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THE JOURNAL OF GEAR MANUFACTURING

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Vol. 34, No. 3 GEAR TECHNOLOGY, The Journal of Gear Manufacturing (ISSN 0743-6858) is published monthly, except in February, April, October and December by Randall Publications LLC, 1840 Jarvis Avenue, Elk Grove Village, IL 60007, (847) 437-6604. Cover price $7.00 U.S. Periodical postage paid at Arlington Heights, IL, and at additional mailing office (USPS No. 749-290). Randall Publications makes every effort to ensure that the processes described in GEAR TECHNOLOGY conform to sound engineering practice. Neither the authors nor the publisher can be held responsible for injuries sustained while following the procedures described. Postmaster: Send address changes to GEAR TECHNOLOGY, The Journal of Gear Manufacturing, 1840 Jarvis Avenue, Elk Grove Village, IL, 60007.

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THE GEAR INDUSTRY'S INFORMATION SOURCE

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Mahr Inspection

As market pressures increasingly require gearboxes to become smaller, quieter and more precise, designers and manufacturers face numerous challenges. Learn more about what the MahrGear GMX 400 can do with this video at *www.geartechnology.com/videos/The-MarGear-GMX-400/.*

EMAG Gear Manufacturing Line

EMAG can help make gear manufacturing quicker and more efficient with its VLC line. Learn more by watching this video at *www.geartechnology.com/videos/EMAG-VLC-/.*

Social Media

Whether it's KISSsoft's latest software release, Sandvik's cutting tool developments or Klingelnberg's Closed Loop System, you'll find the latest product and industry news at our Twitter, LinkedIn and Facebook sites. Visit our homepage, *www.geartechnology.com* for the latest developments.

Gear Talk with Chuck:

In "Lesson's Learned," our resident gear blogger Charles Schultz discusses the importance of learning from your mistakes and owning up to them. (*www.geartechnology.com/blog/lessons-learned-2/*)

"Innovations in Mature Products," examines the importance of studying what already works in a particular application before starting a new gear design. Schultz cites the oil field pump jack market as an example.

(*www.geartechnology.com/blog/innovation-in-mature-products/*)

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The Advantage of Supreme Productivity
GE20A
The Game-Changing Mitsubishi GE Series CNC Gear Hobbing Machines.
A quick glance at Mitsubishi's GE Series Gear hobbing machine doesn't reveal the truth behind it's real power. However, when you evaluate the output the full picture is dramatic and clear. With an all new, utlra-efficient dry cutting design, the GE series machines produce gears up to 50% faster than previous technologies—with all the precision your specifications demand. This kind of boost in productivity is sure to help you be more competitive in the marketplace and pump up your profits. Experience the world-class performance of the GE series hobbing machines at www.mitsubishigearcenter.com or contact sales at 248-669-6136.
GE20A
GEseries

Honored and Impressed

Publisher & Editor-in-Chief
Michael Goldstein

At the AGMA annual meeting last month, the association presented me with its Distinguished Service Award. It was a great privilege and honor to be recognized in this way, most especially because I've found that my own ideals often mirror those of the association, whether by fostering education or by encouraging you to give back to the industry in a variety of ways. You can read some of my thoughts along these lines in my acceptance speech, which we've reprinted on page 78.

Now more than ever, I am thrilled to be affiliated with AGMA, as the association begins its hundred and first year and continues to reinvigorate and reinvent itself for the 21st Century. AGMA's new president, Matthew Croson, took over last year with a fresh vision and boundless energy. At the meeting, I witnessed the transition in leadership for AGMA's board of directors. And while the association will miss the enormous capability of outgoing Chairman Dean Burrows (president of Gear Motions), I believe the association will be in good hands under the guidance of incoming Chairman Jim Bregi, Jr. (president of Doppler Gear). As a third-generation gear manufacturer, Bregi will bring both a wealth of knowledge and experience as well as enthusiasm to his office.

AGMA is not the stodgy Old Boys Club one might expect from a manufacturing association more than a hundred years old. In fact, the ideas in some of the presentations at the annual meeting were progressive, modern and fresh.

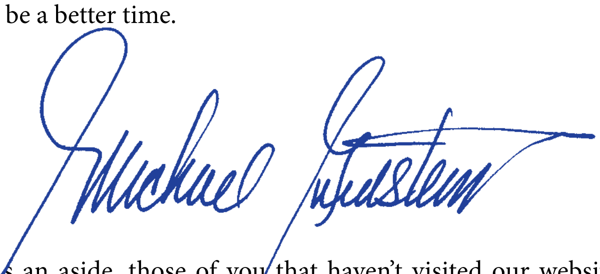
For example, there were several presentations on the IoT (Internet of Things) and the importance and impact it will have on the manufacturing community. One of the presenters, Joel Neidig (director of R&D for ITAMCO), has been a leader in transforming his own company to start taking advantage of this new and important technology. I'm happy to report that Joel, in future issues, will be writing a column for us on IoT, which should give you some overview of the things going on and its importance to manufacturers everywhere. Joel will also be heading up a series of AGMA IoT workshops, where you'll be able to learn ways to implement this new technology in your own manufacturing environment.

One of the presenters remarked that you really need to start today understanding and implementing IoT in your factory as it will be important in one year, critical in two years and, in the presenter's opinion, if you haven't begun implementing this technology within three years, it may be too late. Many of you can remember the transformation from mechanical machines to NC machines, and then later to CNC machines, and how everything changed as a result. I have a feeling that the upcoming transformation might be even greater that we experienced with the advent of the computer.

Another example of the insight available at the AGMA annual meeting was the presentation on the economy of the gear industry by Jim Meil of ACT Research. Jim has over three decades of experience, having recently retired as vice president and chief economist of Eaton Corporation, with prior experience at Chase Econometrics, and has been a regular presenter at the AGMA annual meetings. Not only does Jim have a great insight to the manufacturing community, but has a great sense of humor, for an economist. I'm happy to announce that in the near future, Jim will also be writing a regular column for us, giving all of us an economic insight to the manufacturing community.

I am a strong believer in the value of participating in your industry's association. This means more than paying dues or attending the yearly convention. But as I mentioned in my remarks at the award ceremony, being a member is only the first step. To get the real value, you need to get involved in committees and events, which shouldn't be viewed as an obligation, but rather an opportunity. There's no better way to guarantee your personal and professional continuing education. Your company gains credibility, along with extremely important strategic, business and marketing value. And on top of that, the industry as a whole benefits from your participation. Everybody wins.

And right now, AGMA seems to be on a roll. If you aren't already involved, or if you aren't involved much, there will never be a better time.



P.S. As an aside, those of you that haven't visited our website lately should be aware of the enormous breadth of knowledge that is available in the GT LIBRARY. I'm happy to report that we now are getting nearly 11,000 unique visitors to just that one feature on our website every month. Although we are starting on our 34th year of publishing this magazine, I feel that we are embarking on a whole new phase of our existence. I am as excited today about the information we're going to be bringing and our place in this industry as I was when I first started the magazine in 1984. We have been, and will continue to be, The Gear Industry's Information Source.

Liebherr

INTRODUCES INTERNAL GEAR TOOTH PROFILE GRINDING TECHNOLOGY

Liebherr offers a new internal gear tooth profile grinding technology, based on its proven OPAL grinding technology, involving a belt drive spindle, which can be fitted to the standard GH 4.0 grinding head as well as to the new GH 5.0 and GH 6.0 grinding heads. Initially, the internal gear grinding arm is available in two different sizes, while others are to follow shortly. Custom internal gear grinding arms can be developed to match customer workpieces.

Gear grinding to Liebherr quality standards is feasible for internal gears, using a range of different grinding arms that each fit the GH 4.0, GH 5.0 and GH 6.0 grinding heads.

Faster switch between external and internal

"Simple changeover between external and internal gears takes a maximum of half an hour," Dr. Hansjörg Geiser, head of the gear cutting machinery development and design engineering team, explains. "You detach the external gear grinding disk or worm, hang the internal gear grinding arm on the hardened stop bars to ensure repeat accuracy and fix it in place with a handful of screws, then tension the belt-drive disk and the belt and attach the cover."

Internal gears can then be ground using a grinding disk of 100 or 125 millimeters in diameter — a Liebherr innovation. The external gear grinding head does not have to be touched, and external gear grinding quality is again the same as before once the internal gear grinding arm has been detached.

IG Opal 4.0 is the name of this innovation that functions at a maximum spindle speed of 12,000 rpm. A larger version, the IG Opal 4.1, featuring a maximum grinding disk diameter of 125 millimeters, is also already available. Both arms were successfully tested using CBN and corundum disks. Where dressable grinding disks are used, the internal gear grinding arm travels up to the grinding dresser that is also used for external gear grinding.

One sophisticated customer comes from within the Liebherr Group

All internal gear grinding arms are modelled in 3D and can be used in very confined spaces. "Collision inspections are simple and extremely reliable," emphasizes Andreas Mehr, who is responsible for grinding and shaping technology development and consultancy at Liebherr-Verzahntechnik GmbH. "Small-diameter internal gear teeth can therefore also be machined quickly and easily.

Liebherr-Aerospace, which uses Liebherr gear cutting machinery to manufacture their own components, is one of three first buyers of this new technology. As in the case of external gears, this new internal gear teeth technology works with a multi-rib grinding disk system that can rough- and finish-grinding. That is particularly important to users, who regard speed and costs as important, for instance customers from the aerospace industry. Grinding disks made of dressable corundum or electroplated CBN can be used in conjunction with the spindle. These are also manufactured at Liebherr's plant in Ettlingen (Germany).

For more information:
Liebherr Gear Technology, Inc.
Phone: (734) 429-7225
www.liebherr.com

Gleason

INSPECTION SYSTEM OFFERS KEY MEASUREMENTS ON SINGLE PLATFORM

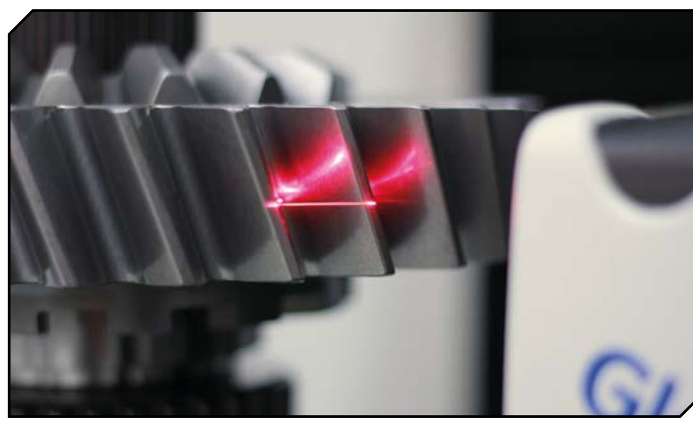
Gleason Corporation's new 300GMSL Multi-Sensor Gear Inspection System had its European première at the Control Show in Stuttgart/Germany May 9–12, 2017.

The versatile platform of Gleason's 300GMSL Inspection System provides the classic tactile probing methods for inspecting conventional gear data on spur and helical cylindrical gears as well as straight, spiral and hypoid bevel gears with a diameter of up to 300 mm. In addition, the new inspection system allows non-contact laser sensor scanning of tooth flanks to support gear development. Complete topography data can be recorded far more rapidly than with conventional tactile probing, with comparable results.

The integration of laser scanning and associated 3D graphics with CAD interface considerably expand both the functionality and the range of applications for this machine platform. The new option makes the 300GMSL the ideal solution for research and development applications for both prototype and production parts or when reverse engineering is required. The 300GMSL Inspection System is also an ideal fit for rapid measurement of topography in regular production operation and satisfies the increasingly stringent requirements on gear inspection. Compliant, soft materials (such as plastic gears, for example) can be inspected without sustaining damage.

Further options such as surface finish measurement or Barkhausen noise analysis to inspect grind burn reduce operating costs, annual maintenance and certification costs and space requirements by offering multiple technologies on a single machine platform.

Another highlight at the Control Show in Stuttgart was the 300GMSP Analytical Gear Inspection System which was designed for use directly in the production environment and which yields reliable measured results in demanding environmental surroundings. To achieve this, the 300GMSP has integrated systems to compensate for temperature fluctuations and to dampen vibration in the production environment. The 300GMSP is especially suitable for applications in the aerospace and automotive industries, but of course also well suited for the inspection of high-quality gears in other sectors of industry.



The Closed-Loop Function, available for many years in bevel gear production and developed by Gleason for cylindrical gears in 2015 for direct transmission of measured data to the production machine, is part of the standard repertoire of the GMS series of machines from Gleason Metrology Systems.

The inspection systems presented was accompanied by high-precision workholding solutions for metrology applications to boost measuring efficiency to the next level.

(Gleason and GMS are registered trademarks of The Gleason Works, All Rights Reserved)

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

Klingelnberg

EXHIBITS CLOSED LOOP SYSTEM AT CHINA INTERNATIONAL MACHINE TOOL SHOW

At the China International Machine Tool Show (CIMT) in April, Klingelnberg unveiled a range of new products — including the closed loop concept for cylindrical gears. The innovative concept was demonstrated on the Viper 500 cylindrical gear grinding machine in combination with the P 26 precision measuring center.

CIMT is one of the world's largest trade shows for machine tools and a meeting place for machine manufacturing companies from around the globe. The show took place in Beijing April 17–22, 2017. Klingelnberg is reaffirming its role as a systems supplier with a broad product portfolio, which it highlighted at the show. But the main focus of this year's exhibit was the closed loop system, which is now capable of networking a cylindrical gear machine directly with a measuring device. With the closed loop concept, Klingelnberg presented its Chinese customers an innovative solution for a fully-automated quality loop in cylindrical gear manufacturing.

Focus on digitization in production

Until now, the technology of the closed loop concept with networking of machine tools and measuring machines was reserved for bevel gear machines. Klingelnberg unveiled the transfer of automated machine correction to cylindrical gears for the first time in Asia at CIMT. The technology doesn't just create a network of in-house machinery alone. Rather than developing a self-contained solution, the company has set its sights on compatibility. The closed loop for cylindrical gears is based on a universal XML-file. The description is freely available.

Klingelnberg has established an integrative cyber-physical system in its own bevel gear manufacturing side, which fully links design processes to production processes. For this system the company received the Industry 4.0 Award in the "Integration Design & Production" category late last year.

Viper 500 cylindrical gear grinding machine

The new closed loop concept for cylindrical gears can be implemented with the Viper 500 cylindrical gear grinding machine, among others, which Klingelnberg demonstrated live at CIMT.

The Viper 500 delivers cutting-edge technology for a fast, efficient production process. It is designed for component diameters up to 500 mm, and specifically for small to medium-sized batches, and is available in three different configurations: profile grinding, small grinding wheels for special jobs and multi-grinding wheel technology (K), as well as generation grinding (W). The Viper 500 W configuration allows both profile grinding and continuous generation grinding on the same machine — with minimal retooling time.

P 26 precision measuring center

Klingelnberg consistently strives to develop innovations and solutions to enhance productivity — and sets the same standard for measuring technology, focusing on shop floor deployment of measuring centers in addition to integration into the closed loop concept. Thus the P 26 precision measuring center provides improved conditions for direct use on the production line — and can be networked into the closed loop system.

The fully automatic CNC-controlled precision measuring center is designed as a compact unit for the workpiece diameter range up to 260 mm. The machine can be used for a host of measurement tasks: inspection of cylindrical gears, pinion type cutters, and shaving cutters; worms and worm wheels; hobs and bevel gears; general dimension, shape, and positional deviations of axially symmetrical workpieces; measurement of cams and camshafts; and measurement of rotors.

For more information:
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Phone: (734) 470-6278
www.klingelnberg.com

Mahr Federal

ADDS DYNAMIC MEASUREMENT AND OTHER FEATURES TO MILLIMAR C1200 DIGITAL IC AMPLIFIER

Several new features have been added to Mahr Federal's Millimar C1200 Digital IC amplifier, increasing its application range and user security. The new functions include dynamic measurement capability, enhanced display tolerance viewing, and password protection for the setup menu. The Millimar C1200 Digital IC amplifier is a low cost, easy to view and use readout. It is designed to replace analog meters, as it offers analog-like display performance with very fast response technology. The high-resolution display provides clear digital and analog readings with selectable resolutions/scales.

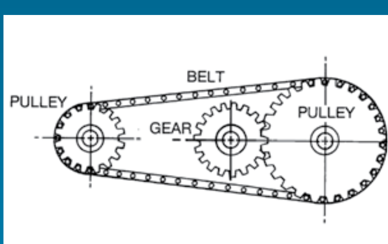
The dynamic measurement capability added to the C1200 allows users to capture max, min, or max-min (TIR) values. During measurement, the digital value is held while the analog position is marked by blue lines on the scale.

The second new feature allows asymmetric tolerance markers to be displayed on the scale. The display can be set to center on the tolerances rather than the nominal size.

Finally, security is enhanced with password protection for the setup menu, which can now be locked and accessed using a 4-digit PIN number. When enabled, a prompt appears when accessing the setup menu. Arrow keys are used to enter the password.

Operating features for the Millimar C1200 Digital amplifier are set up using the five-button keypad and visual menu options. In addition to the new features, the C1200 comes with these standard features: Unit selection (in/mm/µm); Normal/Reverse polarity; Measuring range; Preset; Factor; Tolerance entry. When tolerances are used the display shows pass/fail status using green/red color on the backlit display. Data output is available using MarConnect cables for Digimatic, Opto-RS 232, or USB interface. Output type is auto-sensed by the cable connected to it. External wireless may also be used.

For more information:
Mahr Federal
Phone: (800) 343-2050
www.mahrexactly.com



Dillon Manufacturing

OFFERS VARIETY OF WORKHOLDING SOLUTIONS AT EASTEC

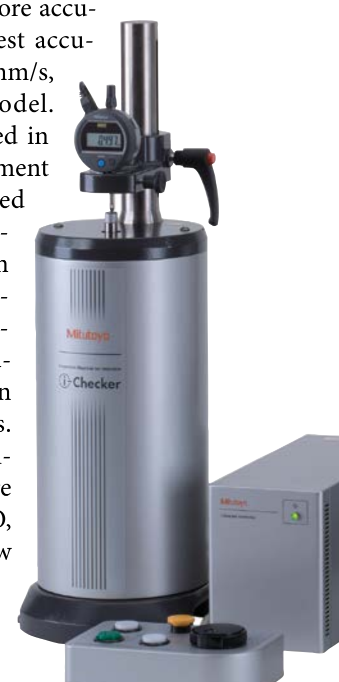
Dillon Manufacturing featured a wide variety of workholding products during EASTEC including soft jaws, hard jaws and full grip jaws for Serrated, T & G, Acme, and Square Key type chucks, as well as collet pads, and more. Full grip "pie" jaws from 6 to 24-inches in diameter, as well extra high jaws to 10-inches in height for longer service life. The company also exhibited collet pads and collet pad jaws, monoblock jaws, and vise jaws. Dillon featured special soft and hard jaws to fit virtually any brand chuck. Their standard and custom chuck jaws and collet pads and jaws are ideal for high speed machining, as well as precision boring, tapping, drilling and finishing across virtually all industrial markets. All Dillon jaws and related products are made in the United States.

For more information:
Dillon Manufacturing
Phone: (800) 428-1133
www.dillonmfg.com

Mitutoyo

RELEASES INSPECTION INSTRUMENT FOR INDICATORS

Mitutoyo America Corporation recently announced the release of the i-Checker, an inspection instrument specially designed to calibrate a variety of indicators, including bore gages, Digimatic indicators, dial indicators, dial test indicators and linear gages. The latest iteration of the i-Checker is at least 2× more accurate than the previous model, achieving the highest accuracy level in its class of (0.1+0.4L/100)μm. At 10 mm/s, speed also is improved 2.5× vs. the current model. All functions necessary for inspection are combined in the control box, reducing operator fatigue. Adjustment of the measurement position is easily accomplished due to semi- and fully automatic measurement functions, thereby dramatically reducing inspection time. Digital indicators equipped with a data output function are efficiently checked due to spindle positioning at the inspection points and measurement results are fully automatic. Operators can create and print simplified inspection certificates. Hardware setup is simple and straightforward—simply plug in a USB cable. The updated i-Pak software includes the most recent standards for ASME, ISO, and JIS. Previous models can be upgraded with new software and controller.



For more information:
Mitutoyo America Corporation
Phone: (630) 820-9666
www.mitutoyo.com

Lucifer Furnace

MODEL 42GT-H12 OVEN INSTALLED AT R. HUETER

R. Hueter Co, a northeast CNC machine shop specializing in male and female RF connector contact production has added a Lucifer Furnaces' heat treating oven to meet their growing heat treating needs.

Adam Hueter, operations manager, chose Lucifer Furnaces because of their reputation for delivering high quality products at an affordable price. Model 42GT-H12 was customized as a bench top unit. With a chamber size of 9-inches × 12-inches × 12-inches, this oven is insulated with 5 inches of both insulating firebrick and mineral wool backup. 4 kW power allows fast heat up to 1200 degrees Fahrenheit.

GT ovens, built for operation using inert atmosphere, are crafted with a continuously welded outer steel shell and gasketed roof plate. A strong seal on the double pivot door is achieved with a square gasket around the door perimeter to form a tight seal to the oven faceplace. Swing bolts with T handles make clamping easy.

The stainless-steel liner baffles the work chamber from the side wall heating elements and directs the air flow horizontally through the chamber for uniform heating. Hueter chose a Honeywell DC2500 temperature controller with a soak timer to shut off heating elements at the end of a programmed cycle in addition to a flowmeter mounted and piped to the oven for easy connection their atmosphere supply. Hueter plans to use the furnace primarily around 600 degrees Fahrenheit for 2-hour cycles to achieve a specific Rockwell hardness with small lots of Becu pins under a nitrogen atmosphere to reduce surface oxidation in order to achieve a scale free, bright finish. After installation, Hueter notes: "Right now the oven is running like a dream! I am completely satisfied with my Lucifer Oven and your team has given me great support along the way."

For more information:
Lucifer Furnaces, Inc.
Phone: (800) 378-0095
www.luciferfurnaces.com

Upgrading Your Toolbox

Manufacturers Focus on Tool Design, Material, Coating, Machine Tool Options and Cutting Parameters

Matthew Jaster, Senior Editor

First, the to-do list: Cutting tools need to reduce overall costs, increase tool life and regularly maintain the highest levels of productivity. Many of these requirements need to come from a customizable solution; one that is typically developed hand-in-hand with the customer from start to finish. This involves everything from tool design and cutting parameters to the material and coating options available. Here's a roundup of some of the cutting tool trends, technologies and challenges in the industry in 2017:

Gleason Q&A

Kurt Switzer, senior product development engineer at Gleason Cutting Tools, recently spoke with *Gear Technology* on some of the trends regarding materials, tools, coatings and machine tool developments.

GT: What are some of the most recent innovations in cutting tool materials in 2017?

Switzer: MC90 is still the most recent commercial addition to the gear cutting tool market. Due to the trend toward increasing stock removal rates, there is a corresponding effort towards developing materials with the required red (or hot) hardness.

GT: What are the benefits for gear applications and why does the performance of the material depend greatly on how the material is produced?

Switzer: Because of the highly alloyed nature of [MC90] and other high performance materials (e.g. ASP2048, ASP2052, ASP2060), they can only be made by particle metallurgy processes. Conventional ingot casting results in excessive segregation preventing hot working of the ingot into a usable bar. Materials like vanadium enhanced M35 are about the highest alloy materials still used in gear cutting that can be made by conventional casting.

GT: Anything interesting happening in tool coatings today?

Switzer: Balzers introduced Balinit Altensa coating a couple years ago. While this coating is designed to perform well in high stock removal rate applications (high heat), its performance benefit to cost has prevented it from gaining popularity in the United States. Testing of this coating continues though, and it still may find some use in high speed gear cutting. Since the advent of TiAlN coatings on the cutting tool scene in the 1990s, the main driving force for new tool coatings has been towards increased stability at high temperatures. New cutting tool coatings now boast oxidation thresholds in the neighborhood of 1200C, which makes them ideal for dry cutting and aggressive stock removal rates even when cutting wet.

GT: How have these coatings evolved in recent years?

Switzer: Cutting tool coating technology tends to evolve rather slowly. There are three very popular coating chemistries still in use, TiN, TiAlN and AlCrN, but the technology behind these coatings was commercialized in the early 1980's. Aluminum Chromium Nitride based coatings now dominate the gear cutting tool market, although there are indications its rapid growth is starting to plateau. There are few a coatings which might make bring significant changes to this market (e.g. CBN or α-Al_2O_3), but perhaps fortunately for tool manufacturers, the technical barriers to their application have yet to be overcome.

GT: What role is IIoT (Industrial Internet of Things) playing in optimizing the cutting tool market today?

Switzer: Big data and especially its analysis will play a major role in optimization of tools and their optimum use in daily production. Short-term, we see more opportunity in optimizing the actual use of tools, the optimum point of reworking or sharpening tools to avoid unnecessary tool life loss. In the long run, data studies may affect the use of materials and coatings with specific applications, learning more as systems provide more correlated data.

Gleason stick blades.

GT: Is there anything Gleason is going to promote in these areas at Gear Expo this year?

Switzer: Gleason will present the complete array of its gear manufacturing tools, including latest systems for bevel gear cutting, latest hob, shaper cutters, Power Skiving tools with state-of-the-art materials and wear coatings. We will also show solutions for the optimization of customers' tools and tool life management.

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

Event Spotlight: AGMA Steel for Gear Applications

In a recent conversation with AGMA President Matt Croson, he discussed a new AGMA course this fall that will examine some of the emerging alloys and materials that gear engineers will be able to adopt in the future. "AGMA's Steel for Gear Applications," provides detailed information to make use of steel properties in a system solution and understand the potential that different steel options can offer for various applications. Students will explore the how the production of the steel can affect the performance of the material and also the final component and system. The course will be facilitated by Lily Kamjou, a senior specialist in Ovako's Industry Solutions Development department. It is an advanced level course and qualifies for those individuals pursuing the Advanced Gear Engineering Certificate.

For more information:
AGMA
Phone: (703) 684-0211
www.agma.org

Material Spotlight: Ovako's IQ-Steel

Steel components are increasingly required to withstand high, multi-directional loads and the purity of new generation IQ-Steel from Ovako is further developed to meet the stress demands of today's high performance parts. It not only has dramatically increased fatigue strength in all directions, but can also help customers to achieve lighter, stronger, more efficient and compact component designs.

IQ-Steel is one of Ovako's new attribute brands and is an isotropic, ultra clean steel with properties that match remelted steel. The pure and highly consistent qualities of the steel are achieved without the complex processes inherent in remelted steels which add considerably towards energy consumption and material price.

Unlike standard grades that are shown to incur time and money costs for the customer, cleaner high-performance steel grades by Ovako can ensure both quality and continuity of production. They are ideal for gears, camshafts and other steel parts.

"We increasingly hear from customers in the marine, energy, transmission, engine, light and heavy vehicle and wind power sectors that standard engineering steels are just not suitable for tougher jobs. The problem with conventional steels is they are produced in a process where inclusions are stretched and elongate in the rolling direction," said Göran Nyström, head of group marketing and technology at Ovako.

