of fibers causes a significant effect on linear shrinkage. The asymmetric, ridged nature of the glass fibers restricts shrinkage of the polymer matrix in the fiber orientation direction, while the direction perpendicular to that shows lower shrinkage than the base polymer (Ref. 20). Senthilvelan et al. (Ref. 8) show an increase in involutes profile form deviation among polyamide 6.6 fiber-reinforced gears when compared to homogeneous polyamide 6.6 gears.

Table 1 Gear data

	Pinion	Gear
Module (mm)	3	3
Pressure angle (°)	20	20
Number of teeth	32	41
Tooth width (mm)	20	20
Addendum coefficient	0	0

Shrinkage creates profile deviation and run out, which correspond to the eccentricity of the gear teeth. Both parameters have a strong influence on the transmission error. Gear tooth profile and lead deviations were measured on three teeth, which are equally spaced. If there is not deviation, the theoretical and measured traces would be superposed. The involutes profile was measured from the tip circle diameter to base circle diameter.

The fiber orientation shrinkage effect was taken into account by standard commercial molding process simulation software, although form deviation is also observed. The measurements show an increase of thickness near the tooth top of the pinion and wheel. This derives from an over-estimation of the shrinkage value in the mold cavity. Conical shape on the pinion and the wheel was also observed (Fig. 3); this is supposed to come from a differential cooling during part ejection.

The maximum involute profile form deviation in a reinforced polyamide 6 gear are 82 μm (ISO 1328 Quality 12) for the pinion and 54 μm (ISO Quality 11) for the wheel. Tooth profile modification, in relation with the metrology results, was implemented in the load sharing simulation software developed by the LaMCoS laboratory.

Numerical Model

The numerical model is based on the procedure developed for steel and polyamide 6.6 gears; this procedure is divided into the three principal steps (Ref. 21). Initially, tooth geometry is obtained with tooth corrections adapted to molded gears. The second step consists of an unloaded kinematics simulation to determine the potential contact zones, while the load sharing between all the teeth in contact is computed in the last step. When torque is applied for each quasi-static position, the instantaneous pressure distribution can be

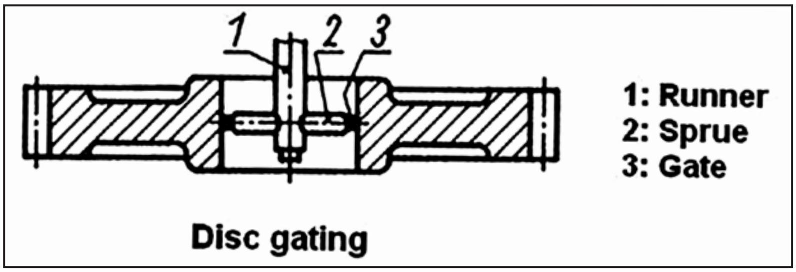

Figure 1 Gating location.

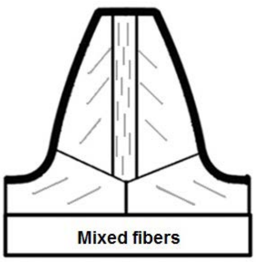

Figure 2 Fibers distribution outline.

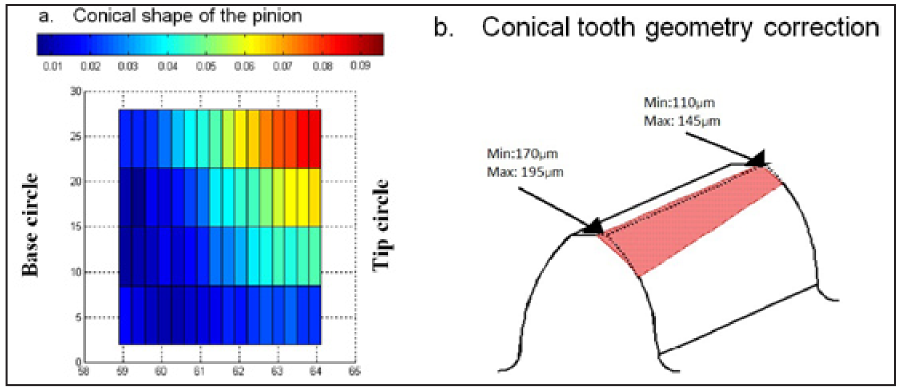

Figure 3 Conical shape.

estimated for all the teeth in contact simultaneously. Finally, it is possible to calculate the meshing stiffness, the stress in the tooth roots, and the loaded transmission error. The third step integrates the viscoelastic displacement and the loading history in the case of PA6+30% GF material.

Steps 1 and 3 must be modified for the gears made of PA6+30% GF materials. In step one the geometry — due to the shrinkage presented on Figure 3 — was integrated. In step 3 a new behavior model based on the method proposed by Letzelter et al. (Ref. 16) for a homogeneous polyamide 6.6 was developed.

Mechanical behavior of polyamide 6+30% GF. A description of the viscoelastic properties of polyamide 6+30% GF comes from a generalized Kelvin-Voigt model (Fig. 4). The main differences consist of adding the elastic behavior of the fiber into the displacement model and integrating their anisotropic organization. The generalized Kelvin-Voigt method takes into account the viscoelastic behavior of polymer and establishes a relation between the temporal displacement and the total strain. For a sample of l length, the global displacement at instant t, $u(t)$ is obtained with Equation 1:

$$u(t)=l.\sigma(t)\sum_{i=0}^{n}\Delta J_i\left(\frac{dt}{dt+\tau_i}\right) l.\sum_{i=0}^{n}u^i(t-dt)\left(\frac{\tau_i}{dt+\tau_i}\right) \quad (1)$$

Where $\sigma(t)$ is the stress level, τ_i and u^i respectively, the retardation time and displacement of a block i in the generalized Kelvin model, and n is the number of blocks. Relation (Ref. 1) is used to solve the load sharing problem in the third step of the process. First, it is necessary to determine the viscoelastic properties ΔJ_i and τ_i. These values are determined with DMA (Dynamical Mechanical Analysis) tests at different frequencies, temperatures and humidity ranges.

Load sharing model. The method to solve the instantaneous load sharing is based on a unique process used for all types of gears made with steel or steel/polymer materials. The final displacement at a node is obtained through the combination of the equations of displacement compatibility and torque equilibrium. The influence coefficients methods (Ref. 22) solve this multi-contact problem.

In the case of plastic gear, it is necessary to know the loading history and displacements of the gear and pinion. Consequently, the local meshing on the contact zone developed for polymer gears is different from those developed for steel gears.