"With superior properties in all directions, IQ-Steel can upgrade the performance of a gear in a transmission, a high pressure diesel injector or a safety critical component that is subjected to high and complex loading. The pure and highly consistent steel quality is ideal for extreme pressures and temperatures where cracking or defects are simply not an option," Nyström said.

"This is why some of the world's most demanding original equipment manufacturers (OEMs) and forging shops are using our IQ-Steel grades to handle the strain of higher and more complex loads," he added.

Comparisons of the fatigue strength

of IQ-Steel and conventional steel found that Ovako grades can obtain around 900 MPa in fatigue limit both in the longitudinal and transverse directions, compared to 400 to 500 MPa in conventional steels.

For more information:
Ovako North America Inc.
Phone: (803) 802-1500
www.ovako.com

Star SU and Samputensili Q&A

John O'Neil, engineering manager-gear tools, at Star SU and Dr.-Ing. Deniz Sari, gear technology manager at Samputensili Cutting Tools, recently spoke with *Gear Technology* on some of the trends regarding materials, tools, coatings and machine tool developments.

GT: What are some of the most recent innovations in cutting tool materials in 2017?

Sari: Most of the recent effort has been centered on the optimization of the gear tooth manufacturing system. This involves the tool design, material, coating, machine tool options and cutting parameters that best suit the goals of the customer and unique demands of the application. The latest developments in cutting tool materials include heat resistant properties for use at higher cutting speeds.

O'Neil: For existing material technologies, properties like higher wear resistance, enhanced thermal stability and conductivity have evolved significantly. In recent years, the relationship between tool supplier and end user has become more important to find a best fit tool solution for today's production demands. To reach this goal, computer simulations and complex analysis methods (3D modeling and chip formation programs, for example), are being used more often.

GT: What are the benefits for gear applications and why does the performance of the material depend greatly on how the material is produced?

O'Neil: Today, gear production demands are tailor-made cutting tools for each gear related to material, geometry and application. To manufacture high performance gear cutting tools out of the newest cutting materials to satisfy these demands, experienced knowledge of cutting tool manufacturing is required.

For example, dry hobbing of an automatic transmission component using a steel hob with AlCrN coating was presented for cost improvement. No cycle time reduction was needed so the application of a carbide substrate should yield significant tool life savings. To be cost effective the carbide hob would have to make 2× the number of parts per use and 1.5× the number of uses. A test was initiated using a carbide hob with AlCrN coating. The final result with the latest AlCrN advancements is 7.5 × parts per use and 1.5 × number of uses. Sample photo of edge wear after 12 reconditionings. Coating wear is ~0.123 mm and edge wear is ~0.051 mm.

GT: Anything interesting happening in tool coatings today?

O'Neil: New developments in the AlCrN-Familiy of coatings to increase gear cutting productivity and tool life. Wear resistance, oxidation temperature and thermal conductivity have all been enhanced. For existing coating technologies, the properties like higher wear resistance, enhanced thermal stability and conductivity.

GT: How will these coatings evolve in the future?

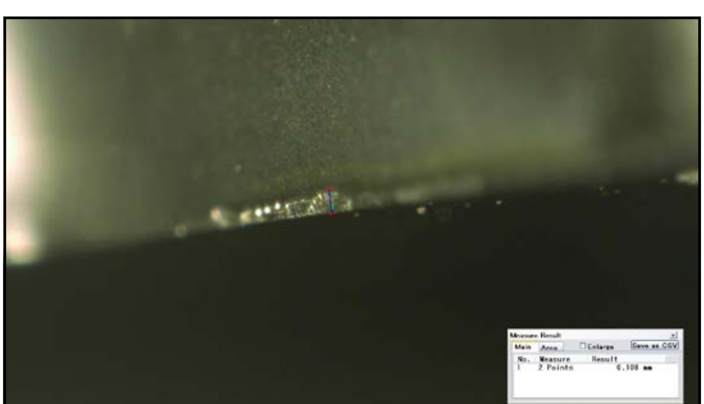
O'Neil: In the next 5–10 years we expect the incremental improvements of current technologies to continue. For example, since the introduction of the AlCrN coating, there have been several incremental improvements on this technology base, each resulting in tool life improvement of 30% in some cases. In other cases coating advancements have allowed for tool base material changes to a less expensive grade without affecting performance.

GT: How significant is the custom cutting tool market today?

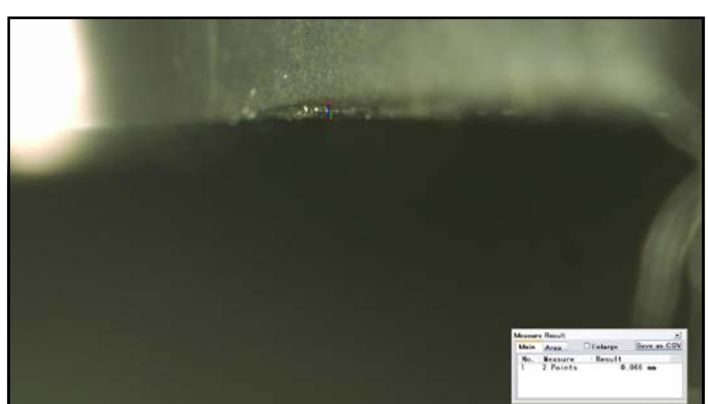
O'Neil: Due to the wide range of influences on the gear cutting process, a standard cutting tool cannot satisfy the market demands like custom designed gear tools are doing today. Offering the market, a dedicated custom tool solution should be the gear tool suppliers standard. A custom hob design may have modifications to the generating diameter to enhance the strength of the tooth tip for example.

GT: What role is IIoT (Industrial Internet of Things) playing in optimizing the cutting tool market today?

O'Neil: An increased number of sensors and improved data analyzing



Sample photo of edge wear after 12 reconditionings. Coating wear is ~0.123mm and edge wear is ~0.051mm



Evolution of AlCrN coating, flank wear reduction in this case was 39%. Photos are of lower left flank of a dry cutting hob.

leads to a better understanding and choice of cutting parameters in gear cutting processes. With this improved process understanding, the tool supplier can choose the best tool solution regarding design, cutting material and cutting parameters to improve productivity and tool life. A further process knowledge combined with an advanced process monitoring will also help to avoid excessive tool wear and provides indicators for an on-time tool replacement.

GT: What role is software playing in this area?

Sari: While new cutting materials offer advantages to customers they present challenges to the application itself. New software and sensor analysis is required to ensure a stable process and utilization of the entire tool potential. Tool design and cutting parameter analysis software such as *SpartaPRO*, developed by WZL at Aachen University, is used to insure the process parameters are ideal for the tool material and coating.

GT: Is there anything Star SU and Samp is going to promote in these areas at Gear Expo this year?

O'Neil: The newest technologies for materials and coating for gear cutting tools, including carbide hobs and Scudding cutters coated with Oerlikon Balzer's BALANIT ALTENSA coating, the high-speed coating solution that realizes productivity gains and efficiency.

We are also featuring the FFG Modul H 200 vertical hobbing machine. The H80/100/160/200 series is the latest version of our hobbing machine line for small applications, specially engineered for automotive. These machines have been designed for dry cutting operations in particular, although using oil or emulsion is possible. Now this machine is available with an optional extended radial travel, incorporating the working range of the H80 up to the H200.

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

Product Spotlight: LMT Fette

The reprocessing of precision tools significantly lengthens a tool's life cycle and reduces production costs. Depending on the degree of wear, a gear hob can be reprocessed 15 to 20 times. Professional reprocessing at the LMT Fette service center returns the tool to a new condition. As a tool producer, LMT Fette offers all reprocessing steps for gear hobs from a single source: Deburring, regrinding, cutting edge preparation and recoating in manufacturer's quality.

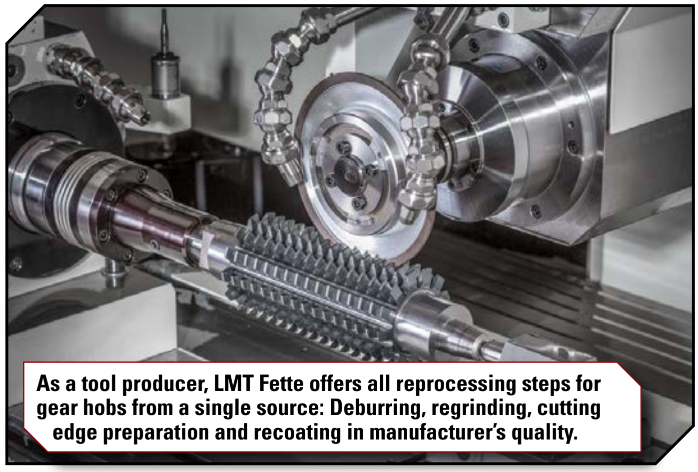
LMT Tools offers customers an individual pick-up and return service. This is done by its own service employees. They collect tools directly from customers and deliver them again after they have been reprocessed.

"Our service employees are experts with technical know-how and can answer questions directly on site," says Christian Johns, who is responsible for the gear cutting tool service segment, while explaining the benefit of personal customer contact.

For additional flexibility, LMT Tools provides its customers with service boxes. These boxes are equipped with suitable packaging material and a UPS label for direct shipping to the reprocessing location.

To document the entire life cycle, there is an accompanying card for each tool. The grind amounts and the respective reprocessing date are documented on this card. This way, the customer can track constant tool performance and keep stock to a minimum.

Furthermore, LMT Tools also does a wear assessment. Wear is determined precisely and individually for each tool. Finally, only the necessary amount of material is removed with each grinding operation. "This way our reprocessing experts achieve the maximum number of tool uses from the predefined tool life," explained Johns.



As a tool producer, LMT Fette offers all reprocessing steps for gear hobs from a single source: Deburring, regrinding, cutting edge preparation and recoating in manufacturer's quality.

For more information:
LMT Fette
Phone: (847) 693-3270
www.lmt-tools.com

Market Forecast: Cutting Tools

February U.S. cutting tool consumption totaled $174.98 million according to the U.S. Cutting Tool Institute (USCTI) and AMT – The Association For Manufacturing Technology. This total, as reported by companies participating in the Cutting Tool Market Report (CTMR) collaboration, was up 1.1% from January's $173.05 million and up 0.6% when compared with the total of $173.88 million reported for February 2016. With a year-to-date total of $348.02 million, 2017 is up 4.5% when compared with 2016.

These numbers and all data in this report are based on the totals reported by the companies participating in the CTMR program. The totals here represent the majority of the U.S. market for cutting tools.

"There is a feeling of optimism in the air that is backed up by the positive growth the cutting tool market data shows after the first 2 months of the year," says Steve Stokey, president of USCTI. "Manufacturing continues to be a hot topic and continues to have a seat at the table in the new Trump administration. The strong dollar will continue to challenge our ability to export but with the US automotive and aerospace markets remaining steady, it should provide a firm foundation for growth as the other industrial sectors rebound from a weak 2016. This should bode well for cutting tool manufacturers."

Scott Hazelton, managing director of economics and country risk at

IHS Markit adds that "The economy is enjoying improved business and consumer confidence, resulting in strong momentum in employment growth and single family housing as well as a rebound in nondefense capital spending, including the important energy sector. Consumption of cutting tools is forecasted to respond with increasing growth over the year. Acceleration of growth in 2018 is expected as tax reform and infrastructure investment will enhance the investment outlook."

For more information:
AMT
Phone: (703) 893-1151
www.amtonline.com

Industry Spotlight: Oerlikon Balzers

Oerlikon Balzers, the coating specialists from Liechtenstein, have commissioned their new Customer Center for the North Germany region in Bielefeld, after relocating from the previous site in Spenge. The new site in Bielefeld will allow Oerlikon Balzers to combine the services offered at their existing sites in Spenge, Herford and Hildesheim. "In the last few days we have transferred all coating systems and equipment from Spenge to Bielefeld. The relocation went well, and we have already restarted production. All staff from Spenge will continue to be employed at Bielefeld, and we are all looking forward to the new premises," says Hendrik Alfter, CEO of Oerlikon Balzers Germany. The second stage will see the site at Herford integrated into the new Customer Center by the end of summer 2017. The full production capacity of the site at Bielefeld will be reached in early 2018 after the site at Hildesheim is relocated. The aim of the new Customer Center is for Oerlikon Balzers to expand its range of individualized solutions and to optimize processes and internal workflows so that it can respond to customers' wishes with even greater flexibility.

For more information:
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Phone: (800) 792-9223
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Gear Design Deconstructed

Jack McGuinn, Senior Editor

How difficult is it to design a gear? It depends upon whom you ask.

How difficult is it to choose the correct method for *making* that gear? Extremely difficult. Choosing the correct process is paramount in shepherding a job from blank page to the finished part print. Thus the gear engineer must ensure that what goes on the blank page is something that can actually be manufactured.

"Preparing the manufacture of (for example) a cylindrical gear is in most cases more complicated than the gear design," says Hermann Stadtfeld, vice president-bevel gear technology-R&D, Gleason Corp. "Picking the right manufacturing methods and calculating optimal machine settings regarding geometry, as well as productivity, is key and has significant influence on the physical properties of a gear."

Thus while stipulating that the role of the gear engineer (designer) in and of itself is not the most daunting job in gearing, it is certainly among those requiring the widest breadth of knowledge. The *design* process begins with four deceptively brief questions, the answers to which will help in determining the correct manufacturing process:

1. What kind of gears should you use?
2. What should they be made of?
3. How should they be made?
4. How should they be checked?

Adequately addressing each of the above questions requires expert knowledge over a range of gear making-related disciplines, including heat treating; materials; workholding, inspection; standards (both ISO and ANSI/AGMA); reverse engineering; gearbox and machine upgrades; custom gearbox design; specification development; project management; chamfering or deburring; and vendor qualification.

It is the responsibility for sorting out all of the above in the manufacture of a custom gear that makes designing a gear correctly the first time such a critical process.

In-House or Outsource?

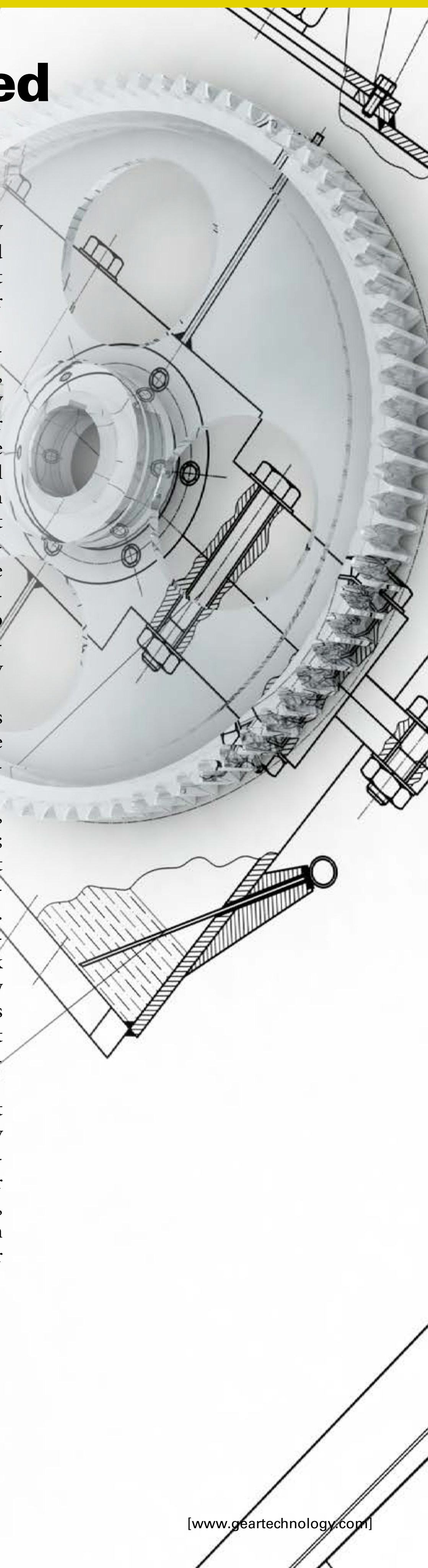
You might be thinking — how many design (new part) projects are addressed on a daily basis? Do operations exist where it is all new gears, all the time? Or are they typically freelance consultants?

"Whenever gear design or manufacturing is a core skill for a company (e.g., gearbox manufacturers), they will try to get onsite employees for their gear design," says Thomas Tobie, head of the load carrying capacity of cylindrical gears department at the Gear Research Center (FZG) at TUM. "Due to the fact that gear design is often very application-specific, only an onsite employee is capable of dealing with every application-specific difficulty. Companies who are not focused on gear design or manufacturing as a core competence usually hire consultants for single projects."

Adds Alex Kapelevich, AK Gears — "Gear designers are typically onsite employees. There are not so many contracted gear consultants."

On the other hand, Charles Schultz, chief engineer, Beyta Gear Service; *Gear Technology* blogger, explains that "Traditionally, gear companies had in-house design-and-build capabilities. For a variety of reasons — aging workforce, changing business models, lack of trained engineers & designers — few still offer this one-stop shopping. Lots of custom equipment is still built, but machine builders frequently use off-the-shelf gears and gearboxes."

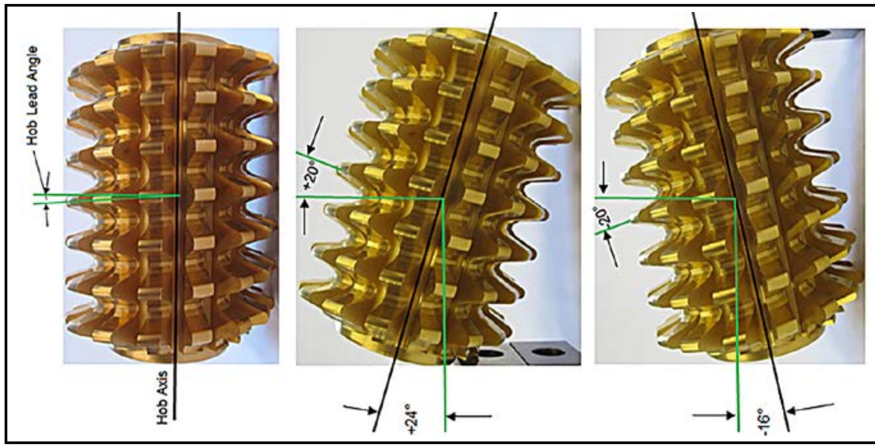
Stadtfeld states that "Companies that manufacture gears for a living on a daily basis usually have their own gear designers; (but) there are consultants that offer such a service. Also Gleason, KISSsoft, Romax, SMT, etc. develop gear design software which they sell, but also offer gear design services."



It's All About the Manufacturing

Given the breadth of knowledge required for designing — and manufacturing — a gear, an ability to work seamlessly within other disciplines in making that happen is crucial.

"The gear design is done by applying some software tools, says Stadtfeld; "given the fact that a cylindrical gear can be defined with 5 values — number of teeth, module, helix angle, profile shift factor and edge radius — the design is not as complicated as preparing the right manufacturing scenario."



The choice how to set up a hob has consequences for surface and productivity. (Courtesy Gleason Corp.)

Schultz believes that "Good designers understand the process capabilities of each manufacturing step and incorporate them into the design. It is always great to get "buy-in" from the rest of the team that confirms your understanding of their work."

"A good gear designer is a mechanical engineer whose background is all of this," says Stadtfeld, adding, "A gear designer is always considering the kind of manufacturing and heat treatment which is available for a certain new gear design and factors those practical manufacturing aspects into a new design."

Standards and the Bigger Picture

For FZG's Tobie, the process is about much more than geometry: "For gear designers, it is very essential to have deeper knowledge, or at least experts, alongside who have knowledge about machining, lubrication, material properties or heat treatment processes, as the requirements on a good gear design are very versatile. In recent years the general trends towards increased power density, high reliability, good efficiency and adequate noise behavior require the design of optimized gears. This optimization has to be done at a very high technical level and requires consideration of many — sometimes even contrary — effects."

And then of course there are standards — ISO and ANSI/AGMA to sort out.

"Good design is compliance with specifications and robust service life," Schultz says. "While there are differences in standards, a 'good' design will 'rate' in any of them. In the future expect to see more 'convergence' between the standards."

It is Tobie's belief that "For many fields of application, it is common practice that the verification of the load carrying capacity is made according to relevant standards (ISO, AGMA), as it is often specified and required by the customer. Therefore, a fundamental knowledge about current standards is often required. For other fields of application, different in-house specifications may be given (e.g., car industry). In such cases standardized methods often are not so important for the gear design."

Training & Education

This is as good a spot as any to wonder what kind of training gear engineers typically receive. Given how many things there are to deal with, one wonders where to begin.

"In (those) companies focused on special products (e.g., automotive gearboxes), it is common to develop a new product based on former products using the gained experience," Tobie points out. "Thus, the gear designer is gaining knowledge on the job. This is a great benefit — especially for young engineers. Besides that, seminars and trainings focused on gear design can be helpful for more experienced employees to get a new perspective on well-known processes."

"There are few "typical" designers," Schultz declares. "Some have an academic background, others are engineers by training. Others come up 'through the ranks' of machinists, drafters, or other positions. The job requires a variety of skills along with an interest for seeing how gears work. Leonardo da Vinci did not have an engineering degree and still managed to do some amazing gear designs."

Is there a "most difficult" gear to design and manufacture?

Stadtfeld — "Cross axis helical, bevel gears and most complicated are hypoid gears." Schultz — "Probably worm gears, as there is no recognized 'system' and lots of variables to deal with." Tobie — "In general, there is a great diversity of gears (spur vs. bevel gears, module <1 mm gears vs. module >20 mm gears), of which every gear has its own specialties which have to be considered in the design process. Nevertheless, it is always a great challenge to design a gear, if different requirements, which are often contradictory, have to be taken into account. Consequently, the 'most difficult' gear has a very good power-to-weight ratio, low noise excitation, and is very cost-effective (as) it can be manufactured in single-part production."

Software

As software continues to evolve in various capacities as an essential tool for gearing, one wonders how it affects gear engineers (designers).

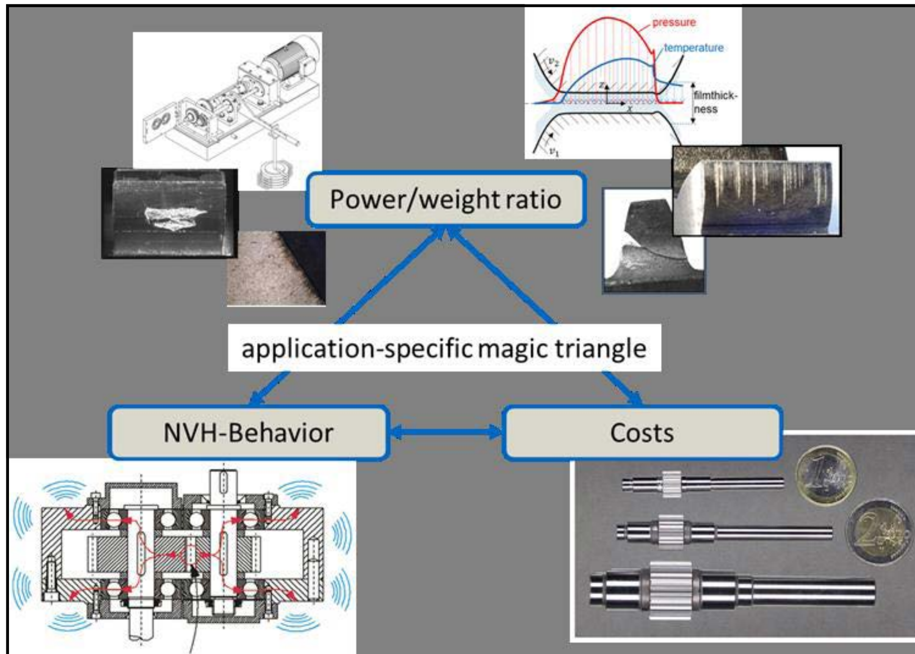
"A little knowledge is a dangerous thing," Schultz cautions. "Some of the more advanced software packages allow novices to 'design' gears and make beautiful 3-D renderings that are not the best solution to the problem. Software is a tool, and like any tool, the more experienced and skilled the operator, the better the results."

As for Tobie — "For today's gear designers it is absolutely indispensable to have a basic knowledge of how to use common calculation tools for designing gears. As the requirements — which have to be considered carefully — are steadily increasing, a computer-aided design is necessary. Besides using modern calculation tools, every gear designer should still be capable of understanding the basic principles of calculating the gear geometry and the load carrying capacity of gears without help of calculation tools, respectively."

The Latest Technologies

How are gear engineers affected by the latest technologies, things like 3-D printing and the Industrial Internet of Things (IIoT)?

"In general, new technologies will lead to new developments also for gear specifiers and designers," says Tobie. "In large companies these advanced technologies certainly already have an influ-



Despite the many considerations that must be addressed, it all begins with the application (Graphic courtesy FZG).

ence on the daily work of gear designers. Nevertheless, many gear manufacturers are companies of small to medium size, and for these companies at the moment the effect is still small because many of the named technology advances are still subjected to ongoing research projects. Regarding IIoT, an online monitoring of the gear condition and the remaining lifetime will be possible in near feature. Furthermore, 3-D printing will allow fast and cost-efficient manufacturing of individual gears made of different types of materials.

"Nonetheless, gears are elementary mechanical components, and the basic requirements will remain unchanged in the next few decades. It is therefore very essential for gear specifiers and designers to keep in mind the fundamental basic knowledge about gears, in addition to the knowledge about new technologies."

Says Kapelevich, "A designer should be aware about new technologies and understand their requirements (mechatronics), capabilities (3-D printing), and potential efficiency (IIoT). Certain gear designs which had been impossible to manufacture have become possible due to 3-D printing, for example. Gear designers welcome the new opportunities and take advantage of them."

Schultz adds, "3-D printing has great potential for pattern and tool design, as well as 'proof of concept' on new products."

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When the Gearing Gets Tough

Sometimes semantics can get in the way of comprehension. We learned in the accompanying article that "gear design" is not *necessarily* at the top of the list of hair-on-fire, fire-in-the-hole scenarios. "Necessarily" is the keyword in this instance, as the following from Alex Kapelevich and Thomas Tobie provides scenarios of when gear design is indeed something that might keep a designer up at night.

Alex Kapelevich

Because gear design requires not only general knowledge of gearing, but also clear understanding of gear drive application, operating conditions (load, RPM, life, temperature range, etc.), dimensional and envelope constrains, specifics of selected gear fabrication technology (accuracy, production volume, productivity, cost, etc.), materials, lubrication, and many other aspects. Besides the gear design, there are other critical stages in gear drive development, e.g. — manufacture, inspection, assembly, and testing that must be done appropriately. But gear design is a major contributor to required gear drive performance.

Thomas Tobie

I think that designing a "standard" gear is no more difficult than designing some other machine elements; but for many applications a standard gear design is not sufficient.

In recent years the general trends towards increased power density, high reliability, good efficiency and adequate noise behavior require the design of optimized gears. This optimization has to be done at a very high technical level and requires consideration of many — sometimes even contrary — effects.

Some examples why such optimized gears are maybe quite unique:

Combination of high load, sliding motion, friction and temperature load that results in a complex stress condition and high stress levels leading to high requirements on material, lubricant and manufacturing quality

Elastic deformations under load which require modifications of a few microns during manufacturing to reach a good load distribution and noise behavior

Lubricant film with a film thickness significantly smaller than a human hair has to separate the loaded surfaces under the above described operating conditions (high pressure, sliding, temperature)

I think it is the combination of all these effects and requirements that makes the difference and makes it difficult to design an optimized gear for highest demands and reasonable costs at the same time.

In fact, our main goal and approach is still to improve gears as a whole and covering all the aspects — load carrying capacity, noise behavior, efficiency, costs, etc.

For this we try to understand the physical-mechanical — and sometimes also chemical mechanism — to quantify the relevant influence parameters and to bring this into calculation methods.

So I believe that there are three main topics of our continuous work: Developing improved calculation/simulation tools, try to develop standardized rating procedures and to establish standardized test procedure for influence parameters which cannot be covered by simulation only.

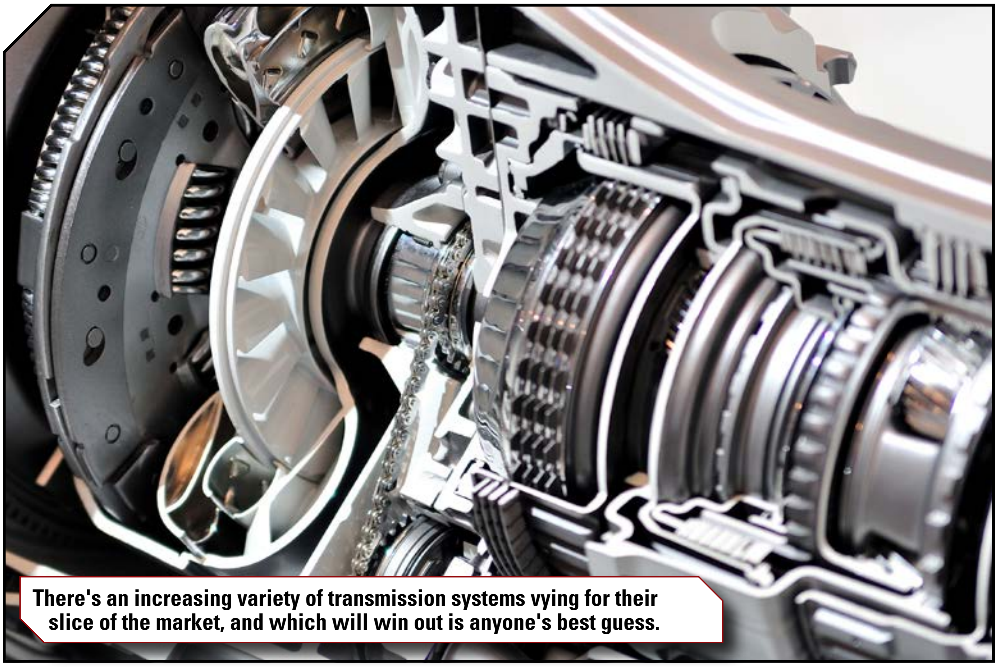
At the end, a good designed gear has to take into account many requirements from material, heat treatment, lubricant, manufacturing, gear geometry, etc., and in many cases compromises are needed to fulfil all requirements. The best selected lubricant will not help if an inappropriate material is used, and vice versa. Also, the best rating procedure for micropitting will not help if the gears fail by scuffing.

Transmission Throwdown

Which transmission system will come out on top is a hot topic in the automotive community. With multiple transmission-centric conferences on the horizon, there will be plenty of debate, but how much will the answer actually affect gear manufacturers, and when?

Alex Cannella, Associate Editor

It's transmission season here at Gear Technology. CTI Symposium USA is right around the corner, and across the pond, the International VDI Congress "Drivetrain for Vehicles" is coming up in July. Both conferences are entirely focused on one topic: automotive transmissions, and that means it's on our minds, too. CTI will feature over 70 presentations, while VDI will have over 80 lectures from 12 different relevant fields. Both conferences have a heavy focus on educating attendees on the technical aspects of what's going on with autos transmissions today and what's right around the corner tomorrow, and between the two, there's going to be a lot of intellectual discourse to digest over the coming months.



There's an increasing variety of transmission systems vying for their slice of the market, and which will win out is anyone's best guess.

Starting closer to home, CTI will feature a number of leading experts in the field of transmission technology, including plenary speakers ranging from representatives of major automotive companies such as Ford, GM, BMW and Nissan to the Environmental Protection Agency. As one might expect, plenary speakers will be spending plenty of time discussing the future of the automotive powertrain, but topics covered everything from quality management to technology compliance.

The rest of CTI's many seminars fall into a few different categories. A few main points of attention are hybrids and continuously variable transmissions (CVT), but there will also be plenty of discussion about new transmission concepts andindividual transmission components. Other topics include safety and cyber security, design methods and tools, control systems, launching devices and commercial vehicles. Alongside the conference, over 70 exhibitors will be in attendance to show off the latest advances in automotive transmissions.

Preceding the CTI conference will be a two-day seminar on the basics of automotive transmissions and the Agile in Automotive USA Conference. The Agile Conference focuses specifically on the agile design philosophy and how to utilize its tenets and best practices when developing transmission technology. After two years of success in Europe, the conference will make its U.S. debut alongside CTI.

The seminar, meanwhile, highlights different conventional and electrified drive concepts common in the industry today, different design layouts for transmission systems and drivetrain management. The seminar will be presented by the Institute of Automotive Engineering at the Technical University of Braunschweig, the head of which, Dr. Ferit Küçükay, is also the chairman of CTI Symposium Berlin, which you can catch in December.

If you can't make it out to CTI USA and don't mind the trip out to Bonn, Germany, you can get another in-depth look at the future of automotive transmissions by attending VDI in July. In addition to the 80 plus presentations planned for the show, over 1,500 international participants and 100 exhibitors are expected to converge on VDI, offering plenty of opportunities to mingle and network with other industry thinkers and fellow company leaders.

VDI's "Drivetrain for Vehicles" will be accompanied by two other VDI-run conferences: "Control Solutions for Transmissions" and "Transmissions in Commercial Vehicles." "Control Solutions for Transmissions" will focus on different control fields ranging from sensors to interfaces, along with the benefits that stem from using those solutions. "Transmissions in Commercial Vehicles," as one might expect from the name, will specifically discuss innovations, trends and operating strategies pertaining specifically to commercial vehicles.

Lectures will largely be grouped by transmission type, with discussions being held on almost every transmission, including hybrid, automatic, CVT, manual and dual clutch transmissions. There will be a particular focus on hybrid transmissions, with one lecture track even focused specifically on the 48V hybrid transmission, which according to Küçükay, will become increasingly common in the industry in the future.

"Due to the legislative CO_2 target emissions and high cost for hybridization, 48V mild hybrids will become a relevant technology within the next years," Küçükay said. "With electrical powers up to 20 kW hybrid functions such as recuperation, boosting or coasting offer a fuel consumption reduction of about 20 percent within legal cycles. Another benefit of a 48V system is the coverage and integration of auxiliaries with a high power demand such as e-booster or electric catalyzer. Some manufacturers of premium vehicles already introduced 48V systems for series applications. In the near future 48V systems will be introduced for smaller vehicle segments such as the C-segment."

Other topics will include virtual engineering, NVH and discussing individual components such as gears, couplings and clutches. Meanwhile, plenary lectures will focus on the higher level questions in the industry, taking a look at concepts such as autonomous driving, geared transmissions and how they relate to fully electrified drivetrains, and how to get by in an industry that's in flux.

And the industry certainly is in flux. Technology is advancing at a breakneck pace, and some automotive experts are saying that even technologies that are difficult to imagine today such as autonomously driving cars will be entering the market and becoming more commonplace within the next decade. With so many new advancements in the industry, the automotive market has a number of big questions it needs to work out, with new technologies clashing with old, established systems for market dominance. In another decade, the automotive industry could look completely different from how it does now.

The biggest question being asked in the industry right now (and one you'll definitely hear at VDI) is a simple one: which transmission?

That may sound like an obvious centerpiece of discussion for a transmission-oriented conference, but the debate is one the entire industry, not just transmission specialists, is watching. The automotive market is being divided between an increasingly diverse array of transmission systems, and the question of which will eventually become the transmission of choice is one that nobody seems to be able to agree on.

And not only is the market divided by an increasing number of transmission types, it's also fractured regionally. Depending on which continent you're in, favored transmission types and their market shares completely vary. North America, for example, is dominated by automatic transmissions. According to a 2014 article put together by Wajih Hossenally and Chris Guile of IHS

Automotive and run in *CTI Mag*, 75 percent of the North American market is controlled by automatic transmissions, with CVT being the second most prevalent transmission type at 12 percent and manual only holding 8 percent.

But go to Europe, South America or South Asia, and the manual transmission reigns supreme, making up 65 percent, 81 percent and 72 percent of their cars produced respectively. Go to Japan and Korea, and you'll find the highest concentration of CVT transmissions, representing 30 percent of all vehicle production in the region, alongside 40 percent automatic transmission and 19 percent manual. If you're focusing on individual markets like North America, there are some pretty clear preferences, but marketing oneself globally is a more ambiguous proposition.

Add in DCT transmissions, which are also vying to break into the market, alongside the advent of every flavor of hybrids (both modular and dedicated) and fully electric cars, and there are a lot of different transmission designs with no one-size-fits-all solution to sweep the market in sight.

But for the average gear manufacturer, the great transmission debate, and any eventual answers the industry might come to, is of less concern than one might expect. No matter the transmission, cars will still need gears. And while, yes, different transmission types require different numbers of gears and that could affect market demand, it's highly unlikely that the industry's need for gears will be going anywhere. The only contender that could possibly derail the geared transmission system is a fully electric drive that skips the transmission system altogether, but according to Reishauer's Marketing Manager, Walter Graf, even a fully electric system could arguably require gears to operate.

"The car manufacturers have a whole range — hybrids, petrol, ICE drives, maybe even hydrogen in the future," Graf said. "But all of those need gears to some extent. There are electric drives that don't need gears. The question will be in the future: what percentage will they have amongst electric driven cars? The answer I can't give you. You find when you check the literature, some people say 'yes, they will need gears,' some say 'yes, they will need gears, but three-speed, two-speed is enough,' and some will say 'no, one-speed drives is good enough,' and I think the jury is still out on that one."

While Graf is hesitant to pass judgement, Küçükay is more optimistic and notes that regardless of whether or not electric drives utilize gears, transmissions won't be going anywhere anytime soon.

"Transmissions as we know them today will only vanish when the internal combustion engine is not necessary anymore, meaning close to 100 percent of the vehicles are pure electric," Küçükay said. "This change will not take place in a foreseeable future and even for pure electric vehicles, transmissions with two and three speeds become relevant. They offer a cost-effective alternative and are needed in higher vehicle classes to ensure launch and climbing capability, while maintaining performance as well as maximum velocity requirements."

ECM's FLEX heat treating system. ECM will be the only heat treatment exhibitor at the CTI Symposium in May.

"Is it really a big hoopla and should [gear manufacturers] really be worried about it? I would say no," Dennis Beauchesne, general manager at ECM, said. "I would say that the types of gears we're going to see might be different. We're seeing a lot more powder metal gears coming out...and of course, there's always 3D additive manufacturing gears, as well, that are coming out, but I don't see those taking effect for many of the gear manufacturers for 10 years."

Even if electric drives do become the de facto standard, and even if they do so without using any gears, it won't happen for quite some time. According to some predictions put together by PricewaterhouseCoopers last year, electric cars will only make up 35 percent of the North American market in 2028. PwC expects hybrids to be the dominant car of choice and make up 51 percent of the market, and those are guaranteed to still require gears.

So while, yes, electric drives have the potential to work with just a single speed gearbox, it's difficult to envision a nightmare scenario in which electric drives conquer the entire market and put all us gear guys out of work. The advent of hybrid and electric cars doesn't necessarily have to be looked at as a net loss, either. Graf also notes that the same mentality that is a driving force behind the switch to hybrid and electric cars is also currently benefiting the gear grinding industry.

"Because of energy consciousness, the gears have to be more accurate, so we figure that gear grinding will become more important than it is now," Graf said. "It's already very important; all the American manufacturers now grind their gears. That wasn't the case maybe 10, 15 years ago."

Beauchesne's own take on the industry's future is that he believes CVT transmissions will start muscling in on 5- and 6-speed transmissions for smaller gas motors within the next few years. The 8-10-speed transmissions will stick around far longer, but they'll also be in direct competition with hybrids and electrics and may ultimately be replaced.

"Obviously the trend is to get away from gas engines," Beauchesne said. "So the higher torque transmissions won't be needed as much, and if we get into more self-driven cars, then there's even less need for the higher torque transmissions."

Unfortunately, there's little chance of any new premium 11- or 12-speed transmissions becoming commercially widespread to drive up gear demand. While current transmissions will be around for many years to come, one thing the automotive industry has mostly come to a consensus on is that the diminishing returns from upping the number of gears in a transmission have officially crossed the threshold of becoming cost prohibitive.

"There is no logical reason or tangible benefit for increasing the number of speeds for conventional powertrains beyond 10-speeds for passenger car and light duty applications," Dr. Hamid Vahabzadeh, chairman of CTI Symposium USA, said.

Another batch of automatic transmission pinion gears is prepped for heat treatment at an ECM facility.

"I think if you made a gearbox with more than 10 gears, the gains would be minimal and the complexity to manufacture and the cost would be prohibitive," Graf said.

Under Beauchesne's view of the future, the transmissions that are the gear manufacturing industry's current cash cow will one day become obsolete, as most technology eventually does, and for some, that could be an intimidating prospect to consider. But as Graf also highlighted, that eventual day is a distant

Over the past few decades, Reishauer has noticed gear grinding consistently continue to become more relevant, and according to Graf, that trend will continue.

one, and the technology that will take over will be almost as hungry for gears as the technology today.

The other big shift in the auto industry, the one towards automated driving, isn't setting off any alarm bells for gear manufacturers, either. The idea of self-driving cars is currently capturing the industry's attention, and while it's a fascinating trend to follow, having a computer behind the wheel instead of a person isn't likely to affect the gears side of the industry too deeply.

While gear manufacturing in the automotive industry looks stable, gear manufacturers should still endeavor to pay attention to how the industry develops. With a strong market that looks like it will continue to prosper and no major technology dilemmas on the horizon, it's true that gear manufacturers in the automotive industry don't have to worry about where to get their daily bread. But while there's no reason to start losing sleep over whether electric cars will conquer the market or not, manufacturers will still need to pay attention to the needs of up-and coming technologies and adjust their manufacturing capabilities to match what that new tech requires to remain competitive. According to Beauchesne, so long as gear manufacturers keep up with the times, there will be work no matter which way the tide flows in the larger debates wracking the industry.

"The net result, I think, as long as you're following what's necessary in CVT transmissions and hybrids and electric transmissions, there will still be machining and gears needed for those applications," Beauchesne said. "So net result: the number of gears being manufactured and the number of machine operations that are being done in the automotive industry will still be really high. We're not being replaced by plastic gears, or anything like nylon gears. Obviously, the shape of the gears in the transmission are going to change."

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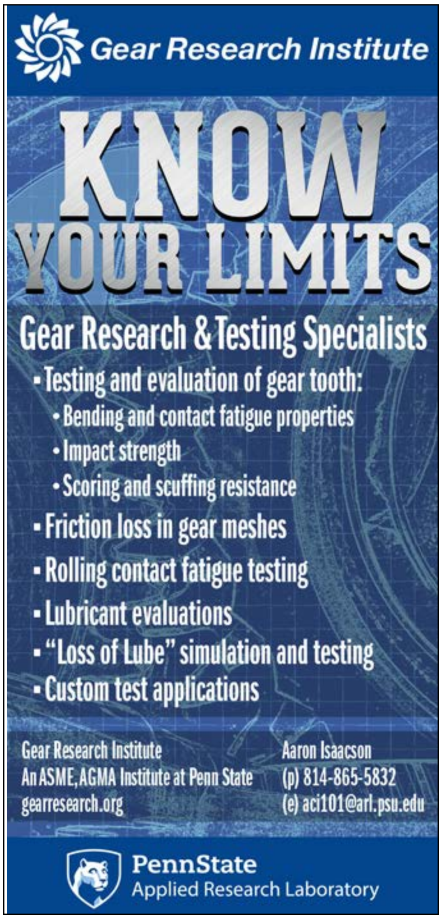
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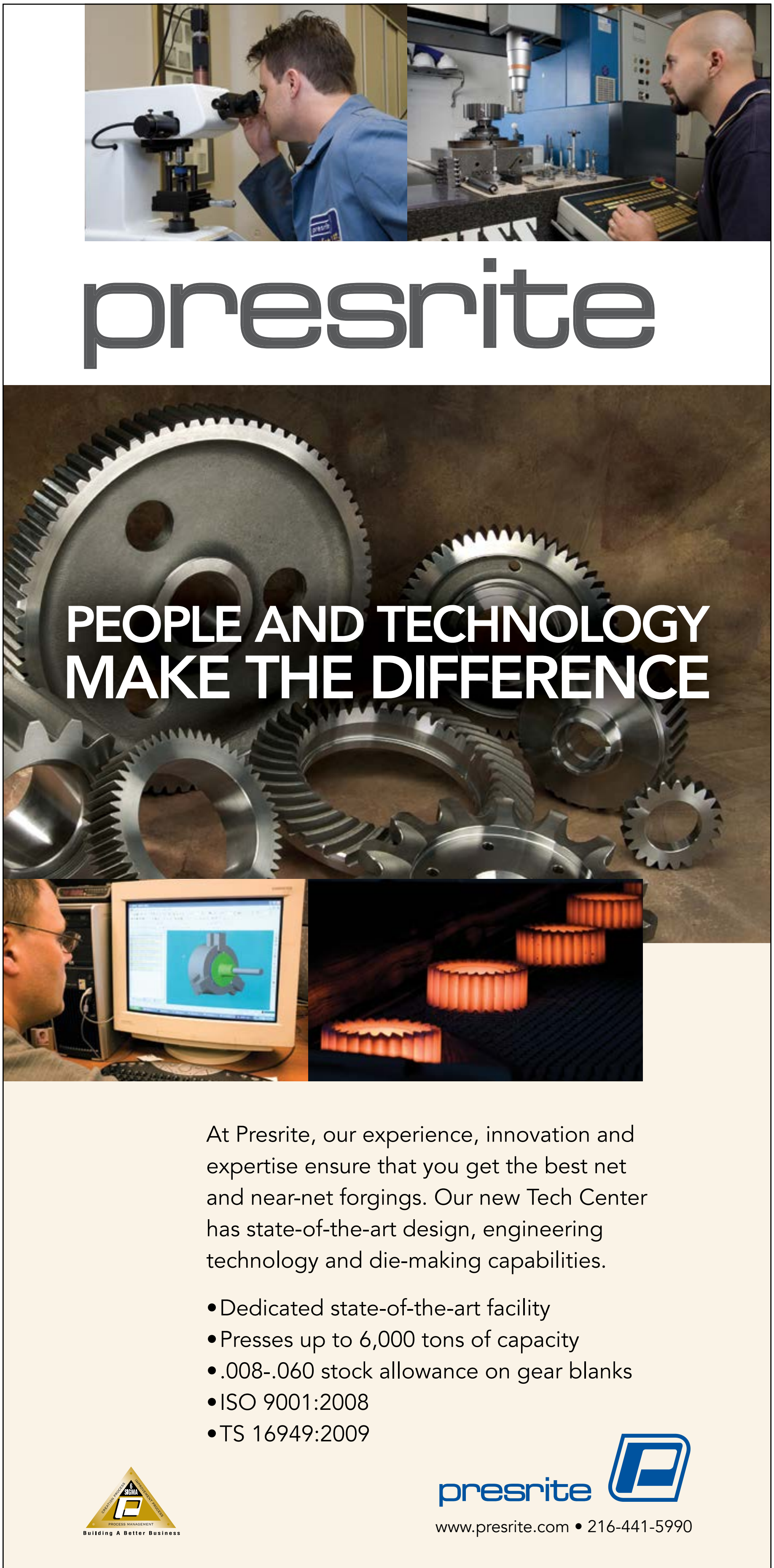
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Can Lean Manufacturing Kill Your Job Shop?

A Tale of Two Companies

Joe Arvin

The presidents of two manufacturing companies were having a drink in the lobby before the start of their trade association's annual meeting. The first was Jim from BloatCo, and the other was Steve, who was with Slimline Corp.

As people in the same industry tend to do, they got to talking about their respective companies. Jim, the president of BloatCo went first.

"We're a job shop very similar to yours, and we supply a mix of commercial, high precision, and some aerospace. Most of our orders are small production runs. Right now we have a very large backlog, revenue is up, and we're very, very busy," Jim explained.

"Sounds like you're doing real well," Steve said.

"Well," Jim said as he looked down at his drink. "Not exactly - we've got some serious problems. We've got millions of dollars tied up in WIP inventory, and our CPA firm is all over my back on that. Our lead time is 20 weeks and getting longer, and we spend a lot of time on the phone breaking the bad news to unhappy customers about late deliveries. We're spending thousands of dollars each month on overtime and expedite charges."

Looking up from his drink, Jim asked, "So tell me Steve, since Slimline's very similar to BloatCo, are you having these kinds of problems?"

Quickly responding, Steve said, "Well, we used to have a lot of those problems, but then we introduced Lean Manufacturing and the Pull System. Over several months, we saw WIP inventory drop and our production schedules shortened so that orders had a clear path to shipping in just two months."

A bit envious, Jim asked Steve, "That sounds like what we need to do. I'm guessing that now you're really doing well."

Steve said, looking down at *his* drink, "Unfortunately no - now we've got some serious production problems hurting the bottom line."

Surprised, Jim asked, "It was my understanding that you were making a reasonable profit. What production problems are you having?"

Well, it can be any number of things that you just don't have any way to predict. Annually, 30% of our jobs are new, so frequently process changes are required mid-stream. Then there's tooling that's not ready, the wrong type of gauging, parts that need rework, and of course, there's unanticipated heat treat distortion. And I can't tell you how many times we have to stop a job while we're waiting for answers from a customer. The list goes on and on," Steve said.

Jim shrugged his shoulders and said, "So what's new? We have the same problems."

Continuing, Steve said, "What's happening now is that only 50% of our machines are running on a daily basis. Every time we run into a production problem that halts a job, there's nothing else to run - so we get empty machines and operators with nothing to do when we used to have some operators running two or even three machines. Our profits now are almost non-existent."

Finding the Middle Ground

BloatCo and Slimline are both experiencing problems that are not uncommon in the manufacturing job shop environment.

But you might be thinking, "Come on Joe, Lean and the Pull System is a PROVEN METHOD for streamlining any manufacturing operation. If you're not Lean, you're living in the Dark Ages. Get with the program Joe!"

First of all, it's important for this discussion to understand that a job shop is very different from one that manufactures a lot of repeat jobs in medium to high lot quantities. A high volume environment is really the sweet spot for Lean/Pull. However, a job shop, with a continuous variety of complicated parts with many operations, is where things can get tricky in terms of Lean/Pull.

Given that, something to consider is this. One thing I've learned in life is that going to one extreme or the other will most likely cause problems.

On one hand, it is certainly true that having too much inventory on the shop floor is generally not a good thing, and typically lead times will expand, late deliveries will increase, while a lot of your money is tied up. On the other hand, if you've implemented a textbook version of Lean and your Work in Process (WIP) is trimmed to the bone, you might be missing some opportunities for increasing your bottom line. Let me explain.

There are two basic rules about manufacturing. Rule #1: Your best path to profitability is for your shop to be operating at maximum capacity — in other words — keeping the machines running. Rule #2: Problems will inevitably occur that will prevent your machines from running.

It's important to remember that a job shop using Lean/Pull are most certainly not immune from Rule #2 — problems will occur. And when things go wrong, not having work to shuffle around when needed will prevent you from complying with Rule #1 — keeping the machines running. This, in essence, can starve your shop and create some widespread problems. In contrast, in a shop that has some degree of extra WIP, when problems occur, there will be work on-hand that can be used to keep your machines running.

As much as we'd like to think that Lean/Pull's promise as the next evolution of manufacturing is something to fully embrace, the balancing act of production control in the job shop will likely be with us for quite some time until we can accurately predict everything that can go wrong.

There are other ways that having extra WIP on the job shop can benefit you — and actually make you a lot more money — thus dwarfing the relatively insignificant costs associated with excess WIP. For example, with additional work available, an operator can run more than

one machine. In doing this, these operations will, in essence, cost you virtually nothing.

Then there's the issue of machine change-over. Before tearing out a setup, including changing chucks, grinding wheels, coolant, or cutting tools, what if you looked around and found another job you could quickly run that would not require a major change-over. This can be a significant cost saver. In fact, I have seen a major machine set-up change take four hours which was used to run a 20 piece job. Then the machine was changed back for a 15 piece lot with a larger diameter, and then back again for a smaller diameter job. Had work choices been available, eight hours could have been saved on just one operation!

Heat treat presents similar time saving benefits. Let's say you have an eight piece lot ready for carburizing and required 14 hours of furnace time, yet the furnace can accommodate 60 parts. Think of the time savings if you had another job in the department with the same material and depth of case. By running these together, you've saved 14 hours on that second job. Without some additional WIP, you would have no opportunity for batching similar jobs and getting two for the price of one.

These are the type of on-the-spot decisions that a savvy manager can make, and in aggregate, have a serious impact on productivity, sometimes meaning the difference between profit and loss on a job.

Now you might be thinking, "Give me a break Joe — any good manager knows that your scheduling people should sequence the parts to take advantage of these time saving strategies."

As I mentioned earlier, in larger volume operations with repeat jobs, scheduling for these types of time saving strategies is much easier. However, in the job shop, with all the new jobs and differing delivery commitments, this gets very difficult to do unless you have an extremely sophisticated scheduling module — which most small to medium job shops don't have. But keep in mind, unforeseen problems will happen and this can derail even the most sophisticated scheduling module; therefore some additional inventory is essential.

The Tax Implications

Finally, in discussions about WIP inventory, one common concern involves its tax implications. To shed some light on this, I asked Greg Errandi (one of our CPA consultant associates) about the tax implications of WIP. Greg supplied this clarification.

Under the accrual method of accounting, GAAP (Generally Accepted Accounting Principles) requires matching of revenue and expenses. Manufacturing expenses are not expensed as they are incurred, but rather matched with the revenue they generate. Therefore, when WIP and finished goods are produced, all material, labor and overhead expenses related to production are transferred to inventory (a balance sheet item) rather than expenses (an income statement item). As goods are actually sold, the manufacturing expenses associated with them are transferred to the P/L to match the timing of revenue with the expense.

In other words, any expenses associated with the production of goods not sold is not deductible for tax purposes. The accounting effect, is a simple transfer between balance sheet accounts — a decrease of cash and an increase in inventory value for material, direct labor (payroll) or assigned overhead costs.

So as far as taxes are concerned, don't be too quick to panic if there is a relatively reasonable amount of extra work on the shop floor.

Conclusion

When you look to Lean/Pull principles to improve your job shop environment, you should be careful about going too far to the extreme. Being buried in WIP inventory is generally something to avoid. However, having some extra inventory on the shop floor means flexibility. And flexibility is a valuable tool for achieving that ultimate goal of manufacturing — keeping the machines running.