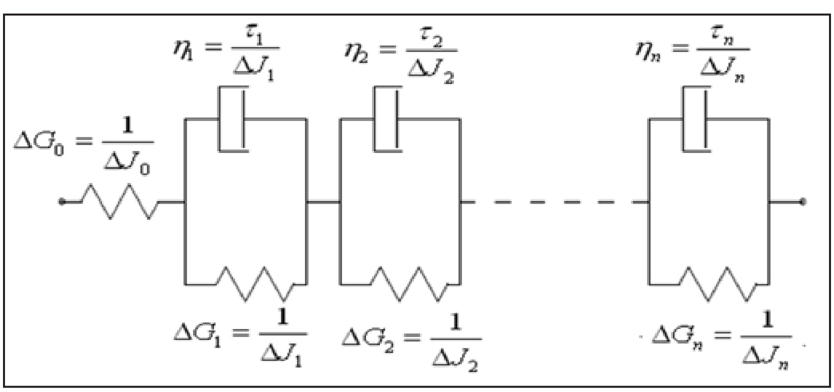

Figure 4 Generalized Kelvin model.

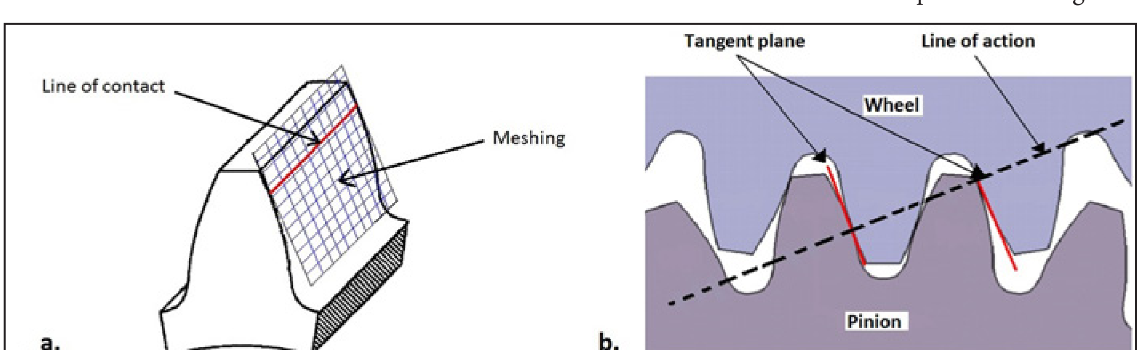

Figure 5 Local meshing on the contact zone.

The surface is larger than the latter, and covers the entire tooth surface (Fig. 5). Thus, for a kinematics position, it is possible to save the displacement of the pinion and the gear for computing the next kinematics position. This is done to account for the displacement history, which is needed to compute the viscoelastic behavior of the polyamide 6+30% GF material.

The equation of compatibility of displacement. The load sharing problem consists of solving the equations of displacement compatibility (Eq. 2) and driving torque (Eq. 3) to balance the torque.

$$p(M_k).e(M_k) = p(M_k).(\delta(M_k) + u(M_k) - \alpha) = 0 \quad (2)$$

$$C_{motor} = \sum_{k=1}^{K} (p_k s_k \vec{n_k} \wedge \vec{M_k}) \quad (3)$$

With K is the number of nodes of the meshing, $p(M_k)$ is the contact pressure at point M_k, $e(M_k)$ is the gap between the profiles of the gear and pinion at point M_k after the loading, $\delta(M_k)$ is the gap between the profiles of the gear and pinion at point M_k before the loading, $u(M_k)$ is the displacement at point M_k and α is the global body adjustment. In Equation 3, s_k is the contact surface around the point M_k and $\vec{n_k}$ a perpendicular vector to the tangent plan.

The influence coefficient. In order to solve the load sharing problem, it is necessary to compute the displacement u_k, depending on pressure p_k. It is possible to write the relation (4) between the displacement and the pressure with the method of the influence coefficients. There are 2 types of influence coefficients:

- Bulk influence coefficients C_{kj}^{V} computed by finite element method. This method is applied on three teeth to deduct the effect of local displacement on the neighboring teeth. Moreover, the finite element method is based on Figure 2, where the fiber presence and its orientation are taken into account.
- Surface influence coefficients C_{kj}^{S} computed with Boussinesq theory (Ref. 23).

$$u_k = \sum_{k=1}^{K} C_{kj} p_j \text{ with } C_{kj} = C_{kj}^{V} + C_{kj}^{S} \quad (4)$$

However, regarding the relation (Eq. 4) proposed for steel gears — in the case of polymer gears, the bulk influence coefficient is defined by the relation (Eq. 5). The geometrical influence coefficient is not linked with the polyamide 6 matrix compliance; it only depends on the geometry and fiber orientation, where J_{mat} is the compliance of the polyamide (inverse of the Young modulus). This distinction could be made because of the pure elastic behavior of the glass fiber and its non-influence on the viscous behavior of the polyamide 6 matrix (Ref. 19).

$$C_{kj}^{V} = J_{mat} C_{kj}^{V*} \quad (5)$$

$$C_{kj}^{S} = J_{mat} C_{kj}^{*S} \quad (6)$$

C_{kj}^{*S} in relation

Equation 6 represents the surface geometrical influence coefficient non-dependent on the material's compliance, but dependent of the fibers' presence. Fibers are presumed purely parallel to flanks in the case of the surface influence coefficient.

The viscoelastic displacement on meshing. The displacement in Equation 1 is combined with the influence coefficient method. The Kelvin-Voigt parameters correspond to the polyamide 6 matrix behavior. τ_i and ΔJ_i remains the same for the surface and bulk material with the assumption that fiber doesn't affect the viscoelastic behavior of the polyamide 6 matrix (Ref. 19).

$$u_k(t) = \sum_{i=1}^{n} u_k^i(t) \quad (7)$$

$$u_k^i(t) = \sum_{j=0}^{n} \left[C_{kj}^{*V} p_J(t) \Delta J_i \left(\frac{\Delta t}{\tau_i + \Delta t} \right) + C_{kj}^{*V} p_J(t) \Delta J_i \left(\frac{\Delta t}{\tau_i + \Delta t} \right) \right] + u_k^i(t-dt) \left(\frac{\Delta t}{\tau_i + \Delta t} \right) \quad (8)$$

k is the index of the meshing nodes and $p_J(t)$ the contact pressure at point j. $u_k^i(t-dt)$ represents the history of displacements caused by the load at time $t-dt$. Fiber orientation is taken into account through C_{kj}^{*S} regarding the surface displacements where fibers are assumed parallel to the surface. C_{kj}^{*V} integrate the fiber influence regarding the bulk displacements.

The system of equations, which includes the relations Eqs. 2, 3 and 8, is used to calculate the load sharing. This is achieved by using a fixed-point algorithm. It is also necessary to create a history of the displacements. To obtain this one, the displacement and the load sharing are calculated for two teeth situated just before they come into contact.

Thermal model. According to several studies, plastic gears have an important temperature increase during running (1). This temperature has an impact on the viscoelastic behavior of the material.

In the case of polymers with rolling contact, Koffi et al. (Ref. 24) show that the friction energy is much more important than the polymer's internal energy. Following the results of the study conducted by Koffi et al. (Ref. 24), Mao (Ref. 25) and Hooke et al. (Ref. 26), the viscoelastic warming can be neglected, compared to the friction warming. Erhard et al. (Ref. 27) defined the bulk temperature variation as a thermal balance between the heating generation $Q1$ by friction and loss through the room temperature convection Q_2.

$$Q_1 = 2{,}6.P, \mu. \frac{i_u + 1}{z_1 + 5.i_u} \quad (9)$$

$$Q_1 = A_1.\alpha_w.(T_{Zi} - T_u) \quad (10)$$

Where P is the power brought by the motor, μ the friction coefficient, i_u, the transmission ratio, z_1, the number of teeth of the pinion, A_1, a geometrical coefficient related to the thermal exchange on the surface of the concerned gear, α_w, a thermal convection coefficient of the concerned gear, T_{Zi} concerned gear temperature, and T_u the room temperature. The thermal balance between Equations 9–10 lead to the gear bulk temperature (Eq. 11).

$$T_{Zi} = T_u + P, \mu. f_{ED}. 136 \frac{i_u + 1}{z_1 + 5.i_u} \left[\frac{k_2.171000}{b.z_i(V_x.m)^{0.75}} \right] \quad (11)$$

Where f_{ED} is related to the meshing duration, V_x rotating speed at the top radius, m the module, b the gear width, k_2 coefficient depending on the gear material couple.

A flash temperature model that estimates the maximal surface temperature variation on a gear tooth flank has been developed by Block (Ref. 28) and Erhard et al. (Ref. 27). This temperature increase is intended to be over an insufficient period of time to locally modify the polyamide 6 contact behavior. For this reason the flash temperature effect on contact displacements is not taken into account for the following model. The polyamide 6+30%GF temperature can be expressed as:

$$T_{max} = T_{Amb} + \Delta T_{Bulk} \quad (13)$$

The temperatures (Equation (13)) are then integrated in the load sharing model together with the humidity rate through modifying the relaxation time τ i.

Thermal expansion. Thermal expansion of polyamide is 3 times higher than steel, and room humidity has an influence on the gear geometry as well. W. Kraus (Ref. 29) proposed the Equation 12 to establish a link between the module and the thermal and humidity expansion effect.

$$m' = m.[1 + \alpha_T.(T_{Zi} - T_u) + \Delta d'.g] \quad (12)$$

Where m is the original gear module, α_T the thermal expansion coefficient, T_{Zi} corresponds to the room temperature, T_u the original room temperature, $\Delta d'$ the humidity expansion coefficient depending on theexposure time and humidity rate, g is a parameter linked to polymer type.

A numerical study taking into account the expansion effect was conducted on the gear data in Table 1 and shows its influence on transmission error.

The expansion coefficient of the polyamide 6+30%GF is approximate by a rule of mixture $\alpha = 27.3 \times 10^{-6}$. A backlash of 0.2 mm was used according the mounting condition proposed by Boyer (Ref. 30). In both cases, with and without Table 2, the expansion effect was simulated. Three parameters were observed — maximal tooth root stress, maximal contact pressure on the pitch circle and transmission error at two different bulk temperatures, 40°C and 80°C. At 40°C, the gear module supposed to be m = 2.998 mm and at 80°C, m = 3.002 mm.

Results from Table 2 show a slight influence of the thermal expansion on flank pressure and tooth root stress. Nevertheless, a difference of 18% is observed on the transmission error amplitude. Therefore the expansion effect can't be neglected.

Experimental Measurements

Testing device. An experimental test bench has been developed by the LaMCoS laboratory. The original characteristic of this bench is the instantaneous measurements of the thermal behavior, done by an infrared camera, and the transmission error; Figure 6 shows a view of the experimental system.

The asynchronous motor (Ref. 1) is powered by a variable speed drive. The mechanical power created by the electrical motor is transmitted by a belt to the rotating shaft of the pinion. The shafts are supported by four plain bearings to limit the dynamical effects. A powder brake (Ref. 2) mounted on the rotation axis of the gear creates a torque. The infrared camera (Ref. 3) is clamped on an original system, able to capture images closed to the tooth meshing in the transverse plane (Ref. 17). Two optical encoders (Ref. 4) are placed on each rotating shaft. The experimental device is fixed on a heavy base plate, and the electrical motor and the support of the infrared camera are clamped on rubber pads.

Transmission error measurements

Transmission error measurements principle. The angular positions of the pinion and gear that give the transmission error are measured with optical encoders directly clamped on the rotating shaft;

Table 2 Results without and with thermal expansion (TE)

	Average Transmission error [mrad]		Transmission error amplitude [mrad]		Flank pressure [MPa]		Tooth root stress [MPa]	
40°C without TE	0.637		0.299		30		9.40	
80°C without TE	1.269		0.310		23		8.82	
40°C with TE	0.649	1,9%	0.329	10%	30.5	1.6%	9.3	0,2%
80°C with TE	1.251	1,4%	0.255	18%	22.5	2.1%	8.4	0,6%

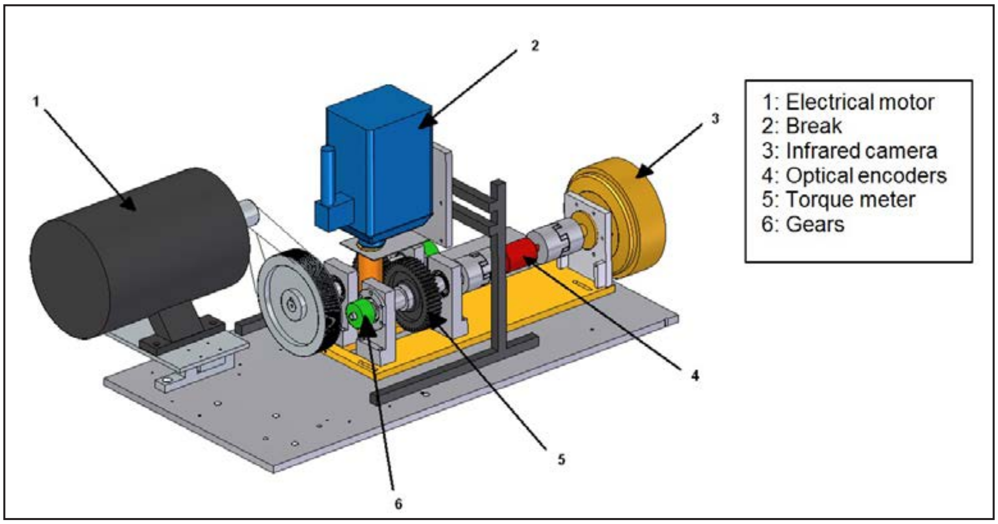

Figure 6 Perspective scheme of the test bench.