A Final Word

If you're having a particular problem or if there is a topic you would like to have addressed in this column, please send me an email at ArvinGlobal@Gmail.com.

Joe Arvin is a veteran of the gear manufacturing industry. After 40 years at Arrow Gear Company, Joe Arvin is now President of Arvin Global Solutions (AGS). AGS offers a full range of consulting services to the manufacturing industry. His website is *www.ArvinGlobalSolutions.com* and he can be reached by email at *ArvinGlobal@Gmail.com*.


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Gear Teeth as Bearing Surfaces

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QUESTION

I am wondering about gears where the tops of the teeth are the bearing surface, e.g.—as used in spur gear differentials. Do these (require) any special construction or processing? Thanks!

Expert Response Provided by Chuck Schultz. Designers frequently have to mount bearing inner races on surfaces that are interrupted by gear or spline teeth or the "runout" area of the cutters used to make those teeth. Bearing manufacturers have their own policies on how much support a particular bearing needs so your best information will come from them. Unfortunately, the bearing company you want to reach is probably busy helping other customers, so here are a few of the design rules I try to follow. I say "try" because with apologies to Yoda, some situations will not quite comply with the rules.

The tolerance of the bearing mounting surface MUST comply with the bearing manufacturer's requirement. Having a bearing "slip" is disastrous under normal circumstances; doubly so when the teeth can act like milling cutters on the bearing bore. You may have to adjust gear geometry to achieve the required fit diameter, as is commonly done with metric spline standards such as DIN 5480.

Some bearings, such as needle roller bearings with thin inner races, will require testing or a bearing manufacturer "sign-off" to be mounted in this way. If the bearing company says NO, you would be wise to listen.

If the total area at the bearing mounting surface is less than 45%, you will want to consider using a larger-bore bearing with a sleeve fitted to the shaft.

All runout and finish requirements of the bearing fit diameter apply to these interrupted surfaces. That means it will have to be ground or hard turned after heat treating if the part is surface hardened.

All abutment dimensions still apply; the adjacent shoulder, roller clearance zone, and corner radii must be held.

As DIN5480's popularity shows, mounting bearings on surfaces interrupted by teeth and cutter is not an unusual requirement. Clever engineers like Leo Goosen (*see Addendum p. 88, 1926 Miller front wheel drive gearbox*) find ways to avoid it, but many successful power transmission products have made it work.

Chuck Schultz is a licensed engineer, Gear Technology Blogger (geartechnlogy.com) and Technical Editor, and Chief Engineer for Beyta Gear Service (*gearmanx52@gmail.com*).


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Girth Gears — More than Just Metal and Teeth

Steve Lovell

Introduction

The clear majority of published knowledge about gear manufacturing relates to two main subjects; material quality and tooth accuracy. In most cases, the mechanical accuracy of the gear blank is taken for granted and, after all, preparing a gear blank normally consists of applying basic machine shop skills taught in high school level vocational technical courses. However, large multi-segmented girth gears do not behave like the relatively compact, rigid, monolithic structures we typically envision when discussing gear manufacturing. Girth gears are very large non-rigid structures that require special care during the machining of individual mating segments as well as the assembled gear blank itself.

It is well known that a gear blank's mounting surfaces must possess certain measures of geometric accuracy, and that the gear's pitch cylinder must bear certain geometric relationships to those mounting surfaces. Moreover, the finest construction materials and the most precise tooth geometry have limited bearing on realized life when these geometric cardinal rules are not upheld. Indeed, the American girth gear rating standard — ANSI/AGMA 6014-B15 — disclaims validity when the required geometric relationships are not achieved. However, what is required to achieve those assumed geometric quality levels in a girth gear may not be so intuitive to the manufacturer or to the purchaser. The following sections will describe common girth gear design features, the normal sequential steps in the manufacturing process, some typical challenges encountered along the way, and the downstream effects of failing to manage those challenges.

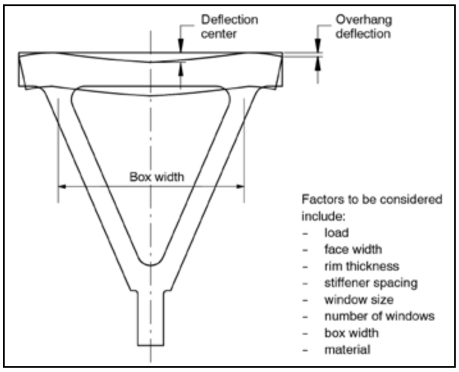
Girth Gear Applications

Girth gears fall into two basic categories; flange mounted and tangential spring mounted.

Flange-mounted girth gears, the more common of the two, are most frequently utilized in "cold" processing equipment such as SAG (semi autogenous grinding) mills and ball mills for use in the mining and cement industries. By current standards, girth gears can be as large as 14 meters (46 feet) in diameter, 1.1 meters (44 inches) face width, and 50 module (.5 DP) tooth size, and weighing upwards of 120 tons. Flange mounted gears rely, in large part, on the mill structure to provide the stiffness and geometric stability required for successful operation.

Spring-mounted girth gears, on the other hand, are typically utilized to drive (hot) rotary pyro equipment such as kilns and dryers. For these applications, a securely bolted flange mount is not a viable option when the temperature of the driven machine is typically hundreds of degrees hotter than the surrounding gear that drives it.

The following discussion will focus on flange mounted girth gears since these applications represent, by far, the larger population.



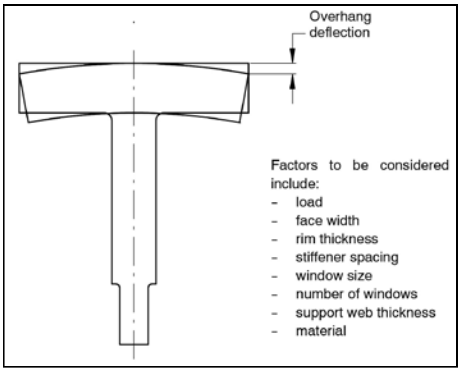


Figure 1 The two basic structural designs for girth gears, consisting of Y-Section (left) and T-Section (right) structures (AGMA). (Drawing from Annex C of ANSI/AGMA 6014-B15; printed with permission of the American Gear Manufacturers Association.

Structural Designs

There are two basic structural designs for girth gears, consisting of Y-Section and T-Section structures (Fig. 1). The Y-Section design is reserved, almost exclusively, for cast steel and, to a lesser extent, for ductile iron. The T-Section is widely utilized in steel and ductile iron castings due to its simplicity and reduced weight. The T-Section is utilized almost exclusively for fabricated girth gears of welded construction. The Y-Section design, when viewed as an independent structure, possesses greater torsional stiffness than the T-Section. However, both designs have many decades of proven reliability and this discussion does not state or imply any preference for either structural design.

Girth gears up to 7.5 meters (24 feet) diameter are typically manufactured in two segments. Beyond this size (Fig. 2), most designs will utilize from four to six segments — depending on the foundry's liquid metal pouring capacity or the largest forging that's available for a weldment. Smaller individual segments also make it easier to adjust for the inherent geometric inaccuracies of raw castings and weldments alike. Splits at the joints are located in the tooth roots and unequal length segments will occur when the number of teeth is not wholly divisible by the number of segments.

Tooth Alignment

The most common girth gears are helical designs due to cost advantage. Spur gears are second in popularity, with double helical designs running a distant third due to their inherent complexity and higher cost of manufacturing. Double helical and spur gear designs may be necessary if the mill bearings cannot absorb the thrust force from single helical designs.

Joint Designs

The most highly stressed region of any girth gear structure is located nearest the joints, where the mating segments are connected. The joint design must pro-

Figure 2 **Girth gears exceeding 24 feet typically require up to six segments.**

vide accurate and repeatable alignment of mating segments, sound tangential buttressing of adjacent teeth across the splits, as well as fixed, creep-free connections during operation.

Some helical girth gear designs utilize joint contact surfaces that run transverse to the gear rim face, and not aligned with the helix angle. This design has generally fallen out of favor because it results in an overhanging "tongue," where the teeth falling directly over the splits lack sound radial and tangential support.

Joint Hardware

Joint designs are thru-bolt connections with threaded fasteners consisting of studs with nuts on both ends. Depending on the designer's preference, the same joint can be designed with more fasteners of smaller diameter, or fewer fasteners of larger diameter. Joint closure is typically accomplished by one of two methods; 1) thru controlled tightening of "super-bolt"-type hardware, or 2) with slugging wrenches and sledge hammers. Although the latter method is still employed, it has been largely abandoned due to the importance of reliable and repeatable joint closing forces.

Joint Alignment Function

The alignment of mating segments is typically accomplished by one of three methods. The more popular designs employ either fitted studs or tapered studs with split tapered sleeves. Third in popularity is the transverse "dog bone" that is centered on, and runs parallel to, the split surface. Each of the three designs has its own peculiar strengths and weaknesses, but each design can effectively accomplish its intended purpose when accurately produced.

Geometric Tolerances

The ultimate goal is to provide an installed accuracy that effectively supports the design service factors. In order for this to be realized, the gear's mounting surfaces must be manufactured to more strict tolerances than those applied during installation. Installed runouts can be adjusted, to a limited degree, thru the use of radial jack bolts and axial shims. These adjustment features are utilized to compensate for normal stack-up of conforming geometric errors on the multi-component grinding mill assembly; they are not intended to make up for a gear blank that was either improperly toleranced or incorrectly machined.

There are three basic sets of geometric tolerances with which to be concerned. The first set is those tolerances that apply to the various manufacturing processes; the ones that define the accuracy and geometric relationships between the datum surfaces, the mounting surfaces, and the finished pitch cylinder. The second set, equally important, are those that specify the gear's installed accuracy in terms of radial and axial runouts intended to place the pitch cylinder in proper relationship with the driven machine's rotational axis.

The above two sets of geometric tolerances are normally specified by the gear design engineer since both have direct effect on design service factors and life expectancy. The third set of tolerances, much less known or understood, is intended to make the first two sets entirely possible. They are the internal manufacturing tolerances applied to secondary features such as machining datums, machine tool setups, process control checks, intermediate verifications, etc. These tolerances, when they are formally defined, would typically appear on the shop routing or on the machine tool setup sheet. Unfortunately, even with the current state of standardization and centralized process control, these internal tolerances frequently reside only in the machinist's "Black Book." We will soon see that the importance of these tolerances cannot be overlooked.

Layout of Raw Segments

Whether working with castings or weldments, the individual raw gear segments must receive a full layout prior to machining. This operation is intended to balance the built-in machining allowance on all machined surfaces, to establish primary machining datums for radial and axial features, to determine whether sufficient machining allowance exists on all surfaces, and to ensure that minimum design wall thicknesses are maintained throughout. In the raw state at layout, it is usually possible to compensate for the more normal and minor geometric deviations that occur without compromising the strength and/or stiffness of the structure. On the other hand, minimum design values for gear rim thickness and joint flange thickness should never be compromised, and these features are difficult to fix when they do not conform to design requirements.

Machine Tool Setups

Girth gears operate in the horizontal axis of rotation, firmly affixed to the rotating cylinder on which they are mounted. However, due to their mass and dimension, they are machined with the rotational axis set vertically. As a result, machine tool setups for individual segments, as well as for the assembled gear, must minimize the effects of externally applied forces, including gravity. For a typical one-piece gear, this would simply mean making sure that the rough component is supported properly and is not distorted by clamping forces. In our case, the girth gear and its individual segments are categorized as non-rigid components. By virtue of their size, weight, and proportions, this inherent structural flexibility is profoundly affected by gravitational force. Following this further, it is not difficult to imagine a girth gear that was not in a relaxed state during manufacturing, and then takes on a different geometric shape when its rotational axis is turned 90 degrees at installation.

The larger the structure, the more sensitive it is to external forces applied by both gravity and the workholding devices. The machine tool setup for each operation must take into account the real potential for geometric deformation from all external forces. Unfortunately, the effects of improper setups and inadequate process controls frequently manifest themselves in the late stages of manufacturing or, even worse, during installation and operation.

Correcting a modest out-of-round condition during installation is generally a simple task, but axial errors are an entirely different matter. During installation it is entirely possible to find a gear rim edge that looks like a lock washer, or a potato chip, or a wave washer, or a combination of these conditions. All of these conditions create installed wobble which translates into drunken lead and wandering contact. It is normally a straightforward task to correct a simple single sine wave condition by shimming axially under the mounting flange. However, attempting to correct one of the more complex, errant geometric shapes will generally produce high levels of frustration and limited improvement at best. This is due to the combined effects of a gear structure that possesses inherently low torsional stiffness and a gear rim whose axial stiffness far surpasses that of the mounting flange.

Let us say we are trying to correct a potato chip (double sine wave) condition during installation on the mill. The mounting flange can be shimmed to make it go almost anywhere you want it to go, but the response at the gear rim edge will be only small a fraction of the shim thickness inserted at the mounting flange. More radical shimming typically does little to improve the installed runout or the wandering contact pattern that it produces. Continue adding shims and the runout signature will change into something entirely different but also unacceptable. It's like a mechanical whack-a-mole game, you can push the bubbles around but you cannot meet the installed tolerance.

These types of built-in mechanical errors cannot be repaired in the field, and the cost of portable cranes, labor, transportation, rework, penalties, and lost revenue can add up to a spoiled annual report. Getting machine tool setups right in the first place requires sound planning and adequate time for execution, and the value of proper process controls and in-process checks cannot be overstated.

Machining of Datum Surfaces

The first machining operation for the raw gear segment is to cut the gear rim edge datum surface, making it a flat and reliable reference surface for subsequent operations. The rough gear segment must be landed on a sufficient number of carefully located support points to minimize the structure's natural tendency to elastically deform under its own weight, and to ensure equal weight distribution across all support points. Furthermore, the locations of, and the forces applied by, workholding devices must be planned and monitored to avoid unwanted elastic deformation. These goals can be achieved in various ways, some more scientific than others, but the results of any such process are measureable and must be verified by reliable means before proceeding to the next machining operation. In-process verification must be carried out with the gear segment properly supported, in the unclamped condition, and in a totally relaxed state.

Machining of Joint Flange Faces

For the majority of today's girth gears, and for the purposes of this discussion, the machined joint face angle is the same as the designed helix angle. This discussion therefore applies equally to spur and helical gears. And it is at this point that the expected gear rim thickness and final joint flange thickness are established. As noted earlier, joint regions and the joints themselves are the most frequent areas of structural failure. Assuming the structural design is adequate to begin with, conformance of the machined joint details cannot be over emphasized. Two factors are in play when joint surfaces are established, listed in order of priority as follows; 1) location relative to the gear rim inside diameter at mid-segment, and 2) final joint flange thickness. Said another way, joint flange thickness may finish up oversize, in order to preserve rim thickness, but it may never be allowed to go undersize. Oversize joint thickness only means that fastener hole spotfaces must go extra deep to maintain proper thread engagement.

Joint face machining will require the same precautions for setup accuracy, uniform weight distribution, and unstressed workholding techniques as previously described. Following the setup, the aim is to produce individual segments with joint faces that are flat, and with helix angles and subtended angles made complementary to their mating segments; all with a high degree of precision. Ideally, when the mating faces of joining segments are brought together, they should be capable of making intimate contact over their entire mating surface area without the need for external closing forces. As a practical matter, this "ideal" state of intimate contact is very difficult to achieve, but rest assured that the degree of angular complementarity of the mating faces will directly affect stresses in the assembly and the geometric accuracy of the gear during installation and in operation.

Joint face machining is accomplished by one of two basic techniques. The first technique employs a large diameter face milling cutter that is accurately inclined on the helix angle or mounting the split joint at the helix angle perpendicular to the face of the cutter. The cutter is then fed horizontally across the joint face for the number of passes required to machine the entire surface area. For each successive milling pass, the cutter is moved inward the amount needed to produce a flat angular surface with no steps at the lines of overlap with previous cutter pass. Poor mechanical alignment of the machine tool, or a face mill body that is insufficiently rigid, can cause multiple hollow spots, or wavy profiles, across the finish milled surface. A joint face that is not sufficiently flat will not seat tightly with its mate, and the tangential tooth buttress effect across the splits will be diminished. The second technique employs a large diameter ball end mill that is fed horizontally across the joint face. The cutter is repositioned in the Z-Axis, according to the helix angle, for each successive milling pass; the spacing of which is selected based upon the cutter's ability to produce a sufficiently flat surface with the given tool nose radius. Although joint face flatness is usually not a problem with this technique, mechanical error and backlash in the machine tool's individual axes of movement, or poor synchronization of the machine's interpolating axes can create errors in both the helix and subtended angles.

There is an alternate philosophy that says the actual sum of the machined subtended angles should be something less than 360 degrees. When joining segments with joints of this type for assembly, their mating faces will first make contact at the tooth root and exhibit a progressively widening gap moving inward toward the mounting flange. This produces a significant gap at the innermost point of interface. The underlying philosophy being that the interference angles provide enhanced joint tightness in the tooth root. However, the fastener preload expended in forcing the interference angles together reduces the clamp load under each fastener, at the joint interface, and causes the assembly to take on an unnatural geometric shape. It also causes alignment holes to assume a dogleg configuration at the interface, making the insertion of alignment hardware an unpleasant mechanical process.

In all cases, the designer should employ a technique known as "joint relief." This consists of relieving the rudimentary portion of the joint surface that resides inboard of the inner most joint hardware holes. This area serves no practical purpose with respect to joint integrity. It should therefore be milled below the working joint surface in order to prevent any potential problems it could otherwise create if left on the same plane.

Joint Alignment and Hardware

The joint hardware serves two purposes — to provide precision radial and axial alignment of segments during assembly, and to make the multi-piece assembly act as a monolithic structure during operation. There are normally two precision fasteners that provide alignment at each joint, with the balance of fasteners providing closing force only. Deep section gears may require a third alignment hole to reduce twist of the split. Joint hardware holes are machined parallel to the gear rim edge which, for a helical gear, means that they are not machined normal to the helix angle.

Alignment holes are very accurately placed and spaced, both radially and axially, as defined on the manufacturing drawing. They must also be precisely positioned relative to the axial datum surface on the gear rim edge. This latter requirement does not normally appear on the manufacturing drawing, but this absence does not mean that it can or should be ignored. If the positions of the otherwise properly spaced alignment hole patterns are not all machined on the same plane, the assembled gear may try to assume the appearance of a lockwasher or some other stepped configuration. This type of built-in error makes it impossible to assemble the gear in a relaxed state, and challenges the manufacturer's ability to provide a support system for subsequent operations that does not add further stress to an already unhappy structure.

Gear Blank Assembly

With all segments having flat datum surfaces, complementary joint face angles, and alignment hole patterns on the same plane and properly spaced, the gear segments should be ready for assembly. The first step is to prepare a proper assembly surface, the flatness of which should relate to the flatness tolerance specified for the gear rim edge and/or mounting flange face. A large machine tool table frequently serves this purpose, but there can be other options. For example, a very accurate and reliable setup surface can be established on the shop floor with carefully placed independent support blocks that are precisely adjusted onto the same plane throughout. The quantity, locations, and spacing of support points for the assembly operation are no less important than they were during the previously described machining operations. A common support should be utilized at each of the joint locations, straddling the split lines.

The individual segments are landed on the prepared assembly surface, one by one, and brought into initial contact with their mates. For a four segment gear, the first two mating quarter segments are brought together to make one half, with the same process applied to the second two segments, and the two assembled halves are finally brought together to make the full gear. Assuming the preceding machining operations were carried out with the necessary care, and once the hole patterns are brought into close visual alignment, the alignment hardware can be inserted with little resistance. With the mating faces making initial contact, and with no closing force applied, the split line gap is checked with feeler gauges to verify angular compatibility of the interface surfaces. Acceptance criteria of the maximum measured gap opening will depend on the gear diameter, facewidth, depth of section, and the designer's threshold of tolerance for inducement of unplanned stresses. In this case — and in the final analysis — basic mechanical knowhow goes a long way towards determining what is acceptable and what is not.

Joint hardware is tightened in planned sequence and at planned stages until the specified tightness has been reached throughout. Ideally the joint faces will make intimate contact over their entire joint surface area, but this is frequently not the case and is not an absolute necessity. For this reason joint tightness should be verified before proceeding with further processing. This test consists of trying to insert a feeler gauge with a maximum thickness of 0.0015" (0.038mm) around the entire perimeter of each assembled joint surface. The measured gap opening, the depth to which the opening extends, the location of the opening, and the area over which the discernible opening exists are the basic criteria utilized when evaluating an open joint condition. As in the previous case, there are no magical acceptance criteria. Basic mechanical knowhow and a good dose of common sense will assist the engineer in determining what is acceptable and what is not. A word of caution — the engineer should look critically at joint openings occurring in the tooth root. Depending on the length of the opening, the resulting loss of tangential buttress effect across the split can allow the first tooth on the trailing side to heel over under load and cause the pinion to find the second tooth early. This is a dynamic pitch error condition that can cause an audible "bump" during operation and, ultimately, can cause tooth failure — typically within the first two teeth on the trailing side.

Turning the Gear Blank

Most assembled girth gear blanks are finish machined on a vertical boring mill (VBM) and, for this reason, the following section pertains to the setup employed on that particular type of machine tool. Ideally, the gear blank will be setup such that all radial and axial features and dimensions can be finished in one setting. This ensures that all specified geometric relationships are produced to their best possible condition.

The first step is to prepare the work support system, the flatness of which should bear direct relationship to the flatness tolerance specified for the gear rim edge. The quantity, location, and spacing of support points utilized for turning the gear blank are no less important now than they were during the previously described machining and assembly operations. Passive restraint in both axial and radial directions is key during finish machining of girth gear blanks.

Clamps can be used during rough cutting operations, to ensure no movement of the piece during heavy cutting, but all finish cuts should be taken with clamps released and only gravity providing the downward restraining force. Chuck jaws may be used to center the piece radially, ensuring that minimum gear rim thickness is maintained throughout, and that all joint split lines are centered on their respective (yet to be cut) tooth roots. As a practical matter, split lines may reside anywhere below the design form diameter, which allows for ample radial adjustment in deference to gear rim thickness. Radial deformation of the gear blank must be avoided. All preload must be backed off during finish machining, while keeping the gear trapped to prevent any radial movement. Proper backing off of radial clamp force is most easily verified by monitoring structural relaxation via dial indicators placed next to each chuck jaw as they are being released. Finally, the gear blank must be restrained to resist any tendency to move tangentially, or circumferentially, due to the inertial changes in rotary motion during turning.

Lifting and Handling

Up to now, much focus has been placed on proper support and workholding to avoid elastic deformation during machining. Another real concern, frequently overlooked, is what happens to the assembled gear when it is lifted and transported between operations. During machining, we can add as many support points as we would like, but this is not the case with lifting. Girth gears are typically lifted by either two or four pick-up points depending on various factors; the more obvious of which being weight and diameter. Lifting tackle can consist of spreader bars, slings, chains, wire rope, or any combination thereof. Regardless of the number of pick-up points, the elastic deformation that takes place during a lift is breathtaking; it's like watching the piece unwrap itself from the floor. The biggest concern is the load that's placed on the joint hardware during a lift, loads that far exceed anything the gear will ever see in service. Putting this into perspective, it is not uncommon to find significant joint misalignment after lifting the finish machined gear blank off the vertical boring mill, and landing it on the gear cutting machine. This is caused by two factors working in tandem — 1) because the fasteners undergo temporary additional elongation during the higher lift loads, allowing the joints to open up due to lost clamp loads; and 2) because additional elongation of the alignment hardware causes necking of their alignment features and a temporarily sloppy fit. High helix angles, as well as the slippery nature of ductile iron, make these designs more susceptible to joint movement during lifting, while spur gears tend to be more stable. Regardless of the joint configuration and material, joint alignment should always be checked before tooth cutting, with the design engineer making technical disposition for any steps that are found.

Double Processing

Consideration for residual stresses plays a major role in the processing of segmented girth gears, significantly more so than with gears of one piece construction. Reason being, residual stresses in a typical one piece gear are rather homogenous and evenly distributed throughout the entire 360 degrees. On the other hand, it is usual for each girth gear segment to be poured from a different heat, to be heat treated individually, and then stress relieved in separate furnace loads. With no two segments having the same metallurgical properties and characteristics, one can imagine how multiple segments can react very differently, very independently, when large volumes of metal, measured in tons, are removed during machining. And due to sheer size and scale otherwise small deformations that occur during machining become major show stoppers when projected out over arc lengths approaching 70 feet (22 meters). The challenge now becomes one of ensuring that the finished gear segments, however many there are, will reassemble into a geometrically acceptable gear when installed on the machine it is intended to drive.

Thermal stress relief is an absolute necessity, as one might expect, but the net benefits of this process should not be overestimated. It is well known that residual stresses can be redistributed, even mitigated, but they cannot be eliminated. For example, in the case of a weldment, it is not uncommon for measured residual stress levels, after a satisfactory stress relief cycle, to be found at or near the material yield strength. This is clearly in excess of what it takes to cause significant geometric deformation during subsequent machining operations. Although multiple stress relief cycles are sometimes employed to achieve a more stable final condition, the effects of each thermal cycle are cumulative, which can cause further tempering and reduce hardness below acceptable levels.

One of the trickiest parts about manufacturing a girth gear is that tooth cutting releases and redistributes the inbuilt stresses that were both thermally and mechanically induced during the various preceding manufacturing processes. A simple way to envision the stress lines in a gear rim is to imagine them as existing like tree rings. A well-known axiom states that the last metal to cool following any thermal cycle will always reside in tension. And, with all forces seeking a natural state of equilibrium, it goes without saying that, conversely, the first metal to cool will always reside in compression. Following the tree rings of residual stress inward thru the gear rim, we pass from maximum compressive stress found at the outer and inner rim surfaces (addendum), to neutral stresses at both one-quarter and three-quarter thickness (pitch line), to maximum tensile stress at mid-thickness (dedendum). During tooth cutting, the compressive and neutral stress regions in the tooth volume are interrupted and nullified, while the compressive stress region opposite the tooth volume is still in compression, and there are no opposing forces remaining to balance the newly exposed tensile stress in the tooth root. The result being that each segment will open up (straighten out) to some certain extent when the gear is disassembled. Said a different way, when the gear is disassembled, the base pitch on each tooth space contracts slightly, which translates into an increased chord length for each gear segment. Given the number of teeth in play, the growth in chordal length can be dramatic; as much as ¾" (19 mm) over 180 degrees. The extent of actual dimensional change that takes place depends on numerous variables including gear diameter, depth of structure, number of teeth, gear material, rim thickness, and tooth depth relative to rim thickness.

The technique that is used to overcome these obstacles is called "double processing" which, as one might expect, consists of machining the entire gear twice. The joint features are semi-finished, the gear is assembled with non-precision process hardware, the assembled gear is then semi-finish turned and the teeth are rough cut. After this, the gear is disassembled, joint features are finish machined, the gear is reassembled with service hardware, finish turned, and the teeth are finally machined to design requirements. To validate the final result, an "open joint inspection" is performed with the gear in a properly supported, unrestrained, fully relaxed condition. Multiple dial indicators, placed in close proximity to one joint, are used to measure the relative movement across that joint while the fasteners are being released. As stated in previous sections, there are no magic acceptance criteria for this test either. Generally speaking, if the alignment hardware can be reinserted without the need for undue external forces, and providing that acceptable joint alignment and tightness are achieved after the fasteners are re-tightened to spec, the gear should be good to go. It should be noted that double processing is not necessary in all cases, and different manufacturers have their own formulae for determining whether double processing should be part of the initial manufacturing plan. However, whether or not the gear is double processed, an open joint inspection should be performed on every finished girth gear; the aim being to gain assurance that the gear can be reassembled and installed, in the field, within the published installed tolerances for radial and axial runout.