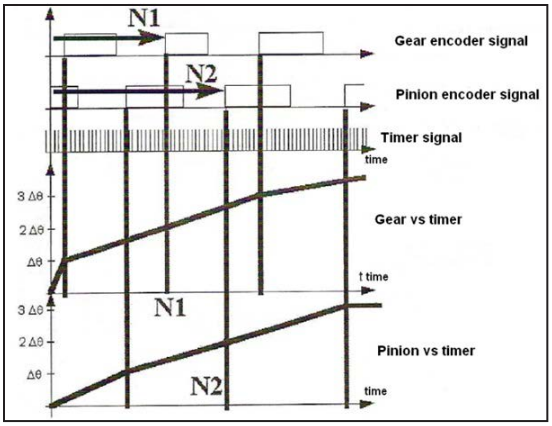

Figure 7 Phase difference encoder (Ref. 14).

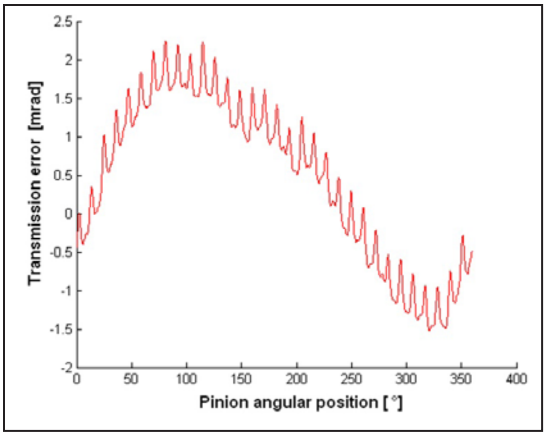

Figure 8 Transmission error on one gear revolution.

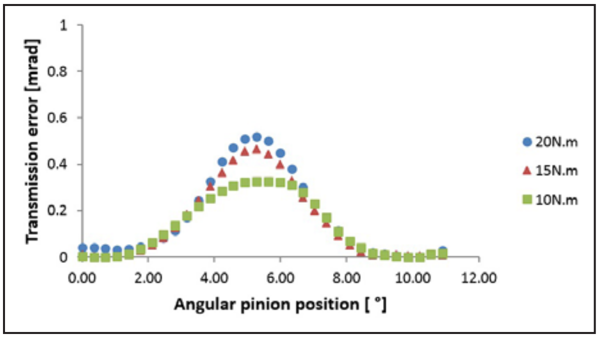

Figure 9 Influence of the torque at 50 rpm.

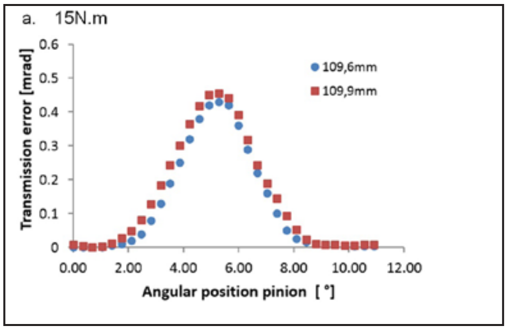

Figure 10 Reference cases at 50 rpm, 20 N.m.

these components measure the transmission error. The principle of this measurement is based on counting pulses delivered by a timer at a very high frequency (80 MHz) between two rising edges of the signal delivered by the optical encoders. This time-counting method must be carried out simultaneously on the two signals with the same reference (Fig. 7, i.e. — the same timer and counter). Then, the time evolution of the pinion and the gear angular positions are defined with a sampling rate given by the number of pulses on each encoder.

The signal of the transmission error is built using the two laws of angular evolution of the encoders. (See the gear and pinion vs. time law curves evolution on Fig. 7). This angular measurement method consists of performing the calculation at the rising edge — either on the pinion signal (pinion rising edge) or on the gear signal (gear rising edge). The transmission error can be given as an angular displacement on either the pinion or gear shaft. In the presented study, the gear shaft angular error is given at a stabilized speed. The principle is based on the timer signal counting between the encoder rising edge.

The numerical treatments of the results are achieved in three main steps:

In the first step, the transmission error measurement is built on a single pinion revolution. The pinion has 32 teeth that correspond to 32 different transmission errors (Fig. 8). The main oscillation, with a 4 mrad amplitude on Figure 8, corresponds to the eccentricity of the shaft.

Second step: to avoid the effect of eccentricity, which is not taken into account in the simulation model, the transmission error on a single gear revolution is sampled in 32 pieces. One sample corresponds to one tooth meshing.

The third step consists of computing the average transmission error on each sample.

Transmission error measurement results. The tested gears data is presented in Table 1. The tests were carried out at low speed in order to conform to the quasi-static conditions. Figure 9 presents the torque influence at 50 rpm. A good agreement regarding the shape of the curve is found with the simulation results presented (Fig. 10).

Figure 10 corresponds to the reference cases used for the numerical validation. Four cases are used at two torque levels and for two center distance values. We can notice that an increase of center distance leads to a slightly higher transmission error (Fig. 10).