Tooth Cutting

If we have implemented the recommendations up to now, then we will have a good gear blank worthy of tooth cutting, and the foregoing concerns for proper support and clamping must carry on to the gear cutting machine. From the grinding mill's perspective the mounting flange is the critical datum, but the gear rim edge is no less important because 1) it is assumed to be parallel to the mounting flange, 2) it is assumed to be perpendicular to the pitch cylinder, and 3) because it is the reference surface for measuring axial runouts during installation.

If the axial and radial runouts were acceptable, while in a relaxed state on the vertical boring mill, then it is merely a case of duplicating those runouts, as close as possible, when setting up on the gear cutter. In any event, the installed runouts on the gear cutter should fall within the geometric tolerances specified on the manufacturing drawing, paying particular attention to the mounting flange to rim edge relationship. However, unlike the vertical boring mill operation, cutting forces encountered during tooth cutting will necessitate secure clamping for both rough cutting and finish cutting, and design runouts must be achieved with all supports and clamps fully tightened.

Modern Manufacturing Technology

The girth gear business is very competitive and manufacturers are embracing new technology out of sheer necessity. The machine tool, cutting tool, and supporting software industries are responding to this demand with entirely new designs and concepts, as well as the adaptation of existing non-gear-making technology to suit the gear making industry. Girth gears which, 20 years ago, might have required eight or more machining operations for completion, are being successfully machined today in nearly half as many setups. Although these refinements are intended to improve both efficiency and quality, the need for in-house expertise is no less important today than it has ever been in the past. In short, new technology makes manufacturing easier and quicker, but it does not guarantee good quality. Modern machine tools, cutting tools, and supporting software are no smarter than the people who purchase and utilize them. If the design engineer does not understand the application, or does not properly define the necessary requirements; if the manufacturing engineer lacks the necessary respect for mass, elasticity, and residual stresses; if assembly and setup equipment consists of slugging wrenches and large hammers; if the machine tool operator and the inspector do not respect the drawing callouts; then a good quality outcome is unlikely regardless of the technological state of art.

Case Study — Due Diligence Failure

The following facts and supporting data relate to a two-segment, ~20-foot (~6 meter) diameter girth gear. These are intended to illustrate the potential downstream effects of previously described failures of due diligence.

The gear in question was produced with incompatible joint angles. This angular incompatibility, caused by inadequate support and excessive workhold-

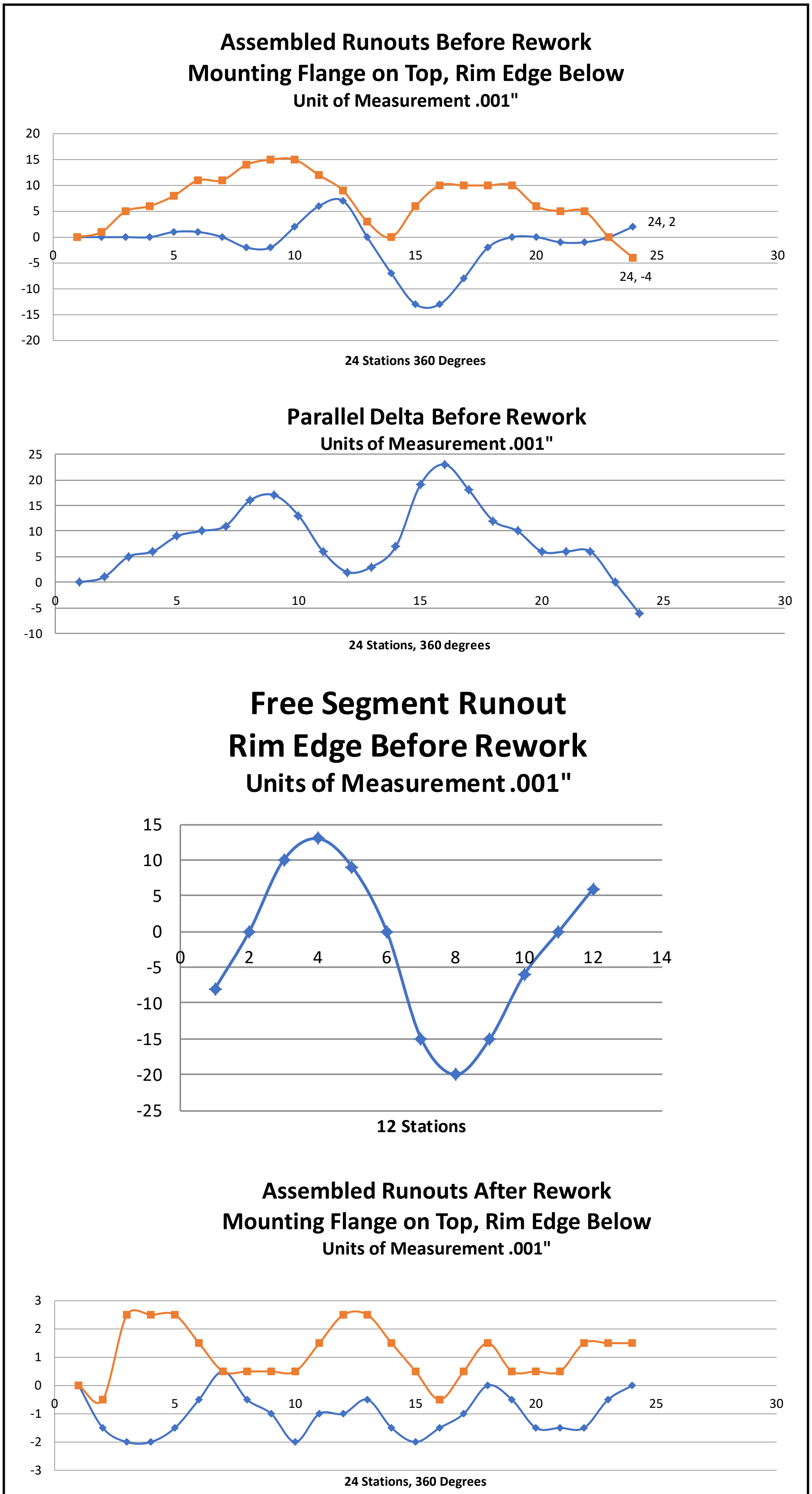


Figure 3 Axial runout measurements pursuant to investigation and rework. (Printed with permission of the American Gear Manufacturers Association).

ing force, exceeded .040" (1 mm) in the helix angles and the subtended angles of both joints.

The gear blank was then assembled into an unhappy, pre-stressed condition in preparation for turning. The workpiece support system and workholding forces applied during turning further complicated the gear blank's already pre-stressed condition. Runouts after turning were measured with the gear still in its clamped condition, making it impossible to detect the magnitude of the induced errors up to this point.

The finish turned gear blank was then mounted on the gear cutting machine, disregarding the geometric tolerances applied to the datum surfaces. And, finally, an open joint inspection was not performed after tooth cutting.

In addition, the gear did not undergo double processing, but the effects of this omission cannot be reasonably quantified due to the magnitude of the other errors that occurred along the way.

The following axial runout measurements (Fig. 3) were collected during the subsequent investigation and rework operations (Figs. 4–5). All measurements were taken with the gear properly supported and resting in a relaxed state of repose.

In order of presentation, the first chart depicts the mounting flange and rim edge runouts, and their interrelationship, as-manufactured. The second chart depicts the parallel delta between these two key features. The third chart illustrates the relaxed condition of one free segment, properly supported and completely unrestrained during measurement. The last chart depicts the mounting flange and rim edge runouts, and their interrelationship, following rework. In this final condition, the gear was installed well within the required installation tolerances and with minimal effort.

Summary

It is important to understand that excellent material quality and extreme tooth accuracy have limited value when the gear's pitch cylinder sees excessive wobble and cranking with each revolution. Girth gear structural designs are, out of necessity, a compromise in terms of stiffness of the discreet component. As a nonrigid structure, the girth gear relies on the driven machine to provide its structural backbone, and this reality presents unique challenges in manufacturing; a time during which this backbone does not exist.

The effects of gravity and clamping force, when not properly managed, can cause elastic deformation of dramatic proportions. Left unchecked, the described deformations will cause installed wobble of the pitch cylinder, wandering contact, and overloading in areas of short contact. Machine tool setups are of paramount importance in minimizing the effects of external forces on the girth gear's structure.

The presence of residual stresses is an important consideration, particularly since each gear segment possesses its own unique metallurgical characteristics. Although thermal stress relief offers a certain degree of stability, it does not preclude geometric deformation caused during machining, and particularly during tooth cutting. For this reason, special processing techniques are frequently employed to minimize the real effects of redistributed stresses.

Finally, the overall goal is to produce a girth gear that is geometrically correct when it is in a fully relaxed state (Fig. 6). A happy gear is one whose pitch cylinder and datum surfaces possess acceptable geometric features and relationships while resting in a fully relaxed state; it must reassemble and install accurately in the field, closely reproduce contact patterns observed in the workshop, and provide uniform load distribution during operation.

Figure 4 **Prepping girth gear segment for reworking.**

Figure 5 **Unassembled segments for 34' (10.5 meters) 4-piece girth gear.**

Figure 6 **Finished 40' (12 meter) 4-piece girth gear.**

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Inclusion-Based Bending Strength Calculation of Gears

Jonas Pollaschek, Christoph Löpenhaus, and Christian Brecher

Today's resource-efficient machine elements provide design engineers with real opportunities—and challenges. Reduced component weight and ever-increasing power densities require a gear design that tests the border area of material capacity. To embrace the potential offered by modern construction materials, calculation methods for component strength must rely on a deeper understanding of fracture and material mechanics in contrast to empirical analytical approaches.

The aim of lightweight designs in drive technology—particularly in relation to E-mobility—can lead conventional design methods towards larger-dimensioned and therefore heavier gears. Calculation methods that empower an accurate depiction of local load and material properties are able to safely push the boundary of gear design into areas that are closer to the ultimate fatigue limit of the material and help to conserve resources that way. For this reason, the aim of this report is to prove a general applicability of the higher-order calculation approach developed by Henser for all gear geometries and material properties. This method will allow for more cost- and weight-effective gear design in the future.

A two-step approach shows the accuracy of the enhanced weakest link model by validation on a small-module helical gear, and a parameter study proves the effectiveness of the enhanced weakest link model by showing the influences of different sized gear geometries and material properties on calculated bending strength. In addition, the main influence parameters on the model and material properties that have different effects depending on gear size are identified.

Introduction and Motivation

The trend of resource-efficient machine elements poses new challenges for design engineers.

Reduced component weight and ever increasing power densities require a gear design on the border area of material capacity (Fig. 1). In order to exploit the potential offered by modern construction materials, calculation methods for component strength must rely on a deeper understanding of fracture and material mechanics in contrast to empirical-analytical approaches. Conventional methods for bending strength complying gear design are experience-based and rely on calculation methods corresponding to standards (Refs. 1–3). In these standards simplifications and analogies are used to gain general validity, without being explicitly validated for all possible gears within the entire design range. Thus, all of these norms reduce the geometry of the designed gear to a standardized reference gear set which has a large database of test results. An advantage of this method for the global load capacity analysis is the ability to derive quickly applicable analytical equations for calculating the load capacity. A disadvantage is the generally too safe gear design and caused by the necessity to ensure that the estimation used in the standard will not lead to a premature component failure.

The efforts in drive technology for lightweight construction—particularly in regard to eMobility—does not allow for conventional design methods excluding higher-order calculations, since the estimations of the conventional designing would lead to larger and therefore heavier gears. Calculation methods that precisely describe gear geometry, load and material properties are furthermore able to determine local stresses and push the gear design closer into areas closer to the limits of nominal material strength in order to save resources. For that reason, the objective of this report is to verify the general validity of the higher-order calculation approach that considers the materials technology, fracture mechanics and FE-based tooth contact analysis developed by Murakami and Henser and show any model limitations.

State of the Art

Gears are one of the most stressed components of drive technology and consequently have the highest requirements on bearing capacity behavior. The method of choice for increasing the load capacity of gears is strengthening the surface area of the gear material. This results in a depth-dependent property profile of the material. Hardness and strength of the surface layer may be three times greater than the core material (Ref. 4). For the majority of gears being used for power transmissions, for instance in vehicles, case hardening is used as a method for creating surface layers of highest strengths (Ref. 5).

Influencing factors on tooth root strength. The tooth root load carrying capacity of cylindrical gears is determined by comparing two distinct properties. On one side, there is the nominal strength of the material the gear is made of, which will be referred to as the material-specific complex. In contrast to this, there is the strain on the gear, referred to as the geometric-functional complex. The ratio between these two factors determines the load carrying capacity of a gear in the form of a safety factor. The wide variety of influencing factors on these two properties can be seen in Figure 2.

Strain. The strain of a gear is determined by its geometric design, its manufacturing, its assembly as well as its field of appliance. In the following section, the influencing factors

This paper was first presented at the 6th WZL Gear Conference USA, June 28, 2016.

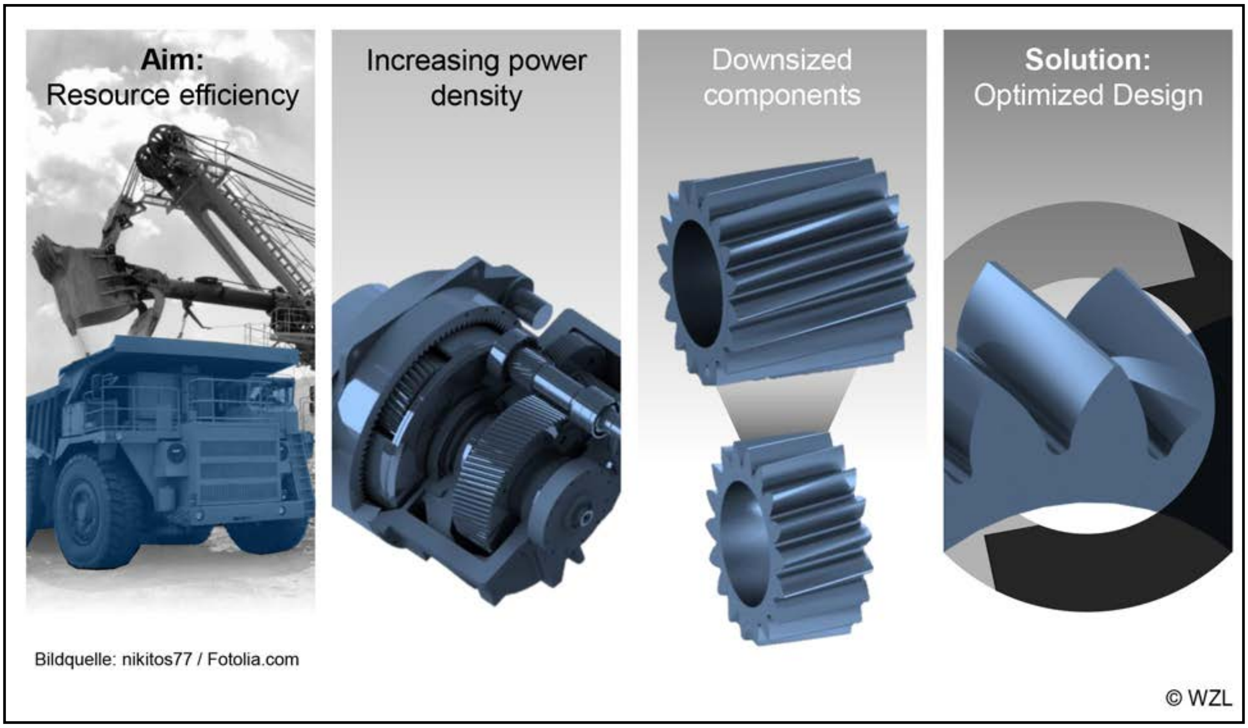

Figure 1 Resource efficiency via optimized design methods.

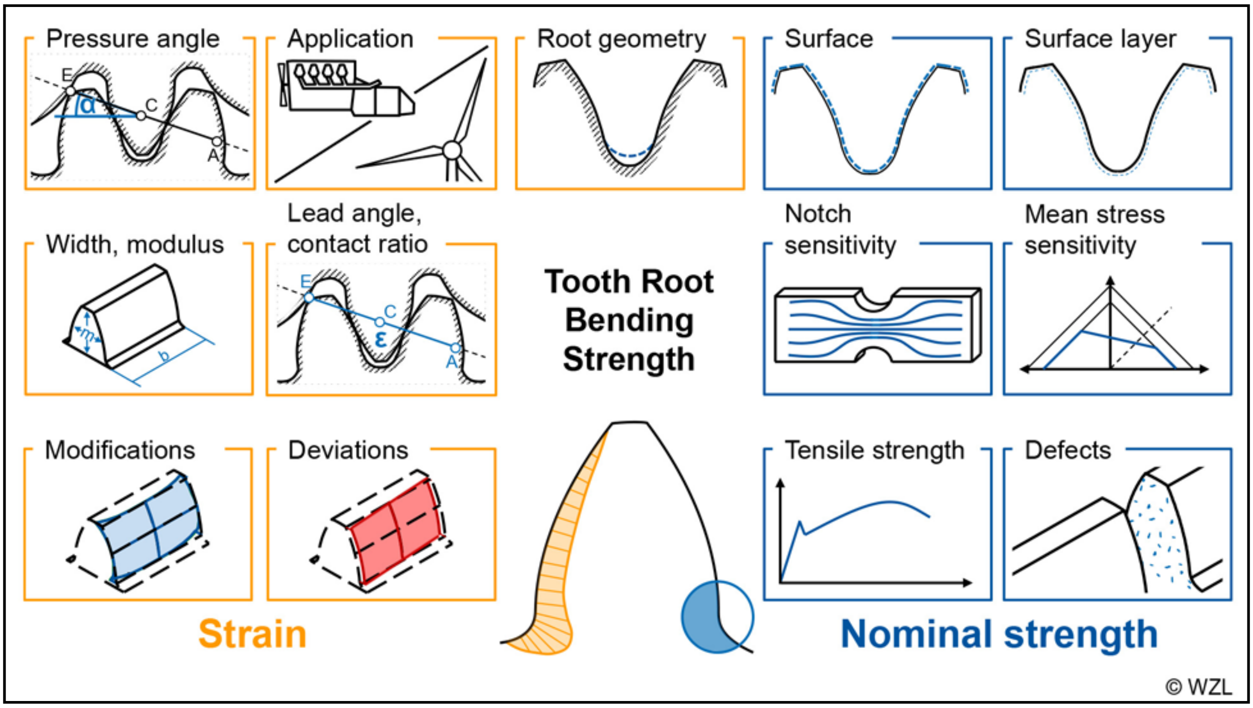

Figure 2 Influencing factors on tooth root load carrying capacity.

summed up in Figure 2 are discussed.

The designed normal pressure angle α_n as well as the effective pressure angle in contact α_{wt} are determining the division of the tooth force into tangential and radial force. The tangential force is creating the bending torque and finally the bending stress in the tooth root itself (Ref. 3).

Normal module m_n and face width b are directly influencing tooth root bending strength. A wide tooth can bear greater forces than a narrow one, because the second moment of inertia is increased. With increasing module, the tooth thickness and with it, the second moment of inertia increases which allows for a greater force to be borne (Ref. 3).

Tooth flank modifications and flank deviations due to manufacturing errors affect the load distribution on each individual tooth. An uneven load distribution leads to locally concentrated contact pressure and root stress. Locally increased stressed can lead to premature failure of the tooth root at the affected location. Therefore, it is mandatory to consider flank modifications and deviations when calculating tooth root bending strength.

The chronological course of tooth load is determined by the application the gearbox is used in. Loads can be homogenous, as for example in turbo gearboxes in power plants, or inhomogeneous, as for example in wind turbines. Fluctuations of torque at the interfaces of a gearbox as well as inside the gearbox due to dynamic effects can severely reduce the load carrying capacity of the gears and therefore the lifetime of the gearbox. (Ref. 3)

The contact ratio defines how many teeth are in contact during mesh at the same time. Generally, a higher contact ratio means higher load carrying capacity because the gear forces are split up between more teeth. Contact ratio is gained by elongating the contact line. This can be accomplished by designing more slender teeth that have a deeper mesh and therefore increase the profile contact ratio ε_α. This leads to thinner tooth roots which can have an opposing effect to tooth root bending strength. The same goes with increasing the overlap ratio ε_β. More overlap ratio means a higher degree of force distribution along a number of teeth, but also leads to thinner tooth profiles in transverse section. This can again weaken the tooth root due to reduced thickness. The ideal contact ratio for tooth root bending strength always has to be a trade-off between force distribution and tooth root thickness.

The contour of a gears tooth root fillet determines how much of a notch-effect is being posed by the tooth slot itself. Conventional manufacturing creates a trochoidal tooth fillet. This does not represent the optimum shape for decreasing the notch that is the tooth slot. Therefore, tooth root optimization in combination with non-conventional manufacturing processes can lead to significantly increased tooth root bending strength (Refs. 6–9).

Nominal strength. The nominal strength of a gear is determined by the choice, the thermo-mechanical treatment, the quality and diverse alterations of the material both before and in application. Analogous to the above explanations (*Strain*), this section will describe in greater detail the single influencing factors on nominal gear strength.

The ultimate tensile strength is defined by the stress that occurs inside the material of a specimen during a tensile test before it fails. This value sets the baseline for the general strength of gearing materials. Gears from materials with high, ultimate tensile strength fail at higher loads than gears from materials with low tensile strength under same conditions.

The mean stress sensitivity describes how much the load carrying capacity of a material is reduced when it is exposed to alternating loads. The mean stress sensitivity can be derived from the materials hardness. Therefore, brittle materials react more sensitively to alternating loads than ductile materials. Investigations of the mean stress sensitivity of case hardened steels depict a mean stress sensitivity of $M = 0.7–0.8$. (Refs. 10–11).

The notch sensitivity of materials describes how their strength is reduced by locally increasing stresses due to shape alterations of the part or specimen. For example, shape alterations can be shoulders, undercuts and recesses on shafts, as well as tooth slots in gears. Every location of a part where local curvature is being altered can be seen as a notch in the sense of a concentrating factor for stresses in the material. Notch sensitivity increases with increasing material hardness (Refs. 11–12).

A gearing material should have a hard, high-strength surface to endure high-contact pressure in the tooth contact. Apart from that, the core of the material should be ductile and elastic to compensate for impacts and to slow down crack propagation, as well as equalize toothing errors through limited, elastic deformation. The measure of choice to create a material that fulfils these requirements is case hardening, where the part gets heated under carbon atmosphere and then quenched to create a martensitic surface layer. This procedure can, however, reduce material strength of the surface layer if not conducted correctly. As an example, impurities can enter the surface layer if the part has not been cleaned accordingly. These impurities generally reduce the surface layers strength. A case hardened layer that is too thick due to a too long carburizing process increases the danger of brittle material failure at the tip of the tooth. Therefore, the correct process parameters have to be set and monitored before and during case hardening (Ref. 13).

During the finishing of the gear's surface, certain structures are created. The depth, orientation and geometrical manifestation of these structures are depending on the chosen manufacturing process, the process parameters as well as the used materials for workpiece and tool. An influence on the surface in the tooth root area are feed marks and generated cut deviations from the hobbing process. These surface deviations can lead to local stress amplification and, therefore, to reduced load carrying capacity. In addition, during grinding of the tooth flank notches can be generated in the tooth root; these notches can reduce tooth root bending strength significantly (Ref. 14).

Calculation methods for tooth root bending strength. The proof of load carrying capacity is one of the most elementary steps during gear design. It delivers the basis on which the subsequent optimization of noise and vibration behavior or mesh efficiency can be carried out. Common key figures to describe flank, root, and scuffing safety according to standards such as ISO 6336 are the safety factors S_H, S_F and S_S. To determine these factors, the material strength is compared to the occurring strain. Both of these figures can be calculated through analytical-empirical approaches or by higher-order calculation approaches such as finite element analysis (FEA). The calculation approach via standards is most common with manufacturers of industry and wind power gearboxes; an increasing number of companies use FEA to model gearbox systems. FE approaches have the distinct advantage of exactly representing surrounding and structure stiffnesses when calculating damage-relevant strains of parts. In the following sections the calculation approach using standards such as ISO 6336 or AGMA 2001-D04, as well as higher-order approaches are discussed.

Standardized methods. Conventional design methods rely on standardized methods to calculate safety factors against tooth root breakage, pitting and scuffing. The calculation approach for tooth root safety S_F according to ISO 6336 is based on conventions and abstractions that are required for a standardized approach. The tooth root load carrying capacity is determined by the maximum tensile stress, or the maximum tangential stress, in profile direction respectively. Fatigue fractures are usually starting from the 30° tangent in the tooth root fillet on the tensile-strained flank. The basic principle behind the standardized approaches is the beam theory. Influences on tooth root bending strength that are not covered by the relatively simple beam approach are considered through correction factors (Refs. 2–3).

In the following paragraphs, the proof of load carrying capacity for cylindrical gears according to ISO 6336-3 "Method B" is presented. In the ISO standard, methods are sorted in ascending order based on their calculation accuracy. Following this logic, "Method A" is the most accurate, but also the most elaborate method. The standard mentions FE-analysis and experimental investigations as suitable for an approach according to "Method A." Methods B through D are based on empirical-analytical equations derived from extensive testing. The main equation to determine tooth root safety is displayed in Equation 1; load carrying capacity is ensured if the safety factor S_F is greater or equal to 1.

$$S_F = \frac{\sigma_{FP}}{\sigma_F} \tag{1}$$

S_F [-] Safety against tooth breakage
σ_F [N/mm²] Occuring tooth root stress
σ_{FP} [N/mm²] Permissable tooth root stress

The term σ_{FP} describes the permissible bending stress in the tooth root. It is determined via extensive and standardized running tests of a reference gear set. To calculate σ_{FP}, Equation 2 is used.

$$\sigma_{FP} = \sigma_{Flim} \cdot Y_{ST} \cdot Y_{NT} \cdot Y_{\delta\,rel\,T} \cdot Y_{R\,rel\,T} \cdot Y_X \tag{2}$$

σ_{FP} [N/mm²] Permissable bending stress
σ_{Flim} [N/mm²] Fatique stress of the standard gear
Y_{ST} [-] Stress correction factor
Y_{NT} [-] Life factor
$Y_{\delta\,rel\,T}$ [-] Relative notch sensitivity factor
$Y_{R\,rel}$ [-] Relative surface factor
Y_X [-] Size factor

The term σ_F describes the occurring tooth root stress; it is to be calculated according to

Equation 3.

$$\sigma_F = \frac{F_t}{b \cdot m_n} \cdot Y_F \cdot Y_S \cdot Y_\beta \cdot Y_B\, Y_{DT} \cdot K_A \cdot K_V \cdot K_{F\beta} \cdot K_{F\alpha} \tag{3}$$

σ_F [N/mm²] Occuring tooth root stress
F_t [N] Nominal tangential force
b [mm] Face width
m_n [-] Normal module
Y_F [-] Form factor
Y_S [-] Stress correction factor
Y_β [-] Helix angle factor
Y_B [-] Rim thickness factor
Y_{DT} [-] Deep tooth factor
K_A [-] Application factor
K_V [-] Internal dynamic factor
$K_{F\beta}$ [-] Face load factor
$K_{F\alpha}$ [-] Transverse load factor

Higher-order methods. In contrast to commonly used empirical-analytical methods for proof of tooth root load carrying capacity, higher-order methods provide a local analysis of strength. Based on FEA, the local strain can be exactly evaluated in every spatial direction and therefore also along material depth. When local strain is faced with local material strength, a prediction of local survival probability can be made.