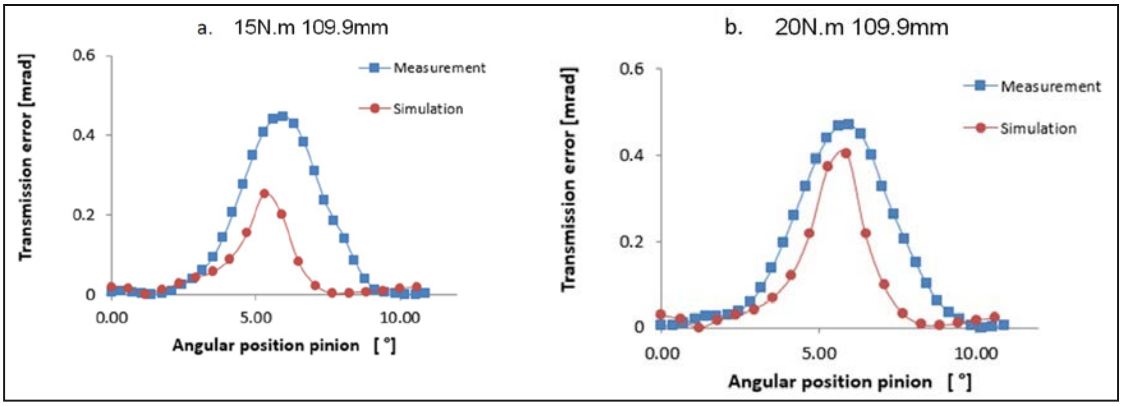

Figure 11 **Transmission error comparison without tooth modifications.**

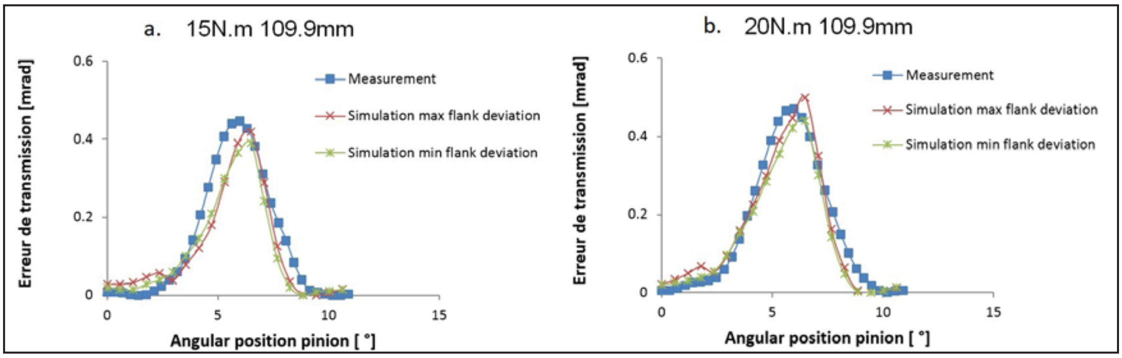

Figure 12 **Transmission error comparison with tooth tip relief modifications.**

On Figure 11, simulations are carried out on a single tooth meshing, which represents one transmission error period, at 19°C and 40% relative humidity; these conditions are close to the glass temperature. Reference case "measurement" — with simulation results, and without geometrical tooth modification — are compared. Similar trends are observed, but the gap between the simulated results and measured one remain important.

On Figure 12, tooth modifications on the pinion and wheel have been implemented as previously described. Two simulations cases are presented — one taking into accounts the highest geometrical deviation measure on the gear flank, whereas the other is taking into account the lowest geometrical deviation. Better agreements between simulation and measured results are observed. Transmission error amplitude difference remains below 10%.

Conclusion

The presented numerical model simulates the loaded behavior of polyamide 6+30% GF gears obtained by injection molding. It is based on three main steps: definition of real tooth geometry, kinematics simulation, and calculation under load. The latter step is used to calculate the load sharing between the teeth and also the transmission error.

Numerical investigation on thermal expansion shows that its effect on transmission error is not negligible. A thermal model taking into account the working conditions to predict the gear temperature was implemented. The simulation and measurement results are used to validate the model. Experimental validations are carried out on a test rig, by measuring the loaded transmission error with two optical encoders. The measurement is based on the angular evolution of the sensors and their phase differences. Results are then filtered on one tooth meshing to remove the eccentricity effects.

At first, similar curve shapes are obtained, but an important difference of amplitude is observed. A better correlation is obtained while implementing the tooth profile correction according to the measurement on molded gears. The next step of the study will focus on the validation of this model on a broader range of spur, as well as helical gear size and, eventually, plastic-metal pairing.

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Fabrice Ville is a professor and researcher at INSA Lyon, where he is a member of the Mechanical Systems and Contacts research group.

Liebherr-Verzahntechnik GmbH

ACQUIRES WENZEL GEARTEC GMBH

Liebherr-Verzahntechnik GmbH, whose range of products covers gear technology and the area of automation systems, has purchased all the shares of Wenzel GearTec GmbH, a manufacturer of gear measuring machines. Since 2004 Wenzel GearTec GmbH, with its registered office in Karlsruhe, Germany, has been focusing on the special area of gear measuring technology and is very successful on the market worldwide with innovative products.

Left to right: Heinrich Bruederle (Wenzel GearTec), Dr. Christian Lang (Liebherr-Verzahntechnik GmbH), Frank Wenzel (Wenzel GearTec), Dr. Hans Gronbach (Liebherr-Verzahntechnik GmbH).

Wenzel GearTec develops and sells gear measuring machines, software, and accessories in Karlsruhe, Germany. The portfolio includes the successful WGT series, which represents a large selection of 4-axis gear measuring machines. The combination of high-precision measuring technology and the specially developed Wenzel GearTec software for gear measurement guarantees the highest level of accuracy when inspecting gears. The machines are used for various applications, including in the automotive area, aerospace, and general mechanical engineering.

Wenzel GearTec will be integrated into the organization of Liebherr-Verzahntechnik GmbH. A partnership with the Wenzel Group was formed in 2015. The integration of gear measuring machines in the Liebherr portfolio aims to be able to offer the customer closed loop system solutions from a single source. The initial attempts will be showcased at EMO 2019 in Hannover.

"We are satisfied with the range of products and concept of Wenzel GearTec GmbH," says Dr. Christian Lang, managing director of sales and marketing at Liebherr-Verzahntechnik GmbH. "We are delighted that the negotiations were completed swiftly and constructively. We can now include gear measuring technology in our range and work together on the technological development."

Frank Wenzel, managing partner of Wenzel GearTec GmbH, adds: "With the existing partnership Liebherr is already familiar with our products and is therefore the ideal company for us to advance and further develop gear measuring technology. We are confident that our company is in good and stable hands."

All employees of Wenzel GearTec GmbH are retained.

"Liebherr is well-known as a reliable employer and we are proud to be part of an international company. Our staff can be optimistic about the future and look ahead to good prospects," adds Heinrich Brüderle, division director of Wenzel GearTec GmbH.

For the time being Wenzel GearTec GmbH will continue to operate under its own name and as a wholly-owned subsidiary of Liebherr-Verzahntechnik GmbH. The existing contracts and legal relationships shall remain in place. The locations in Karlsruhe and Shanghai will also remain. The contracting parties have agreed not to disclose the purchase price as well as any other details. The acquisition is subject to the implementation of certain commercial processes. The process is expected to be completed in June. After completion Liebherr will act as the shareholder of Wenzel GearTec GmbH. (*www.liebherr.com/geartechnology*)

EMAG

WINS AXIA BEST MANAGED COMPANIES AWARD

Strategic vision, capacity to innovate, sustainable management culture and good corporate governance—the "Axia Best Managed Companies Award" sets expectations high for participating businesses. This year, the organizers from the consulting firm Deloitte, the German weekly business news magazine *WirtschaftsWoche* and the Federation of German Industries (BDI) have awarded the distinction to the EMAG Group. A speaker at the award ceremony pointed out that the innovative mechanical engineering company has contributed to securing Germany's economic future and serves as a model for others. The event took place in Düsseldorf, Germany, at the beginning of May.

Small and medium-sized enterprises (SMEs) are essential to the German economy: For instance, they generate more than half the added value and provide nearly 60 percent of all jobs, according to recent data from the German Federal Ministry of Economics. This includes many hidden champions that have advanced to become global market leaders in their industry, such as EMAG: The Group is one of the few makers of

manufacturing systems that can cover the entire process chain from soft machining to hard machining. The company produces complete process chains for automotive manufacturing, as well as, for the non-automotive sector. Over the past couple of decades, EMAG has succeeded in systematically expanding its expertise and tapping into new markets—an achievement that has now been recognized by the "Axia Best Managed Companies Award." The consulting firm Deloitte, the German weekly business news magazine *WirtschaftsWoche* and the Federation of German Industries (BDI) award this quality label to exceptionally well-managed SMEs. To be considered, the award winners must first convince a panel of experts consisting of renowned representatives from business, science and the media. "Overall EMAG distinguishes itself by an exemplary management strategy that combines a strategic vision with the capacity to innovate, a sustainable management culture and good corporate governance. It thus conveys a model for other businesses to follow," points out Lutz Meyer, partner and head of the SME program at Deloitte.

There are a variety of examples that demonstrate what the catch phrase "capacity to innovate" means to EMAG: For instance, the company invests in the development of new production solutions that are crucial for the production of tomorrow's products, such as electric cars, and it is also working on the digitalization of its machines with its "Industry 4.0" solutions. "We are very pleased to receive the recognition that comes with the 'Axia Best Managed Companies Award.' The distinction confirms the work we have been doing over the past few years and also is an incentive to keep making progress," explains Claus Mai, CFO for the EMAG Group. "However, this does not change our goals in any way: With our custom-fit innovations, we help our customers manufacture their products faster, more precisely and more efficiently. This is where digitalization, for example, opens up entirely new opportunities that we will not miss." (*www.emag.com*)

Machine Tool Builders and Diablo Furnaces

APPOINTS NEW CEO

Machine Tool Builders has announced the appointment of **Bill Gornicki** as chief executive officer (CEO) of both Machine Tool Builders (MTB) and Diablo Furnaces based in Machesney Park, Illinois. With 29 years' experience in the thermal processing industry, Gornicki brings a fresh perspective with proven results to leverage the dynamic and diversified companies' offerings of heat-treating furnaces and gear machinery forward to achieve new sales levels. Sustained improvement and long-term growth will be cultivated by Gornicki being intimately focused in operational excellence, expansion of product breadth and capabilities in existing and new markets. Please welcome and congratulate Gornicki in this new role.

Machine Tool Builders is a remanufacturer, recontroller and custom-manufacturer of gear shaping, hobbing and grinding machines. MTB also is the North American sales and service representative for Burri GmbH of Germany and Donner+Pfister AG of Switzerland. Burri GmbH manufacturers' generative grinders and wheel profiling machines, and Donner+Pfister AG manufacturers and remanufacturers gear and Maag gear grinding machines.

Diablo Furnaces is an original equipment manufacturer (OEM) of IQF (Internal Quench) Furnaces, Tempers, Box, Belt, Continuous, Car Bottom, Rotary, Pit, Washers, and other custom heat-treating equipment required for captive and commercial heat treaters. (*www.machinetoolbuilders.com*)

Weiler Abrasives

DONATES ADDITIONAL $25,000 TO SUPPORT WORKSHOPS FOR WARRIORS

Weiler Abrasives, a leading provider of abrasives, power brushes and maintenance products for surface conditioning, renewed its support of Workshops for Warriors in 2019 with an additional $25,000 donation. The company donated $25,000 in May 2018 with the launch of the "Leading a Warriors Charge" campaign in partnership with Workshops for Warriors. The campaign continues through the end of the year.

"Leading a Warriors Charge" is a national brand awareness and fundraising campaign to help Workshops for Warriors, a nonprofit school, in their mission to provide veterans, wounded warriors and transitioning service members with training and certifications, as well as placement into advanced manufacturing careers. Machining and welding are both key components of the school's programs.

"We're so excited to continue our partnership with Workshops for Warriors," says Nate Schmid, director of marketing — Americas, Weiler Abrasives. "The work the school does not only provides those who have served in our military with the skills to pursue a viable career path, but it also offers vital support to the manufacturing industry."

During the 2018 "Leading a Warriors Charge" campaign, Weiler helped raise awareness of its partnership with Workshops for Warriors and fundraised though advertising, video, messaging on product packaging, and signage in distributor showrooms and at special events. Special distributor promotions also garnered additional donations, as did partnerships with other leading organizations in the industry. Combined with Weiler Abrasives' original donation, the partnerships and other fundraising activities have yielded a total contribution of more than $77,000 for Workshops for Warriors.

(*www.weilerabrasives.com*)

Jergens, Inc.

APPOINTS NATIONAL SALES MANAGER FOR WORKHOLDING SOLUTIONS GROUP

Jergens, Inc. announces that **Ken Marvar** assumed the role of national sales manager, Jergens Workholding Solutions Group. "In his new role, Ken is responsible for the sales of our workholding products through our network of partner distributors and for the management of our national network of manufacturers' representatives," says Jergens General Manager, Matt Schron.

Marvar has over 40 years of sales management and customer service experience in industrial and consumer markets. His responsibilities have ranged from new business development to customer retention programs, organic growth objectives, LTA and pricing negotiations, sales forecasting as well as brand identity and marketing strategies. Prior to Joining Jergens, Marvar held senior sales and marketing management positions representing a variety of contract manufacturers.