One approach of calculating load carrying capacity of machine elements is the weakest link model which has been developed by Weibull in 1959 to depict failure of ceramic parts. It states that defects are statistically distributed inside the volume of a part can cause cracks to start and therefore failure of the part to be induced. Defects are defined as all inhomogenities of the material structure; this also includes surface roughness. If the strain at one of these defects excesses the bearable strain, a crack starts. An occurring crack propagates in just a few load cycles and ultimately leads to the part's failure. The statistical distribution of defects is based on the Weibull Distribution — which is named after Weibull (Ref. 15).

Hertter develops a model to calculate local flank and root load carrying capacity of gears. To calculate the tooth root load carrying capacity, he uses a modified form of the normal stress hypothesis as well as the local material strength according to the Goodman diagram based on material hardness (Ref.16).

Stenico considers local tooth root load carrying capacity of case hardened gears based on experimental determined characteristic values and empirical factors. He uses a material-based approach derived from the fracture mechanical Kitagawa diagram. This approach considers local material parameters as well as residual stresses in a two-dimensional space. To calculate the strain he uses commercial FE systems. He validates his calculations by experiments (Ref. 17).

The original weakest link model by Weibull is not capable of calculation load carrying capacity for inhomogeneous material properties. Bomas, et al expand the approach by the consideration of inhomogeneous materials using the example of case hardened steel. The weakest link model is established and solved locally which represents a novelty. By multiplying the local survival probabilities, a prediction of the part survivability can be made (Ref. 18).

Murakami introduces the aspect of defect size when formulating his weakest link model. He describes an empirically founded connection between local part hardness, defect size and the derived local fatigue limit under alternating stress σ_W following Equations 2–4 for volumetric defects and Equations 2–5 for surface defects. The characteristic value **type-set** = ***area*** describes the square root of the perpendicularly projected, largest cross-section of the defect onto the plane of principal stress. He validates his method with extensive tests (Ref. 19).

$$\sigma_W = 1{,}43 \cdot \frac{HV + 120}{(\sqrt{area})^{1/6}} \cdot \left(\frac{1-R}{2}\right)^\alpha \tag{4}$$

$$\sigma_W = 1{,}56 \cdot \frac{HV + 120}{(\sqrt{area})^{1/6}} \cdot \left(\frac{1-R}{2}\right)^\alpha \tag{5}$$

$$\text{with } \alpha = 0{,}226 \cdot HV \cdot 10^{-4} \tag{6}$$

σ_W [N/mm²] Fatigue strength
R [-] Stress ratio
$\sqrt{area}$ [µm] Defect size
HV [HV] Vickers hardness
α [-] Exponent for mean stress sensitivity

Brömsen and Zuber develop a program to calculate the bending strength of any tooth root geometries that combine local load carrying capacity, according to Velten (Ref. 20), with the statistical weakest link model, according to Weibull.

Henser develops a local model for tooth root bending strength that is based on the Zuber's work, which is then extended with the defect size-dependant local alternating stress fatigue

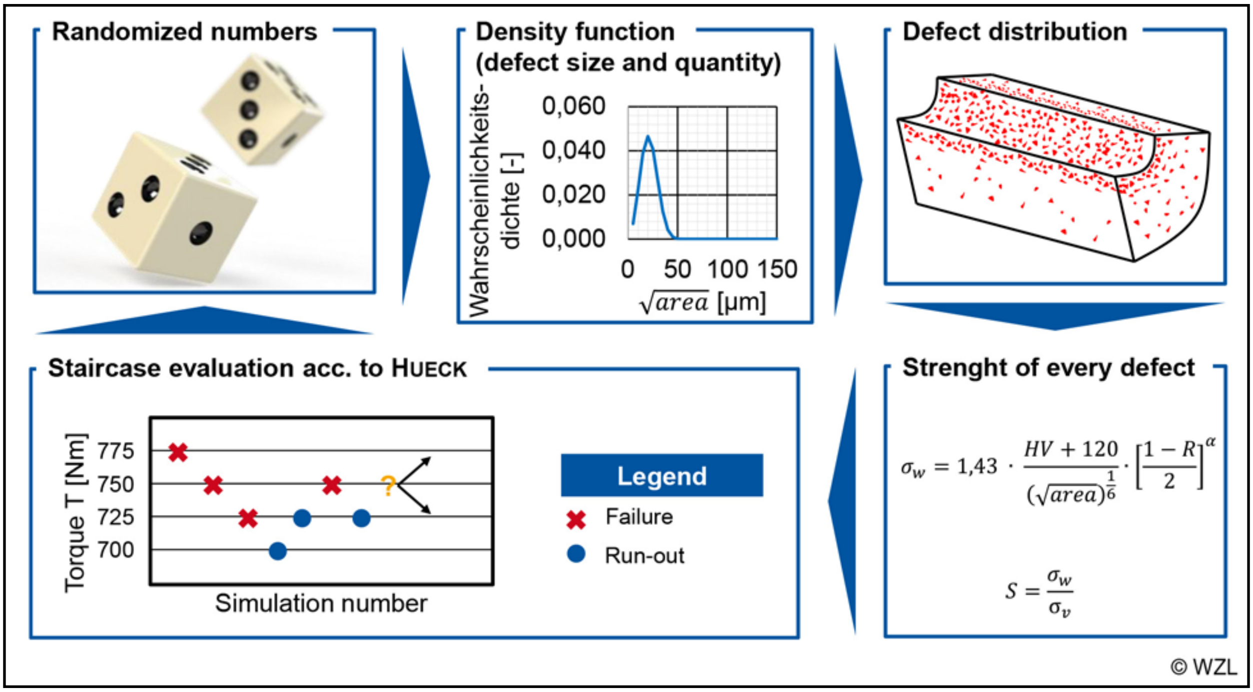

Figure 3 **Calculation approach for local tooth root bending strength (Ref. 15).**

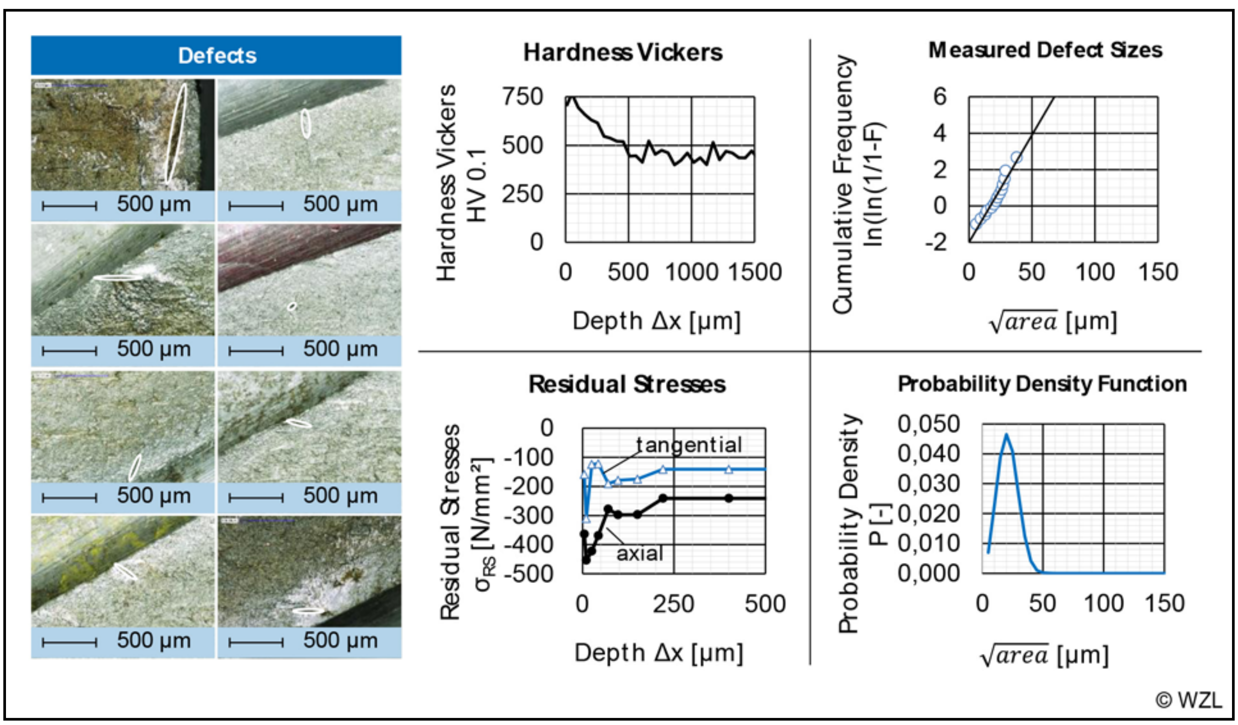

Figure 4 **Material data and defect distribution of cylindrical helical gears.**

limit, according to Murakami. The calculation method is based on the stress tensors in the tooth root area of the considered gear that are provided by the FE-based TCA. The strain state that is derived from the stress tensors is compared to the local fatigue strength of every defect inside and on the surface of the considered volume. The defects are generated by a random number generator in combination with a Weibull distribution. After it is decided for each defect whether or not it leads to a failure of the gear, the input torque is being decreased or increased according to the staircase method by Hueck. If one of the local safeties on each defect reaches a value of $S_{lok} < 1$, this is rated as a failure of the whole gear according to the model. If one tooth root has been evaluated, the next calculation begins for a new defects distribution. This calculation loop is shown in Figure 3.

Validation of the enhanced weakest link model. In the following section a validation of the enhanced weakest link model for tooth root load carrying capacity is conducted and presented. A helical gear set of module $m_n = 1.75$ mm is investigated on a running test rig. Analogous to the tests, a simulation with the enhanced weakest link model is conducted on the same gear geometry. Material properties such as hardness profile, residual

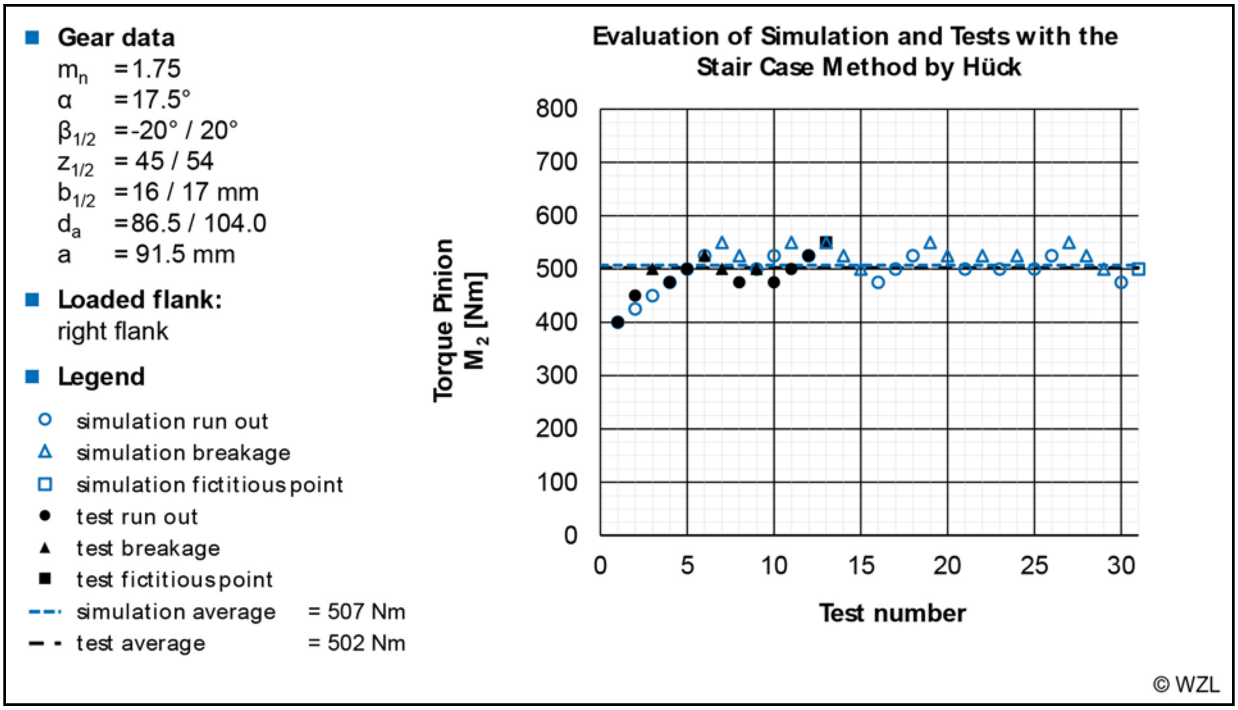

Figure 5 Comparison of simulation and test result for variant with β = 20° helix angle.

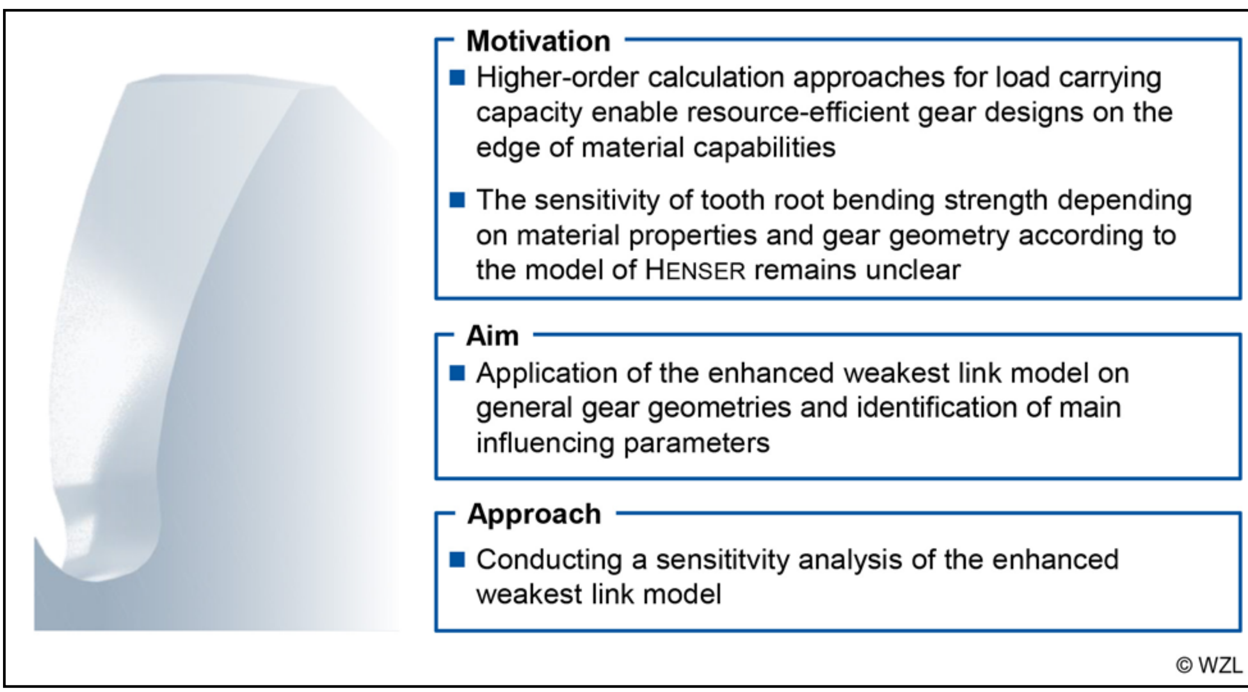

Figure 6 Motivation an approach.

stress profile and defect distribution were measured and used as the input for the simulation model; material properties are shown in Figure 4. The Vickers hardness has been evaluated for a transverse cross-section of a single specimen in the tooth root area starting from the 30° tangent (upper left diagram of Fig. 4). The residual stress profiles have been determined similarly via X-ray diffraction (Fig. 4, lower left). For better accessibility to the root area of the teeth, specimens have been cut out of the whole gears using electrical discharge machining (EDM). The defects have been measured and counted at the breakage surfaces of the gears that showed damage during the running tests (Fig. 4, left and upper-right). The counted and measured defects have been used to derive a Weibull distribution that describes defect size and quantity (Fig. 4, lower right). With these measured material properties all input parameters for the enhanced weakest link model according to Henser.

The resulting fatigue torques of the running tests are compared with the simulated fatigue torques (Fig. 5). The correlation between simulation and real life investigation can be rated as very high. The difference between simulated and tested fatigue torque is 5 *Nm*, which corresponds to a relative difference of 0.98%. This result validates the enhanced weakest link model

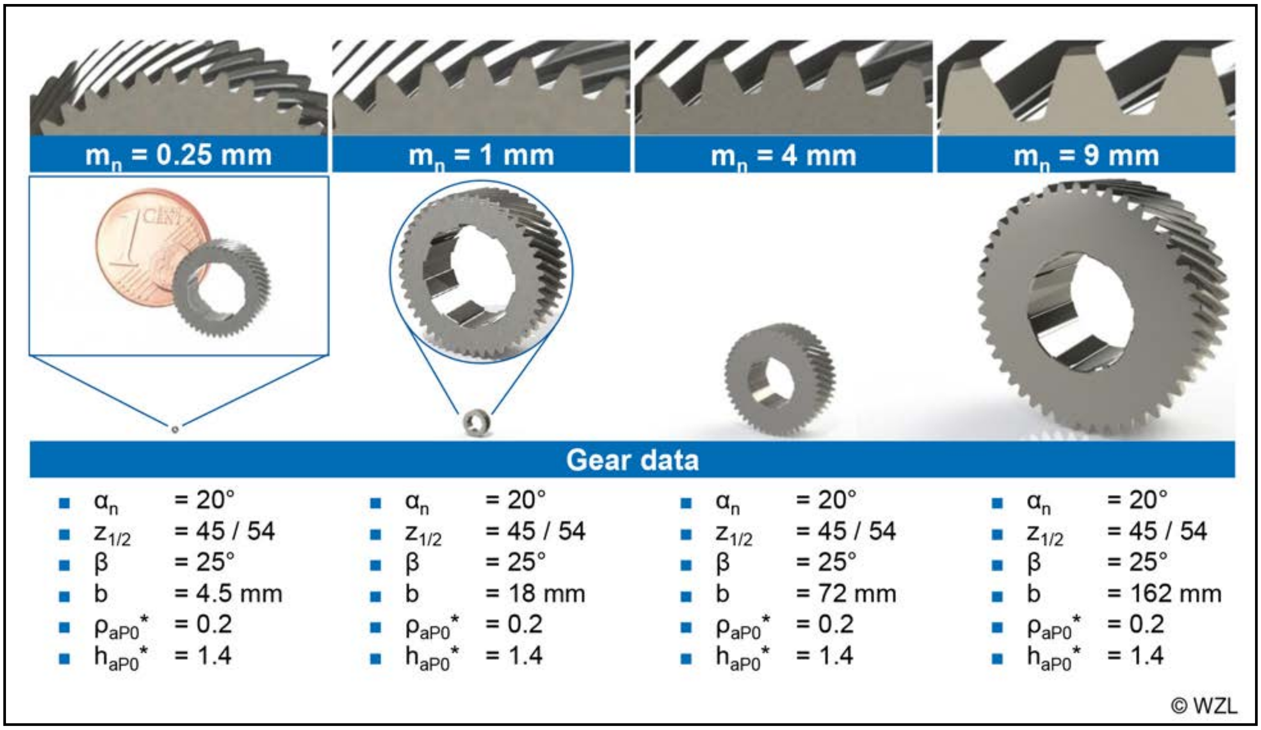

Figure 7 Variation of gear size by varying normal module and face width.

for determining the tooth root load carrying capacity of helical gears with a module of $m_n \approx 2$ mm and a case hardened surface layer.

Objective and Approach

The state of the art shows that local methods for calculating load carrying capacity based on the enhanced weakest link model show very good results for simple specimen as well as beveloid gears of module $m_n \approx 2$ mm. A continuing validation for helical gears and an analysis of the model concerning other gear sizes and an extended variety of material properties is necessary to further broaden the model understanding and expand its area of application.

The aim of this report is to determine the influence of single model parameters on the enhanced weakest link model by conducting a systematic parameter study for different sized helical gears (Fig. 6). The parameter study is preceded by a validation of the enhanced weakest link model for tooth root load carrying capacity for a helical gear of module $m_n = 1.75$ mm. The parameter study itself is based on a selection of input parameters for the model that define the parameter space. A succeeding analysis of the model outputs helps identifying the most relevant input parameters and answers the question whether the calculation approach is a suited tool for resource-efficient gear design.

Sensitivity Analysis of the Enhanced Weakest Link Model

With the validation of the enhanced weakest link model for a certain investigated helical gear set (Validation of the Enhanced Weakest Link Model), a sensitivity analysis concerning the variation of material properties and gear size is a suitable next step to further increase model understanding.

Definition of the design space. The investigated gears are shown in Figure 7. The range of gear sizes has been set to modules smaller than the validated example and higher than the validated example to show a wide spectrum of teeth volumes. The volume of the teeth is an important factor when calculating the statistical distribution of defects inside the material and therefore influences load carrying capacity directly. The gear sizes are ranging from module $m_n = 0.25$ mm up to $m_n = 9$ mm. The face width of the gears is adjusted to match the module with a fixed ratio of $b/m_n = 18$. The number of teeth, as well as all other geometric parameters, are not changed to maintain comparability between the gear variants during the parameter study.

In addition to a range of gear sizes, a systematic variation of material parameters for the enhanced weakest link model is conducted. All six material parameters that serve as input for the model are variated. The parameters are surface hardness, hardness depth-profile, residual stress amplitude, residual stress depth-profile, defect quantity and defect size. A summary of the varied parameters can be seen (Fig. 8) for the investigated gear set of module $m_n = 1$ mm. In addition, the case-hardening-

Table 1 Nominal case-hardening depths (Ref. 22) for investigated gear variants

Normal module m_n [mm]	Recommended CHD_{550} [mm]	Choice [mm]	Scaled to m_n
0,25	none	0,09 (extrapolated)	0,36
1,00	0,1—0,275 (extrapolated)	0,275	0,275
4,00	0,53—0,81	0,65	0,1625
9,00	1,1—1,6	1,275	0,1417

Table 2 Maximum nominal residual stress values and nominal depths of maximum values

Normal mo- dule m_n [mm]	Tangential nominal res. stress value σ_{Etan} [N/mm^2]	Axial nominal res. stress value σ_{Eax} [N/mm^2]	Nominal depth [μm]
0,25	- 310,1	- 453,4	2,23
1,00	- 310,1	- 453,4	6,89
4,00	- 310,1	- 453,4	16,07
9,00	- 310,1	- 453,4	31,53

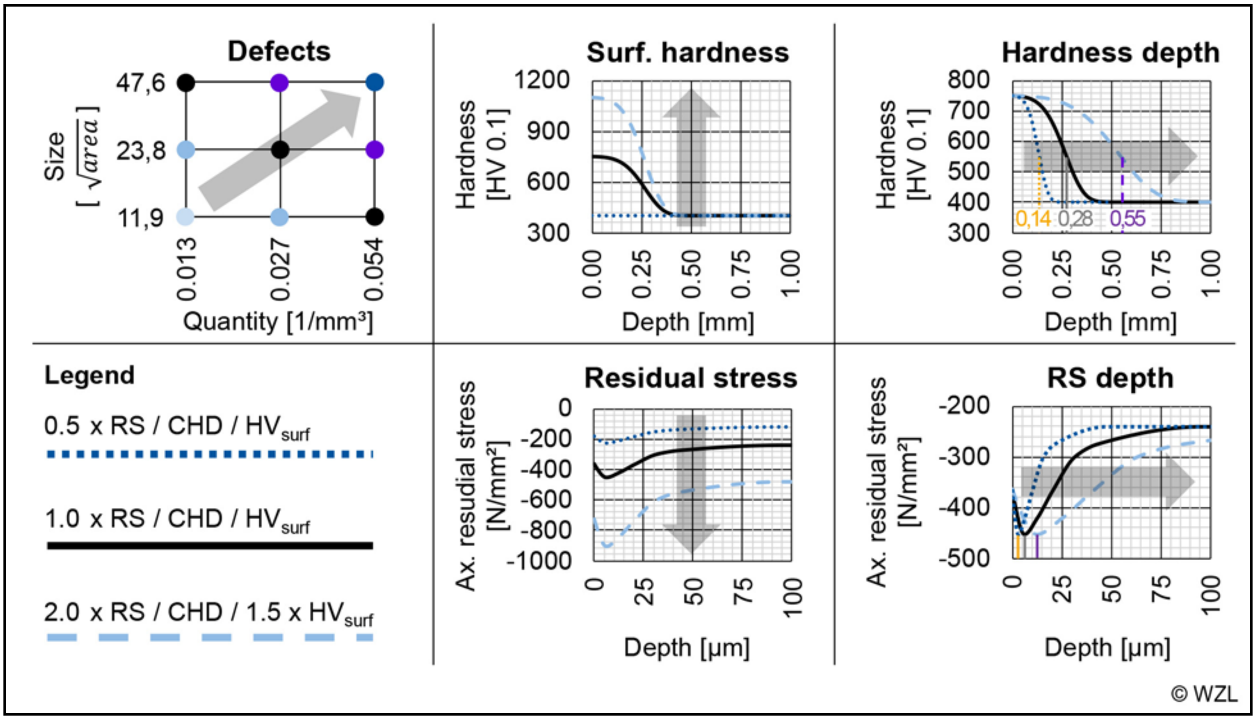

Figure 8 Variation of material properties for exemplary gearset with mn = 1 mm.

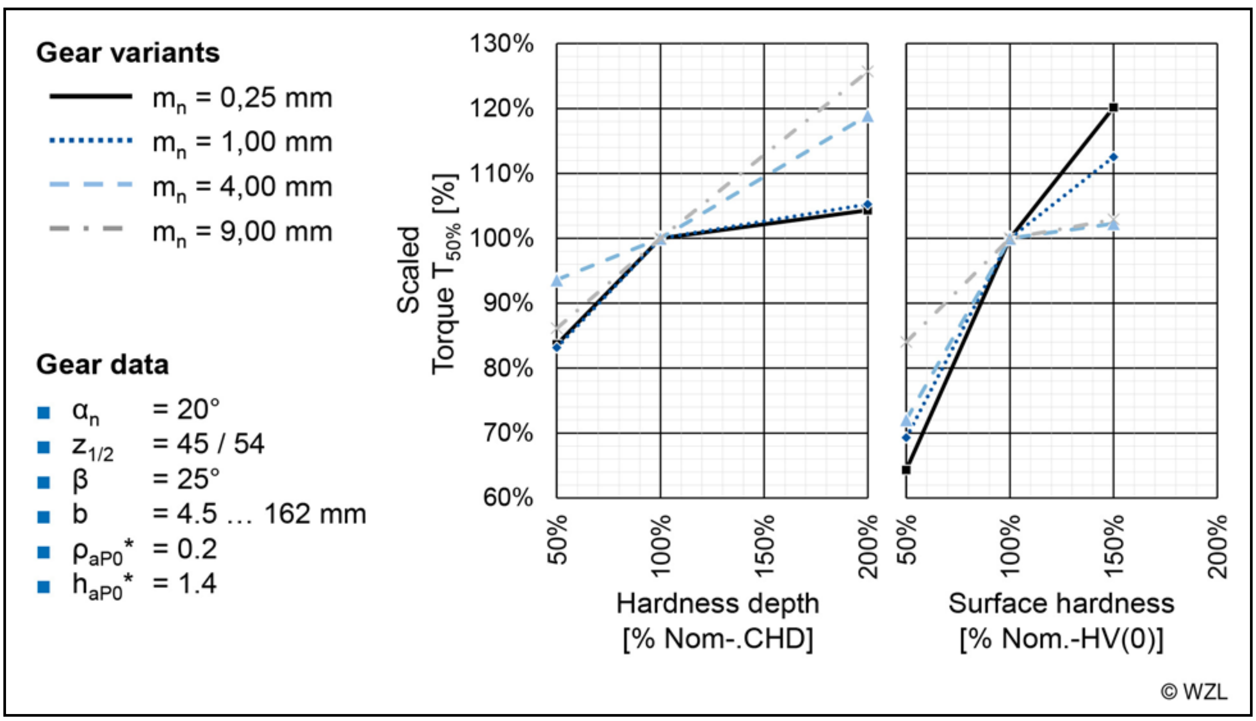

Figure 9 Influence of surface hardness and hardness depth on scaled fatigue torques.

depths can be seen in Table 1. The values have been chosen according to the recommendation in Niemann-Winter (Ref. 22). Table 2 shows the residual stress measurements.

Results. The sensitivity analysis is being conducted according to the design parameters that have been defined in the preceding section. In summary, seven model parameters are being varied: gear size via normal module m_n, surface hardness HV(0), hardness depth HV(Δx), residual stress amplitude σ_{RSmax}, residual stress depth $\sigma_{RS(\Delta x)}$, defect quantity n_{defect} and defect size squareroot of area. The change of fatigue torque depending on the abovementioned parameters is displayed in Figures 9–11. The torques shown in the figures are scaled to the fatigue torques $T_{50\,\%}$ according to the enhanced, weakest link model for the nominal material properties (100 %) that can be seen in section 4.1.

The first set of parameters to be investigated is the hardness $HV_{0,1}$. The effects of varying hardness depths HV(Δx) and surface hardnesses HV(0) on the fatigue torque $T_{50\%}$ can be seen (Fig. 9). The hardness depth has a significant influence on the fatigue torque. Increasing case depth leads to higher fatigue torques. A difference can be depicted between small-module

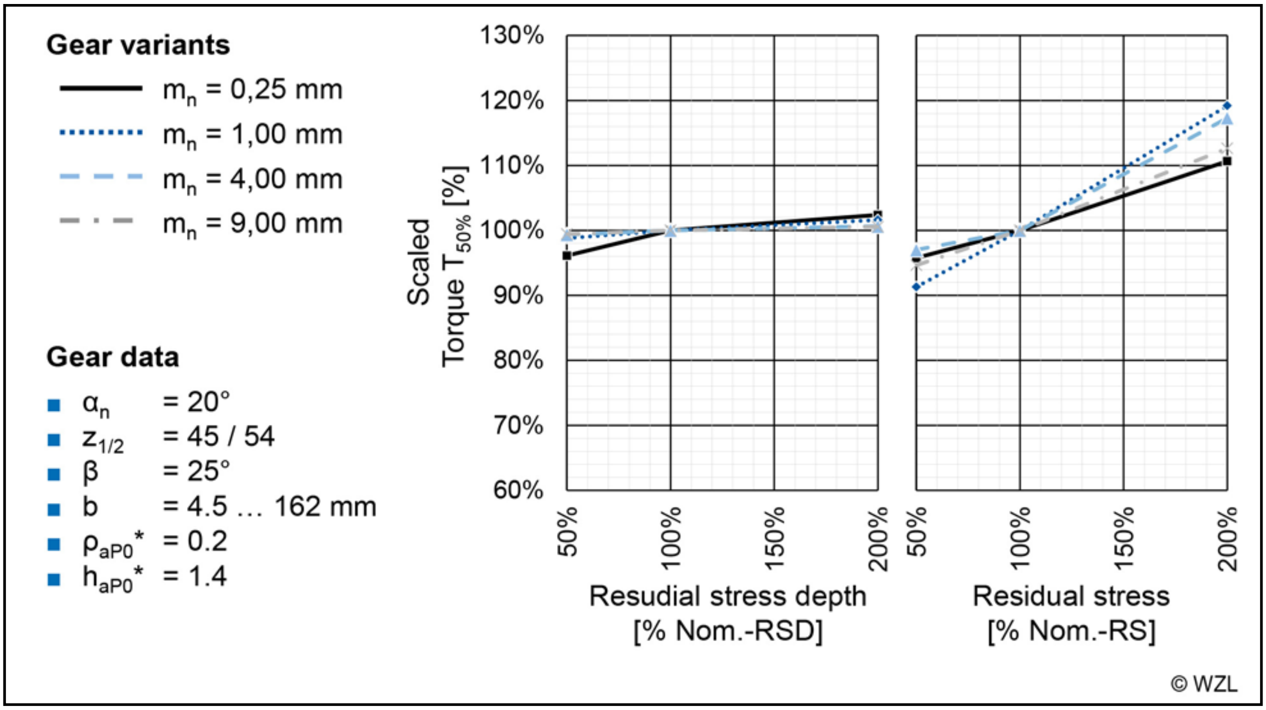

Figure 10 Influence of residual stress and residual stress depth on scaled fatigue torques.

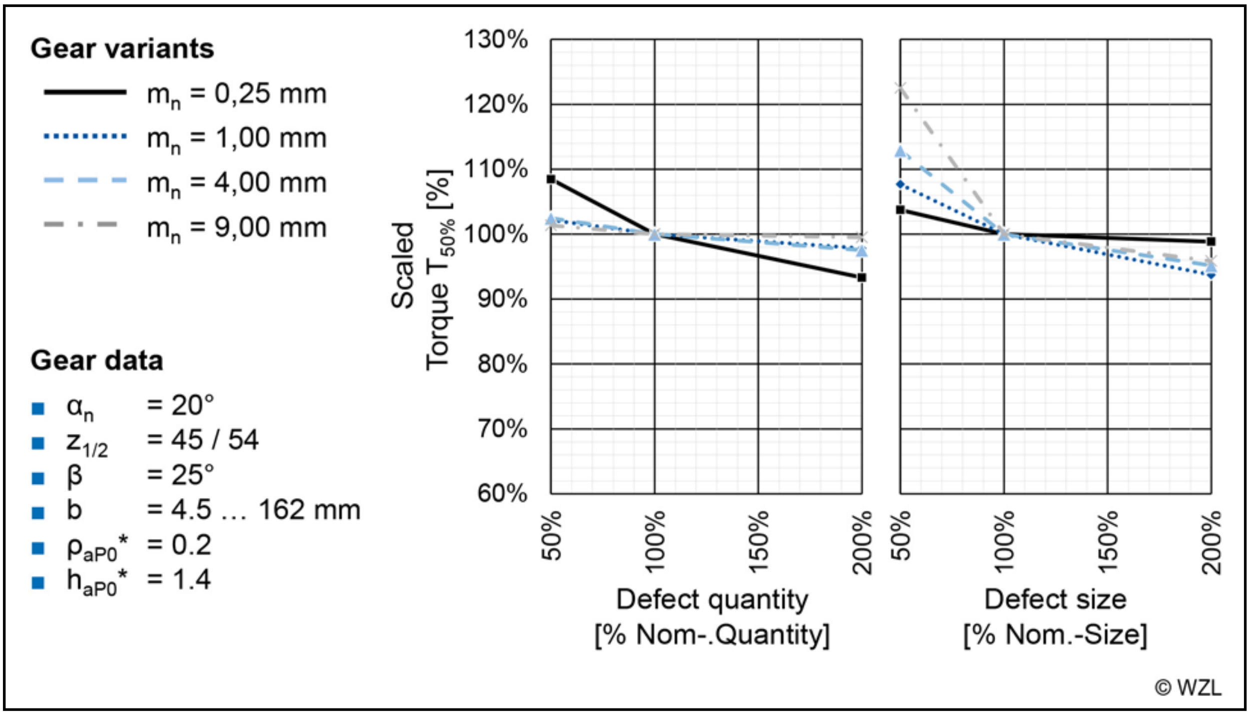

Figure 11 Influence of defect quantity and size on scaled fatigue torques.

and large-module gears. For the large-module gears, the case depth has a nearly linear correlation with the fatigue torque. For smaller-module gears, the effect shows a declining increase of fatigue torque. Therefore, the hardness depth can be considered a module-dependent parameter. This is caused by the non-linear behavior of case hardening depth in dependency of module. Figure 9 (right) shows the influence of the surface hardness on the fatigue torque. For small-module gears, the surface hardness has a near linear effect on fatigue torque. With increasing surface hardness the fatigue torque increases heavily; for large-module gears, the effect is not as distinct. The course shows a declining increase of fatigue torque with increasing surface hardness. This can be explained with the smaller CHD-to-tooth thickness ratio of larger gears.

Figure 10 shows the influence of residual stress depth (left) and residual stress magnitude on fatigue torque (right). The residual stress depth has a small influence on fatigue torque. With increasing residual stress depth, the permissible torque raises only slightly — about 5%. This small effect can be seen with every investigated gear variant. Following this trend, the

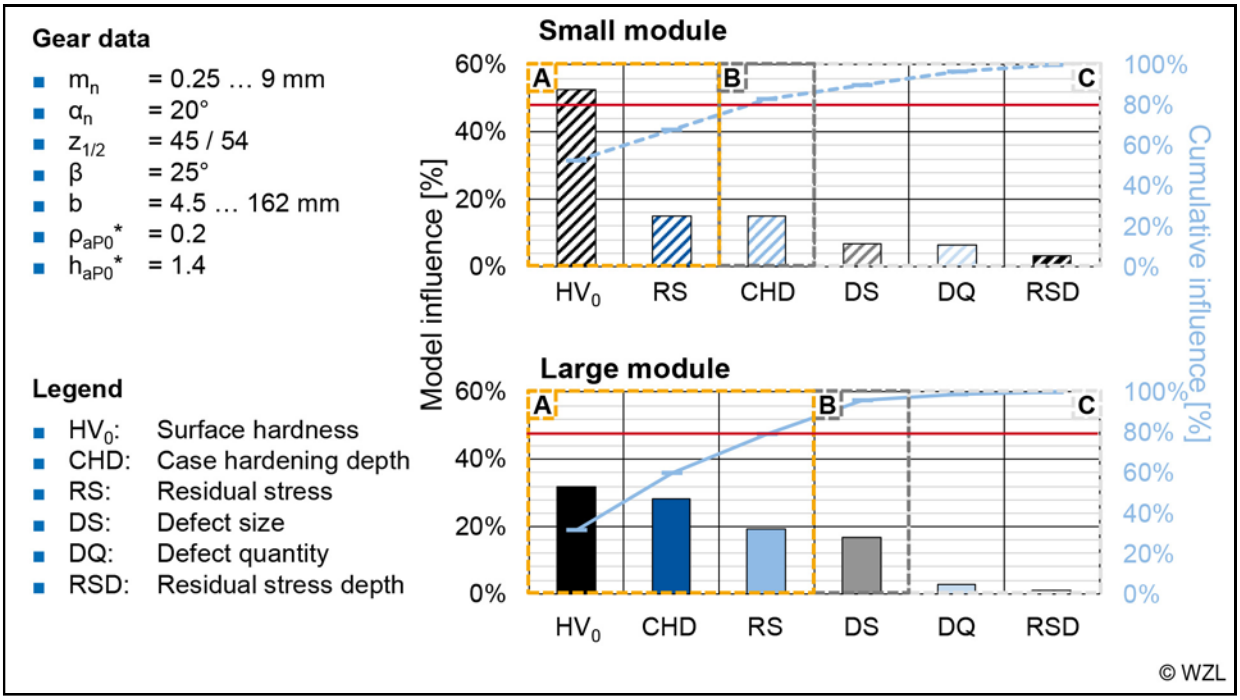

Figure 12 ABC analysis of influence parameters on enhanced weakest link model.

residual stress depth can be rated as a non-module-dependent parameter. Figure 10 (right) shows the effects of varying residual stress magnitudes on fatigue torque. With increasing residual compressive stresses, the fatigue torque increases linearly. The effect is much more pronounced than the effect of residual stress depth. This is explained through the direct reduction of tensile stresses in the tooth root due to compressive residual stresses. Therefore, the strain at each defect is lower with higher compressive residual stresses. The small deviations between individual gear variants lead to the conclusion that the residual stress magnitude is a non-module dependent parameter.

The influence of defect quantity and size on fatigue torque is depicted in Figure 11. With increasing defect quantity, fatigue torque decreases slightly. This effect is strongest for the small-module gear with a normal module $m_n = 0.25$ mm. This can be explained by the small overall probability of defects occurring in the tooth root area of such a small gear. If the defect quantity is increased, the probability is increased and there are more occasions when a defect becomes critical. In simulations, the smallest gear also shows the most spontaneous behavior of failure. This is explained by the same effect of low defect probability in a small volume. According to these observations the defect size can be rated as a limited, module-dependent parameter. In Figure 11 (right) the effect of defect size on fatigue torque is shown. With increasing defect size the permissible torque decreases. This trend is more pronounced for large-module gears. An explanation for this can be found in the larger number of defects that can increase in size in larger volumes — and therefore larger gears.

Conclusions

The results of the sensitivity analysis show differently pronounced effects of the parameters gear module m_n; hardness depth HV(Δx); surface hardness HV(0); residual stress depth $\sigma_{RS}(\Delta x)$; residual stress magnitude σ_{RSmax}; defect quantity n_{defect} and defect size squareroot of area on the scaled fatigue torque $T_{50\%}$. It must be noted that no calculation result differs from the expected result or poses a material-related physical contradiction. This shows the effectiveness and general sophistication of the model. A comparison for gears of smallest, medium sized and larger modules provides insight to the existence of module-specific and non-module-specific influence parameters in the enhanced weakest link model.

The non-linear character of the hardness depth for different gear modules leads to a module- specific behavior inside of the enhanced weakest link model. Small-module gears are influenced more by varying case hardening depths because the CHD-to-tooth thickness ratio is much closer to the value 1 than it is with larger module gears.

The surface hardness shows a distinct module dependency. The results of the parameter study show that the influence of surface hardness decreases with rising module. The investigated gear with the highest module shows a 66% less pronounced behavior when surface hardness is varied than the gear of the smallest module.

The defect quantity shows a module specific behavior for very small gears, because here one defect more or less in the tooth root volume can lead to drastically reduced or increased load carrying capacities. Smaller gears also show a more spontaneous failure characteristic because of the low quantity of defects in the volume. With a higher number of specimen, a mean value can be determined and the spontaneous character of failure can be eliminated.

The defect size is a distinctive module-specific influence parameter in the enhanced weakest link model. It has been shown that the effect of varying defect sizes is much more pronounced for larger-module gears. A reduction of the defect size leads to a significant increase in load carrying capacity for larger gears.

To sum up the results of the parameter study, an ABC analysis (Ref. 23) is conducted. This analysis is based on the Pareto principle which states that 80% of the results are gained at the expense of 20% of the effort. Applied to the model, this means that 80% of the model accuracy can be achieved by considering only 20% of the input parameters. An ABC analysis shows which parameters have the largest influence on calculated tooth root load carrying capacity. It can be stated that the mean influence of surface hardness dominates the model with over 43% model influence. The hardness depth comes in second with 21% model influence. The third significant influence factor is the residual stress magnitude with 16%. These three influences have a cumulated model influence of 80% and are thus identified as the primary model influences. These parameters are marked with "A" in the diagram in Figure 12. The defect size has a mean influence of 12% and for large-module gears even 19%. This parameter is identified as a secondary influencing factor (area "B") for larger-module gears. For small-module gears this parameter is considered insignificant. The parameters defect quantity and residual stress depth show only slight influence on the model and are rated as tertiary influence factors (area "C"). In conclusion it can be stated that the model does not directly follow Pareto principle, with an 80%–20% behavior. In this case 50% of the input parameters influence 80% of the model results for larger-module gears. For small module gears, 33% of the input parameters define 80% of the model outcome. It can also be stated that a separate consideration of small- and large-module gears should be conducted.

Summary and Outlook

The requirements for high-performance yet lightweight power train components rise continuously — especially with regard to electric mobility, where high ratios and low overall transmission weight are demanded. Higher-order calculation methods for load carrying capacity can contribute to resource-saving gear design by allowing designs at the edge of the material capacities and thus better utilization of space in the gearbox production.

This report deals with the investigation of the enhanced weakest link model according to

Henser that is based on a deeper understanding of crack and material mechanics than, for example, empirical-analytical approaches. It is unclear whether a generality of this approach across the borders of considerations in (Ref. 21) can be confirmed. This assessment is based on the results of a systematic parametric study to analyze the model sensitivity to the input parameters gearing size (normal modulus m_n), hardness depth profile, residual stress depth, residual stress magnitude, number of defects, and defect size.

In conclusion, it can be stated that the system behavior of the enhanced weakest link model can be assessed as consistently plausible. Neither for very small, nor even for large gear modules, a significant deviation from the expected strength results is observed. Furthermore, module-specific and non-module-specific system parameters can be identified. This is, for example, the case depth, which, by its non-linear dependency on module, has a stronger influence on bearable torque for small-module gears than for gears of large modules. Finally, the main influence parameters on the model have been identified. The surface hardness, the hardness depth, as well as the residual stress near the surface are the most influencing input parameters for the tooth root bending strength calculation.

The calculation results are consistent throughout all variations and offer a strong motivation to further develop and expand the enhanced weakest link model. The high impact of the defect size on high module gears lead to dedicated investigations of large gears to validate the calculated results. The determination of defect sizes and quantity already in the semi-finished product show opportunities for further research. Furthermore, reverse bending and fatigue strength calculation are possibilities to expand the model horizon.

Acknowledgement. *The authors gratefully acknowledge financial support by the German Research Fund (DFG) [Excellence Cluster 128 "Integrative Production Technology for High-Wage Countries"] for the achievement of the project results. For the software-based achievement of simulative results the authors gratefully acknowledge the financial support for the software development by the German Research Association for Power Transmission Engineering.*

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Performance and Machining of Advanced Engineering Steels in Power Transmission Applications — Continued Developments

Lily Kamjou, Joakim Fagerlund, Brent Marsh and Thomas Björk

It is becoming increasingly apparent that material properties can and will play a greater role than before in addressing the challenges most transmission manufacturers are facing today. Making use of materials' intrinsic fatigue properties provides a new design tool to support the market changes taking place, where current and future designs will require cleaner steels that can perform at higher load levels. This paper discusses the potential gain for the transmissions industry by making use of material properties to support more demanding applications. It describes advanced engineering steels and how they can benefit the industry, through discussing material cleanliness versus performance of gear materials, standardized fatigue testing such as contact and bending fatigue, as well as the machining of clean steel.

(*The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.*)

Introduction

Clean steel in transmission applications. The transmissions industry is under ever-growing pressure to meet the increasing demands of handling higher loads on current and future system generations. In the strive to increase overall fuel efficiency and reach the more and more stringent emissions regulations in the transportation industry, being able to increase power density plays a major role. However, the need to increase power density is spread throughout the transmissions industry and is not only limited to the automotive or heavy duty commercial vehicles.

For a long time, upgrading the potential in the system by changing to cleaner steel has been a well-kept secret, which very few stakeholders have made use of. Seeing how the advanced engineering steels of today can offer huge improvements even without having to make major design changes, making use of cleaner steel can open up many possibilities. Large safety factors, single- and double-shot peening, and superfinishing are being implemented more and more frequently in trying to find ways of enhancing the fatigue strength of the components. Although many are costly, these methods are widely accepted. Switching to a higher quality material has, so far, not really been explored fully.

A higher cleanliness material can offer improvements for both bending and contact fatigue by reducing the probability of finding large, detrimental defects that will act as crack initiators in the loaded volume. So, steel quality does, in fact, have a huge impact on the fatigue life of a component and is the one main parameter that will give the largest gain in fatigue life. This is especially relevant when using high-hardness steels such as carburized grades used for gears and shafts in transmission applications.

Machining. Traditionally, steels with high sulphur content have been preferred for machinability reasons. However, there exists today an urgent need for steels with improved fatigue properties; but a part of producing a steel with improved fatigue properties is also restricting the sulphur content (S-content) in order to reduce manganese-sulphide (MnS) inclusions that can have a negative effect on the fatigue strength of a component.

For machining today — with modern machines, tools, and inserts — there are no indications of a reduced S-content having a negative effect on machining operations such as soft turning, gear cutting, or hard machining. For slower operations such as broaching, series production so far has not shown any difficulties, but may require more examination before giving more general advice. Minimizing the number of unplanned stops, on the other hand, might be improved due to a consistent quality of a material with a higher capability through reduced scatter and the risk of running into large, hard oxides that might cause inserts to fail.

Current manufacturing processes normally need only minor adjustments when making the change to clean steel. An added advantage is that clean steel may also reduce the need for further processing such as shot peening. It is worth noting that for conventional steel, a sulphur content of 200–500 ppm (parts-per-million) is quite common. For clean steel such as bearing-quality steel, the sulphur content will typically be below 100 ppm. To achieve the desired properties of an ultra-clean steel such as isotropic-quality steel, the sulphur level is further reduced and is typically around 10 ppm. While this might require a slightly different approach to machining, the closely controlled properties of the steel — together with advances in tool and insert technology — have made it possible to create very efficient, cost-effective processing solutions for clean steel.

Background (Development of Clean Steels and What They Are)

Development. In order to produce clean steels suitable for today's challenges, steel producers have had to find ways of trying to understand the true inclusion population of the materials. Given that a steel with the right mechanical properties can be developed, fatigue failure is most likely to be initiated by non-metallic inclusions in the steel. In theory, "cleaner" steel with fewer inclusions should have higher fatigue strength. Therefore, it has been important to establish the relationship between steel hardness, inclusion size, and stress limit. While it is well-established that the intrinsic fatigue limit of a steel increases with its strength or hardness by a factor of approximately 1.6 (Fig. 1), it is also true that as the strength of the steel increases, the obtained fatigue limit is increasingly lower than the intrinsic limit (Ref. 1).

This is caused by defects such as inclusions acting as stress raisers and promoting fatigue crack initiation. The reason defect size is of such importance in gear materials is because the steel is used in a hardened state. Through rotating bending fatigue (RBF) testing, it has been established that high-strength steels are more affected by inclusions, and by reducing the size of the main inclusion population dramatically, high-strength steels have the potential to achieve a fatigue limit very close to the intrinsic fatigue limit.

Through a combination of different quantification techniques — light optical microscopy (LOM), scanning electron microscopy (SEM), RBF and immersed ultrasonic testing (UT-testing) — it has been possible to test for inclusions from 2 µm upward in size, and has enabled obtaining a reasonable picture of the inclusion population. Figure 2 shows how the combination of methods can cover a larger inclusion size range and the probability of being able to find a certain size range of inclusions by a certain method. This has enabled the refining of production processes for producing new, cleaner steels and isotropic-quality steels. It should be noted that in this range of isotropic, clean steels the remaining inclusions are not removed, but instead moved to a finer distribution.

Historically, inclusions below 500 µm have been classed as micro inclusions, while everything larger has been classed as macro inclusions. However, modern clean steels have very few large inclusions, and the sizes of the assessed area in standard tests using optical methods are too small to provide any statistical confidence. The result is that any clean steel producer invariably generates only zero ratings. For micro inclusions, the methods generally used today — such as those found in ASTM E45 or DIN 50602 — also provide only a very vague picture of the steel cleanliness, due to the small investigated area.

Producing clean steel. Improvement in fatigue strength is the result of a carefully controlled steel-making process. The probability of finding detrimental defects in the loaded volume needs to be minimized for materials to perform well in high-cycle fatigue applications.

As an example — for clean, scrap-based air-melted steels, the steel making can be divided into four main production stages that affect steel cleanliness. By controlling the steel making throughout the process, improvements in fatigue properties can be achieved — improvements that can and will make a big dif-

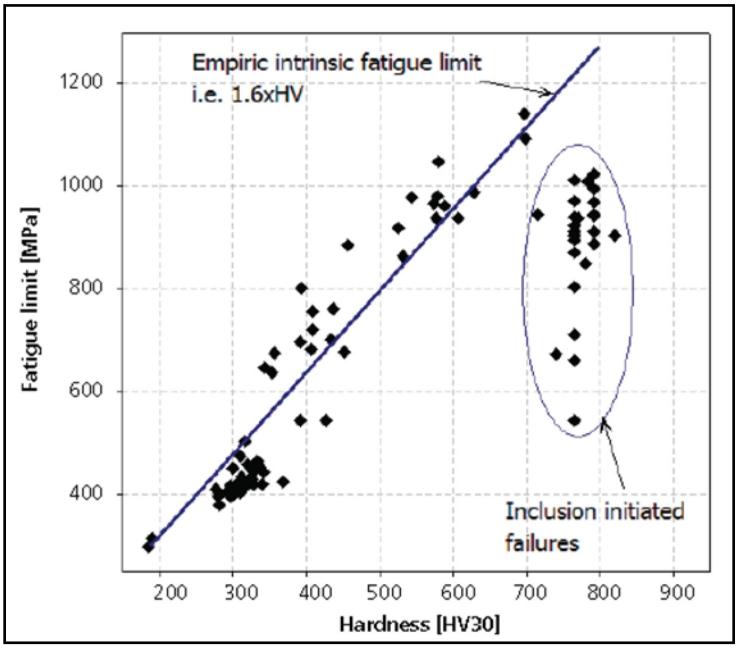

Figure 1 Fatigue limit defined as 107 cycles on rotating bending fatigue samples vs. hardness.