Marvar earned a bachelor of science degree in business administration and communications from John Carroll University. He and his wife Kathy live on the East side of Cleveland and have two grown children. (*www.jergensinc.com*)

Hexagon Manufacturing Intelligence

BREAKS GROUND ON NEW CENTER OF EXCELLENCE IN GREATER DETROIT

Hexagon's Manufacturing Intelligence division recently announced it has broken ground on the construction of a new expansion project on a 5-acre site in Novi, MI. Slated for completion in the Fall of 2019, the 88,000 sq. ft. building will house a technology showroom, a technical training center and a 15,000 sq. ft. laboratory and calibration hub. The two-story office area will have glass walls and windows presenting an exceptional view of the nearly 11,000 sq. ft. Hexagon showroom and demonstration area from both levels. Expanding Hexagon's presence in the Midwest, the Center of Excellence will serve as a cornerstone to support advanced manufacturing in the region. Hexagon will consolidate all of its Manufacturing Intelligence businesses in the greater Detroit area into a central location, which includes MSC Software, Production Software (formerly Vero Software), Q-DAS and its metrology solutions portfolio. Employees from the AutonomouStuff and Safety Critical brands of Hexagon's Positioning Intelligence division will also work from the new site.

The two-story property will meet or exceed all aspects of the current Michigan Uniform Energy code. The building design will incorporate lighting controls and sensors to reduce energy consumption and take advantage of exterior daylight to supplement office area lighting. Focused on the employee experience, the floor plan features open common office spaces and separate huddle areas to encourage collaboration and innovation. All interior spaces will be outfitted with new modern furniture designed for the various ways today's employees work, whether on their own, in teams or informal collaborations. Other employee amenities include a fitness gym, coffee bars, lounges and a modern break room designed for multi-purpose functions including meetings, events and every-day meals and refreshment breaks. A high-tech solutions provider, Hexagon is focused on providing an environment that empowers team work, problem solving, and a high level of productivity among formerly separate areas of the business. The new center will be finely appointed in the Hexagon style with its modern color scheme and other company design elements.

"This is an exciting project for us, as we will utilize our vast wealth of Hexagon technologies during the build process — from total stations for surveying to digital construction. Ultimately, this state-of-the-art facility reflects the next phase in Hexagon's own data-driven evolution across industries to shape smart change," states Angus Taylor, president and CEO of Hexagon Manufacturing Intelligence North America."Our investment in this Center of Excellence allows us to consolidate our technology teams and put them into a 21st century workspace that will serve both customers and employees with the highest quality services and workplace environment." (*hexagonmi.com*)

Forest City Gear

ADDS PROCESS ENGINEER TO 'CUT TEETH ONLY' OPERATIONS TEAM

Forest City Gear has added **Joe Konetski** as process engineer to its 'Cut Teeth Only' operations team, a resource dedicated to meeting fast-growing demand for the completion of gears made from a customer's gear blank.

Konetski joins the Cut Teeth Only Team after serving as a setup technician for a wide variety of gear cutting and grinding machines at Forest City Gear. He is also a graduate of Forest City Gear's four-year Apprenticeship Program, conducted in cooperation with the Rock River Valley Tooling and Machining Assoc. (RRVTMA). The program is intensive, requiring 8,000 hours of on-the-job training, and 604 hours of related training at nearby Rock Valley College, and is the ideal preparation for Konetski's new role, says John Cochran, the Cut Teeth Only Team's Lead person.

"We've cut leadtimes and streamlined production on Cut Teeth Only projects to meet unprecedented high demand with the help of a dedicated team of process engineers that takes ownership of a project from the P.O. through scheduling and production," says Cochran. "Joe's typical of our team: knowledgeable, experienced and, above all, able to wear a multitude of hats." (*forestcitygear.com*)

Exact Metrology

HONORS APPLICATION SPECIALIST

Exact Metrology presented its application specialist, **Greg Hoeting** with the first Golden Circle Award.

This award recognized Hoeting's achievements at the company within the last 11 years. Among these are positive and long lasting impact on internal and external customers, going above and beyond normal job duties to help team members or customers, creating new solutions and opportunities and innovative thinking. In addition, Hoeting perfectly exemplified the goals, purpose, beliefs and ethics of Exact Metrology. He's also authored many articles, contributing to the body of knowledge at the company.

"Receiving the Golden Circle Award has been a great honor for me. Working at Exact Metrology is both challenging and rewarding. I continue to be fully committed to serving customers and contributing to the company's development."

Steve Young, one of the company's co-presidents said, "We are very happy to have Greg on our team. His dedication and knowledge are truly an asset for our company. We hope to continue offering this award in the future." (*www.exactmetrology.com*)

July 23–24—8th WZL Gear Conference USA Westminster, Colorado. Attendees can expect a selection of presentations from the research portfolio of WZL including information on gear design, manufacturing, gear checking, and testing. Highlights include requirements for hard finishing, gear optimization, superfinishing, trends in gear production, Internet of production, gear hobbing, gear modifications and a workshop tour of Kapp/Niles in Boulder. For 50+ years the annual WZL Gear Conference in Aachen, Germany, has been the basis for the exchange of experiences and close cooperation between the members of the WZL Gear Research Circle. The WZL Gear Conference takes place for two days which are exclusively devoted to the latest research on gear design, manufacturing, and testing for the North American market. Register at *www.kapp-niles.com/index.php?id=811&L=4*.

August 6–8—8th CAR Management Briefing Seminars Grand Traverse Resort, Traverse City, Michigan. The Center for Automotive Research (CAR) MBS leads the industry in providing a context for auto industry stakeholders to discuss critical issues and emerging trends while fostering new industry relationships in daily networking sessions. Seminars include targeted sessions on manufacturing strategy, vehicle lightweighting, connected and automated vehicles, advanced powertrain, supply chain, sales forecasting, purchasing, talent and designing for technology, future factories, design optimization, the mobility ecosystem and more. CAR MBS 2019 will focus on the auto industry's commitment to change, across the spectrum of technology, strategy, mobility, policy, and manufacturing issues. This August, join us to connect with more than 1,000 stakeholders, representing automakers, suppliers, startups, media, government, and academia. For more information, visit *www.cargroup.org*.

August 20–22—AGMA Detailed Gear Design Clearwater Beach, Florida. This class, taught by Raymond Drago of Drive System Technology, will provide gear engineers, gear designers and application engineers with: a basic introduction to gear theory and standardization; practical considerations and limitations associated with the application of standard AGMA/ISO durability rating analyses; investigation of the differences in stress states among the various surface durability failure modes, including pitting, spalling, case crushing and subcase fatigue; extended load capacity analysis techniques; consideration of friction in the calculation of surface compressive stresses; and much more. The course is designed for gear engineers, gear designers, application engineers, and others who are responsible for interpreting gear design or who want to better understand all aspects of gear design. AGMA members: $1,395 for first registrant from a company, $1,195 for additional registrants. Member rate is $1,895 for first registrant, $1,695 for additional registrants. Non-member rate is $2,395, $2,195 for additional registrants. Register at *www.agma.org*.

September 9–13—AGMA Basic Training for Gear Manufacturing (Fall) Hilton Oak Lawn, Illinois. Learn the fundamentals of gear manufacturing in this hands-on course. Gain an understanding of gearing and nomenclature, principles of inspection, gear manufacturing methods, and hobbing and shaping. Utilizing manual machines, develop a deeper breadth of perspective and understanding of the process and physics of making a gear as well as the ability to apply this knowledge in working with CNC equipment commonly in use. This course is taught at Daley College. A shuttle bus is available each day to transport students to and from the hotel. Although the Basic Course is designed primarily for newer employees with at least six months' experience in setup or machine operation, it has proved beneficial to quality control managers, sales representatives, management, and executives. Course instructors are Dwight Smith, Allen Bird and Peter Grossi. For more information, visit *www.agma.org*.

September 11–12—Digital Industry USA 2019 Louisville, Kentucky. Digital Industry USA 2019 has partnered with leading industry associations to provide educational content for conference sessions and expert panels during the inaugural event. Leading industry association partners include, CSIA (Control System Integrators Association), ISA (International Society of Automation) and MESA (Manufacturing Enterprise Solutions Association) International. During the trade show's on-floor conference program, industry visionaries will showcase field experiences and case studies that feature real IIoT (Industrial Internet of Things) integration across their organizations. For more information, visit *digitalindustry.com*.

September 17–19—AGMA Fundamentals of Gear Design and Analysis Hilton Oak Lawn, Illinois. Gain a solid and fundamental understanding of gear geometry, types and arrangements, and design principles. Starting with the basic definitions of gears, conjugate motion, and the Laws of Gearing, learn the tools needed to understand the inter-relation and coordinated motion operating within gear pairs and multi-gear trains. Basic gear system design process and gear measurement and inspection techniques will also be explained. In addition, the fundamentals of understanding the step-wise process of working through the iterative design process required to generate a gear pair will be reviewed. Learn the steps and issues involved in design refinement and some manufacturing considerations. An explanation of basic gear measurement techniques, how measurement equipment and test machines implement these techniques, and how to interpret the results from these basic measurements will also be covered. The instructor is William "Mark" McVea. For more information, visit *www.agma.org*.

September 17–19—CTI Symposium China Shanghai, China. The next International CTI Symposium "Automotive Drivetrains, Intelligent & Electrified" will gather in China for the sixth time to exchange ideas on transmission technology developments. With lectures, presentations, keynote speeches and the satellite exhibition "Transmission Expo," the event will provide a powerful framework for high-ranking Chinese and international automobile and transmission manufacturers and suppliers. The focus will rest on strategies, new components and development tools for conventional and alternative drives. China is now by far the world's largest market for plug-in hybrid and electric vehicles. Supported by state programs and directives, NEVs (New Energy Vehicles) aim to cut emissions in urban conglomerations and make the land less dependent on oil imports. By 2020, the plan is to get more than five million electric automobiles on Chinese roads. For more information, visit *drivetrain-symposium.world/cn/registration/*.

A Bar/Restaurant for Gearheads

Joseph L. Hazelton, Contributing Editor

Large gears stand upright near the entrance to GearHouse Brewing Co. A great watering hole for gearheads, the bar/restaurant is decorated inside and out with gears and gear blanks. (Photos courtesy of GearHouse Brewing Co.)

It's called GearHouse Brewing Co. It's in Chambersburg, a small town in south-central Pennsylvania. And it's fit for a gearhead. The bar/restaurant is decorated inside and out with more than 15 gears and gear blanks.

And the decoration can't be missed. It starts right by the front door, on the patio. In the middle of gray paving stones is a bed of gravel. Planted in the bed are two large, rusty gears. You can see them in the photo here.

Behind the two gears is the restaurant's garage door. On the other side is GearHouse's dining room. The garage door was there when GearHouse's owners bought the building. When they converted it into a restaurant, they upgraded the door. Now, it's like a wall of windows.

So, if you go inside and get lucky, you'll get a table by the windows so you can look at the patio gears. And, if the weather's nice, you won't even have to look through glass. It won't be there. By keeping it a garage door, GearHouse's owners made it so they could turn their place into an indoor/outdoor restaurant. When the weather's nice, the door is lifted out of the way. No wall between you and the patio gears.

Even if you're not seated by the windows, you can still see gears inside the restaurant. You can also see gear blanks. Several are prominent. A blank hangs on a wall as decoration. Another sits in front of a sofa as a coffee table. In a hallway, a large, wooden blank decorates another wall.

Now, why decorate with gears and gear blanks? It started when the building was being converted by its new owners: David and Erin Kozloski, Jessee and Candice McMath, and LaVan and Heather Gray.

Years ago, the building was a warehouse for the Cumberland Valley Railroad. The line has since been moved, but the building's past was still present. During the conversion, David and the other owners found lots of railroad spikes and tie plates around the building. They also found: "Some small-tooth gears and axle bits," David says.

Inside GearHouse, the bar's orange tap handles were designed using the gear's cousin: the sprocket.

The bits and pieces helped the owners come up with a name for the restaurant and a plan for the décor. The gears and gear blanks themselves were bought or donated.

Take the two gears on the patio, for instance. First, the larger one was bought by the owners at a local auction. The other one was donated by a customer. The restaurant was just starting out, but people knew about its planned décor. "Word had already started spreading," David says.

So, a customer came to the restaurant one day, the gear with him. "We didn't even know it was coming," David says. Turned out the gear came on a good day. The customer donated it the same day the other gear was being embedded in the patio. Donated gear joined bought gear in the gravel bed.

In addition, GearHouse's décor shows the owners' love of bicycling. "All of us are very enthusiastic in cycling," David says, "or have been at some point." So, gears and gear blanks share space with bicycles mounted on walls.

The owners' enthusiasm is also obvious behind the bar, where they used sprockets in the design of their tap handles. You can see them in the bottom photo.

Now, the handles aren't old sprockets being used in a new way. They were made for GearHouse and started with a simple design, a 13-tooth sprocket. From there, the design was changed until it worked well as a tap handle.

The orange sprocket is also GearHouse's logo. And using it for the handles is right because most of the beers on tap are GearHouse's own brews.

GearHouse offers a lot of beers, and its lineup changes from time to time. In early April, the lineup was 14 brews. Eight were GearHouse's own, the other six: made by other Pennsylvania brewing houses. In late April, the lineup was 11 brews. All were GearHouse's own.

The bar/restaurant can make so many of its own beers because David is a professional brewer with more than seven years of experience. And, among GearHouse's own brews is a nod to industry, an ale called Mad Machinist.