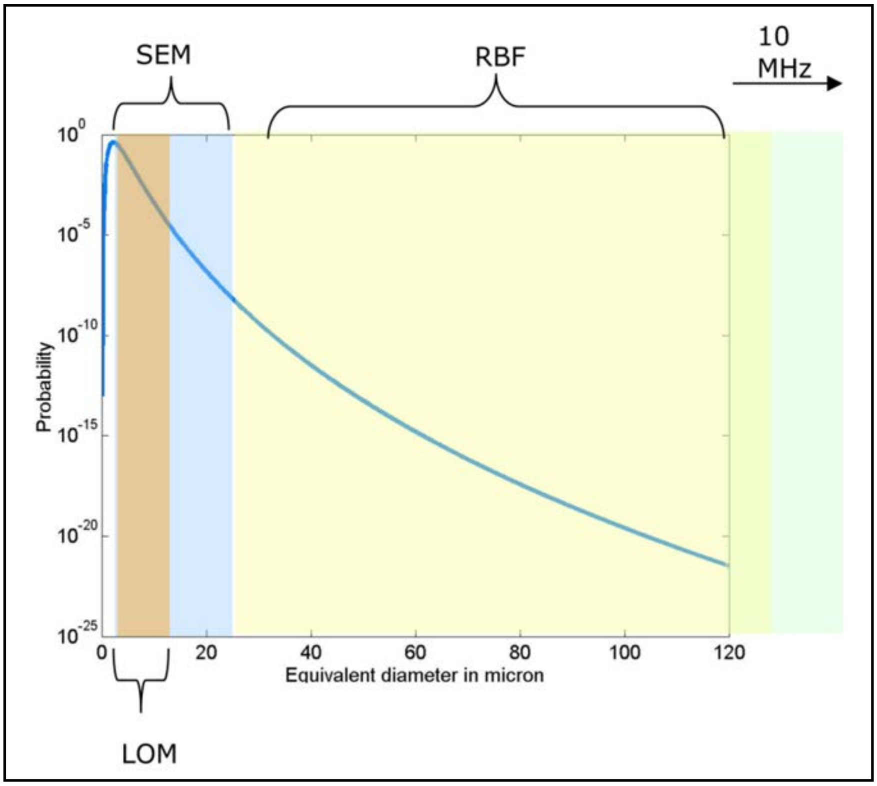

Figure 2 By combining several methods, a reasonable picture of the total inclusion content can be obtained.

ference in gear applications. The production can be divided into the following four main stages:
1. Primary metallurgy
2. Secondary metallurgy
3. Casting
4. Rolling

At each stage there are a number of different parameters of importance. In the primary metallurgy stage, for example, scrap mix needs to be controlled in order to avoid a larger quantity than necessary of certain elements that are prone to forming harmful inclusions and that will be difficult to remove later on. In the secondary metallurgy stage, it is the composition of the top slag along with alloying and degassing that can be fine-tuned to produce different steel qualities. The casting process can vary widely, and to produce clean steel a large casting format, such as ingot casting, is generally used. Some advantages of ingot casting are that it is flexible, gives a good starting format, and because the solidification process is inward and upward, inclusions are generally pushed toward the top. The top is then cut off and scrapped and the amount that is cropped can also be adjusted, depending on grade and quality produced. The final main production stage is rolling, including the homogenization and hot-working of the material into smaller formats.

Starting from a large format such as ingots results in higher area reduction (or reduction ratio) that also has a huge impact on material quality — especially affecting macro inclusions. As an example, an ingot size of approximately 500*500 mm will have a reduction ratio of 65:1 for a 70 mm bar. Actual clean steel production processes may vary depending on the route, quality, and grade, but to achieve the full potential of this type of material, all stages are equally important.

Conventional steels — where continuous casting in small formats is common — are produced in a highly cost-efficient process. It is dependent on being able to cast several heats of the same grade in a row, in order to sustain productivity. It is also often cast in a small format, generally around 240*240 mm, which gives very little area reduction down to commonly used bar sizes —approximately 15:1 for a 70 mm bar. Since hot working and area reduction are needed for eliminating porosity and reducing inclusion sizes, material from small, continuous cast routes tends to have a larger inclusion population and thus a different level of material cleanliness and performance. These types of steels are widely used in the automotive industry and are suitable in applications where loads are low on gears and systems.

Clean steels will generally have oxygen content below 8 ppm and a sulphur content below 100 ppm. Ultraclean steels tend to have even lower oxygen content and an S-content below 20 ppm, thus minimizing the presence of sulphide and oxide inclusions.

Depending on the requirements of the application and what needs to be achieved for current or future generations, there are different levels of cleanliness that will offer different potential. Figure 3 illustrates schematically how defect size affects fatigue strength and what performance can generally be expected from different types of material cleanliness. This can then be translated into a useful tool; for example, for designers looking to increase torque through the system. For many manufacturers the step from conventional steel to a clean steel, such as that of bearing quality, will be a large step, and the one that enables system functionality without major changes in system design.

An important aspect of clean steel and steels produced to suit customer requirements is the potential to reduce scatter in material behavior and properties. That means that the material for that application will behave much more consistently — not only in component life, but also through the manufacturing processes; for example, in heat treatment and machining, which in itself can have a positive effect on total cost, apart from facilitating material processing.

Discussion

Relevance for the industry. As a designer, it can be beneficial to have a certain level of knowledge of how steel cleanliness affects fatigue performance of materials used, thus providing a greater flexibility at the design stage. Through constantly increasing demands, it is likely that many other enhancement processes, such as shot peening or different finishing methods, are already in use.

So far, there are a number of clear cases showing the poten-

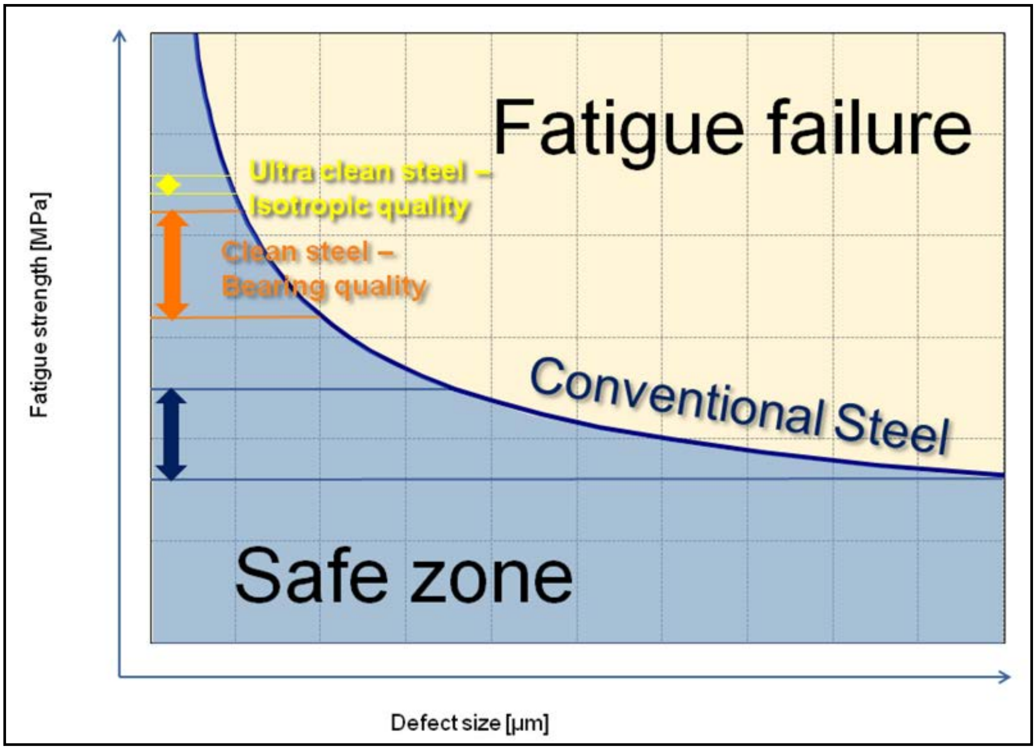

Figure 3 Fatigue strength vs. defect size — schematic illustration.

tial of clean steel. As an example, cylindrical gears handling higher loads through minor changes in the micro geometry, while making use of material properties, have shown impressive results. Through a careful consideration of how these two parameters interact, a premium brand automobile manufacturer has been able to attain the improvements needed for the system requirements in their seven-step, dual-clutch transmission (Ref. 2). By taking a step in the direction of clean steel, the demand for increased system torque could be met.

For some types of bevel gear applications there have also been some real enhancements through making use of clean steel. A well-known driveline producer needed to examine the influence of internal defects on fatigue life, due to inconsistent and inadequate material behavior. Where conventional steels could no longer handle the pressure, clean steels proved able to support the required loads in these systems (Ref. 3). Smaller defect sizes have been the determining factor for, in this particular case, bending fatigue.

The ability to take material cleanliness — defect size and distribution in the loaded volume —into account when designing gears and systems is not straightforward, but there are models that are looking at including that parameter as well. Advanced calculation methods for load carrying capacity enable designing from actual material capabilities in high-performance lightweight powertrain components where high ratios and low transmission weight are real requirements. The enhanced weakest link model (Ref. 4) is based on a deeper understanding of material mechanisms and analyses parameters such as defect size and quantity together with, among others, surface hardness, case hardening depths, and residual stresses.

How clean steel can support current and future challenges. The question is how designers can make the best use of clean steel to solve their own power density challenge. A simplified way of looking at the challenge is to divide it into three levels of effort (Ref. 5), ranging from material substitution to total redesign:

1. The first level can be considered as a way of increasing power density through upgrading the material while maintaining an existing design or making some minor design changes. Such changes could be a change of gear tooth micro geometry, for example, to fully utilize the enhanced bending fatigue strength of the new material at the tooth root, as mentioned above, while reducing contact pressure on the gear flank. It opens up for further extending life of an existing design while delivering enhanced performance.
2. In the second level, the combination of clean steel with some significant internal design changes provides the potential for increased power density. Improved fatigue properties can enable some components to be downsized, freeing up room for the incorporation of additional components. The outcome is that a new generation of powertrain systems with enhanced performance can be dropped into the same footprint as the previous generation. The internal design receives a makeover while the external design remains the same.
3. The third level represents the ultimate use of clean steel to achieve a major increase in power density, with its enhanced fatigue properties providing designers with an important new tool as they create new powertrain concepts. A typical automotive application might be to help meet emissions legislation by introducing different degrees of hybridization and electrification into the powertrain, especially when there is a need to create space for other surrounding systems.

Methods for Verifying Steel Cleanliness/Material Properties

It is vital to quantify steel cleanliness in order to verify that the required fatigue performance can be achieved in the final component. To be able to verify that the steel performs as desired, a combination of methods seems to be the most relevant way in trying to predict how the material will perform. And to be able to implement into material specifications, an understanding of current level of material is necessary.

Implementing a combination of requirements, such as chemical composition, micro and macro inclusions, reduction ratio, and also approved suppliers, has so far proved supportive of ensuring material quality that will live up to customers' actual demands. With the changes being driven mainly by environmental issues in the automotive industry, increasing the system demands and, for example, quality issues in the wind power industry, it is getting increasingly interesting for stakeholders to be more specific in their material requirements. Once hardenability demands are met through alloying strategy, the main factor determining how the steel will perform is cleanliness. That gain in performance cannot solely be replaced by moving to a higher-alloyed steel.

Chemical composition. Increased requirements on chemical composition, including oxygen and sulphur content, will have a positive effect on the material performance and therefore the system performance. Introducing a more stringent chemical composition will result in more consistent material quality and also have a positive impact on the production of the components, making both heat treatment and machining behavior easier to predict.

Macro inclusions. For macroscopic inclusions, relatively crude methods have been used to try to define the acceptable number of rarely occurring large-sized inclusions. These include: step-down tests, in which bars are fine-turned in distinct steps and defects greater than 0.5 mm are recorded; blue fracture tests also record defects larger than 0.5 mm on a bar cross-section that has been hardened, fractured and then tempered blue to increase the visibility of defects. However, these methods do not provide the information needed to define the performance of clean steels, since the probability of finding anything in the inspected area is too low.

10 MHz immersed UT-testing has proven to be a more useful method for inspecting commonly used steels in the gear industry today. This method has the advantage of being able to inspect a fairly large volume in a short period of time. Steel producers generally use this type of inspection as a way of ensuring process quality, but the method can easily be implemented in a customer specification to give an indication of material cleanliness. There are standards in place for this type of inspection, such as (Ref. 6), although it is not uncommon for producers of clean steel to have made improvements for their own testing routines in order to ensure that the method provides as much information as possible regarding expected performance. The result of the testing can be presented as the number of defects larger than the calibration-sized flat bottom hole (FBH) per dm^3 and limits can be set in the material specifications — 0.2 mm FBH/dm^3, for example.

Figure 4 shows examples of ultrasonic testing on bars with a diameter of 65 mm of carburizing steels used for gears in the transmissions industry today. There is a visible difference between commonly used conventional steels (top) and clean steels (bottom), which is the result of the steel-making process as described earlier. In the conventional steel reflections of defects show up in varying color, which changes depending on the intensity of the reflected sound. White areas show 100% reflection, thus indicating large material defects.

For critical components and applications, 100% in-line UT-testing can also be implemented; this testing is generally performed on the finished bar size. For best use of this method — for example, through phased array ultra-sound — a peeled surface is generally required since it makes it possible to look for smaller defect sizes, and calibration to a 0.7 mm FBH is not uncommon.

Micro inclusions. Even though micro inclusion rating in itself will not be enough to determine the material quality and cleanliness, in combination with other methods it can still be a relevant method. Standard methods such as ASTM E45 and DIN 50602 can be improved by, for example, making sure the sampling is increased so that a larger number of samples are inspected by microscope.

To summarize: in order to ensure consistent behavior from the steel, and ultimately the system, combining a number of relevant methods of determining micro and macro cleanliness that will give a good picture of the material and thinking through requirements for reduction ratio, are a good place to start. Also, taking care in specifying chemical composition, including oxygen and sulphur content, and consequently reducing the scatter of material behavior in production as well as performance, will help in determining what to expect from the material.

Fatigue testing. Basic material data is obtained by performing RBF testing on test specimens, providing data for high-cycle fatigue, relevant for these types of applications. Testing is normally performed in the longitudinal direction of the bar since this a common loading mode for some applications and it can also be difficult to prepare test specimens for transverse testing due to bar diameters. Testing in the transverse direction is not as well documented, but for ultra-clean steels with isotropic properties, this type of testing is, of course, common practice. However, since stresses in all directions also need to be considered for gear applications, due to loading mode and material flow in the components, transverse properties are actually likely to give more relevant information about fatigue life than longitudinal testing.

To get a better understanding of the transverse fatigue strength of conventional gear materials as well as clean steels, a method of producing test specimens from a smaller bar size has been developed for a larger test program. The test program should give a clearer picture of how immersion UT-testing and RBF testing in combination can give a better indication of how the material will perform in the application.

Initial testing of the carburizing grade 20MnCr5 with transverse sampling from an rd65 mm bar validates the test method (Ref. 7). Even though the tested volume is small for this type of testing, it will still give a good understanding of how different materials behave when loaded in the transverse direction.

Contact fatigue testing. As a second part of contact fatigue testing of an ultra-clean modified 20NiMo9-7F (158Q), FZG back-to- back pitting testing was performed at WZL in Aachen. The aim was to be able to compare this type of ultra-clean steel to the ISO 6336-5 standard for materials (Ref. 8).

Set-up and method. The gears used for the FZG back-to-back rig testing are of C-Pt-type with a linear tip relief and from the same production lot as for the previous testing done at the

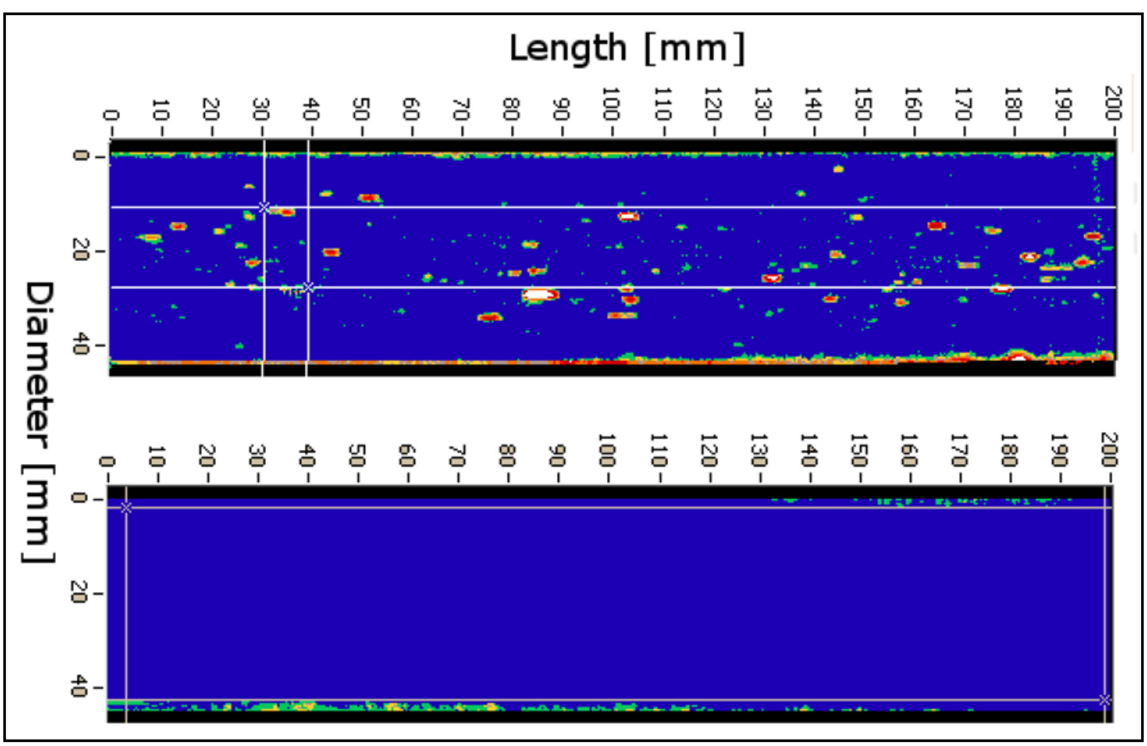

Figure 4 10MHz immersed ultrasonic testing of rd 65 mm bars, carburizing steels of different cleanliness.

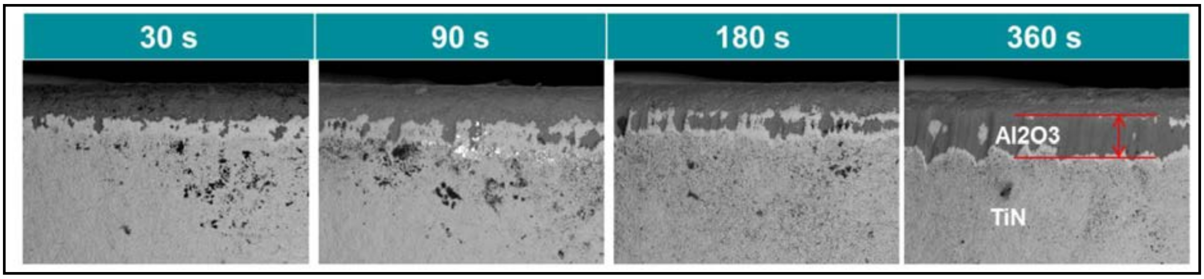

Figure 5 **Micrographs of the flank face of cutting tool recorded after 30s, 60s, 180s and 360s, starting with a new cutting edge in each test (SEM).**

Royal Institute of Technology (Ref. 9). After run-in for 1 h at 135 Nm with a starting temperature of 60° C of the oil, the testing was started at an oil temperature of 90° C and a variable applied torque. Failure criteria was set to pitting area of one tooth > 4% and pitting area of all teeth > 2%. The limiting number of load cycles was 50*106. The staircase method with evaluation according to IABG/Hück was applied, starting at a load torque of 300 Nm and with a step size of 50 Nm (Ref. 10).

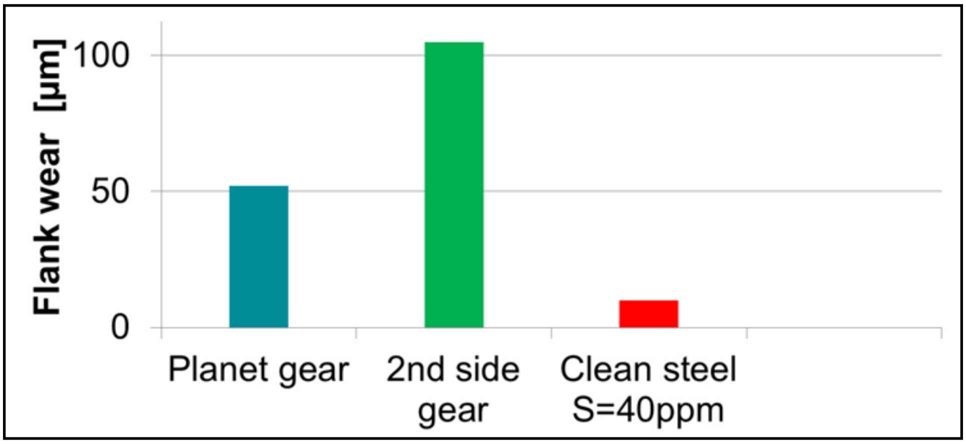

Figure 6 **Flank wear progression on the flank face of the cutting tool at test time of 6 min.**

Results and discussion. Even though the standardized C-Pt-type does not seem to be an appropriate gear geometry for testing these types of materials, the endurance strength parameter of flank stress σ_{Hlim} shows a more than 30% higher result compared to ISO 6336-5 quality class MQ (state of the art in ISO 6336-5). The evaluation was not entirely uncomplicated, since premature tooth meshing caused different types of damages on the gears. By using a different tooth geometry that minimizes premature tooth meshing, an even higher σ_{Hlim} is expected to be reached. It is also apparent that material, manufacturing and design go hand in hand. The material can never perform better than the design or manufacturing parameters, such as surface roughness, for example. This is now being discussed with WZL, together with end users in the automotive industry, in order to identify more relevant ways of testing surface fatigue of clean steels, resulting in useful data, for manufacturers of passenger car gear boxes, among others.

Machining

Machinability of clean steel. Several projects and investigations are ongoing in the field of component machining processes of clean steels. Furthermore, a screening scheme aiming at relevant and repeatable differentiation of the machinability of gear steels is in joint development with a Swedish research institute. The method enables quantified numbers of the steel's machinability displayed in bar charts. The method currently comprises abrasiveness from hard particle constituents of the steel, thermo-mechanical wear of the tool CVD coating, and numbers of chip breakability. The machinability screening method enables industrially relevant and repeatable screening for a high degree of differentiation of steels in mass production of steel components.

In a project with Swedish industry and academia, the introduction of clean steel was considered for a secondary side gear and a planet gear. Insufficient fatigue strength of these two gears limited the possible output torque of the gear boxes, using today's conventional steels, hence the reason for the project. Consequently, increased fatigue strength of these gears would directly benefit the performance of the gearboxes.

Two conventional carburizing steels with an S-content of 200–400 ppm were compared with a clean steel with S = 40 ppm; all three with very similar alloying content. Machining tests were undertaken using gear blanks of the reference steels and bars of the clean steel. The steels were compared with respect to tool life in rough turning; a dedicated machining test of the steel's abrasiveness in turning; and experimentally simulated gear cutting using circular face milling with PVD-coated HSS milling inserts.

The results show that the tool life of the clean steel is on the same level as the reference steels. The dedicated machining test for steel abrasiveness evaluation actually showed that the clean steel generates extremely little abrasive wear on the cutting tool coatings (Figs. 5–6). This is probably due to the low content of hard oxide inclusions of this steel. In addition, the large reduction ratio of the ingot casting process for the clean steel improves the microstructural homogeneity, as well as reducing the number of large oxides, adding to the minimized abrasive wear of the cutting tools of these tests.

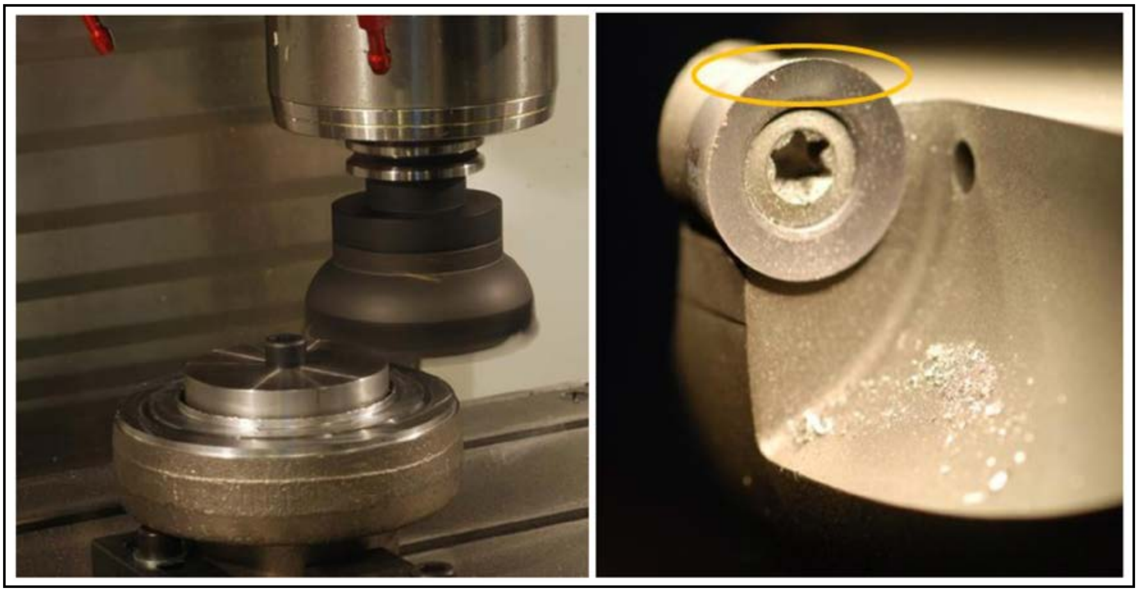

Figure 7 Setup of machining test experimentally simulating the tool wear conditions in gear hobbing.

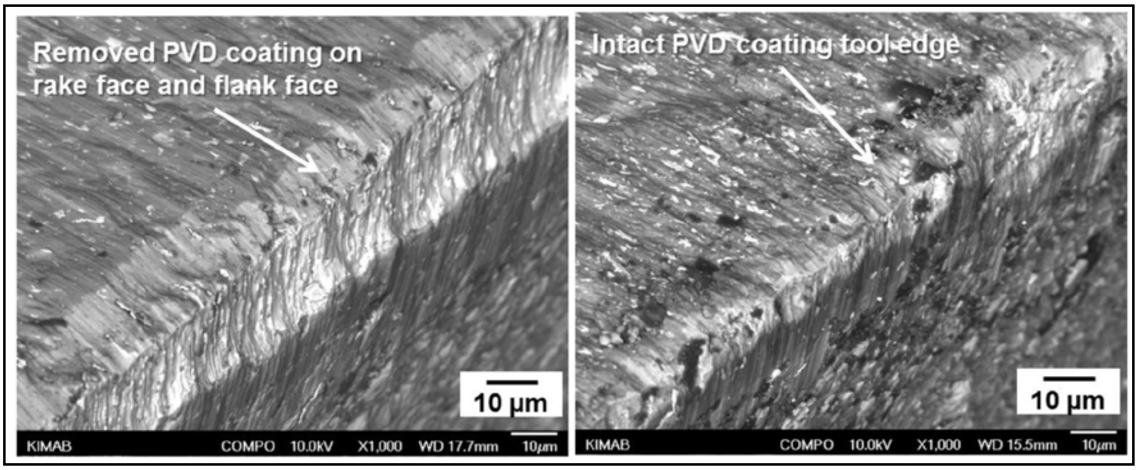

Figure 8 Representative micrographs of the PVD HSS cutting edges subjected to circular face milling at about one-half of tool life at cutting speed vc = 250 m/min; (a) The reference steels of S = 0.04 wt% and (b) the clean steel of S = 0.004 wt% (SEM).

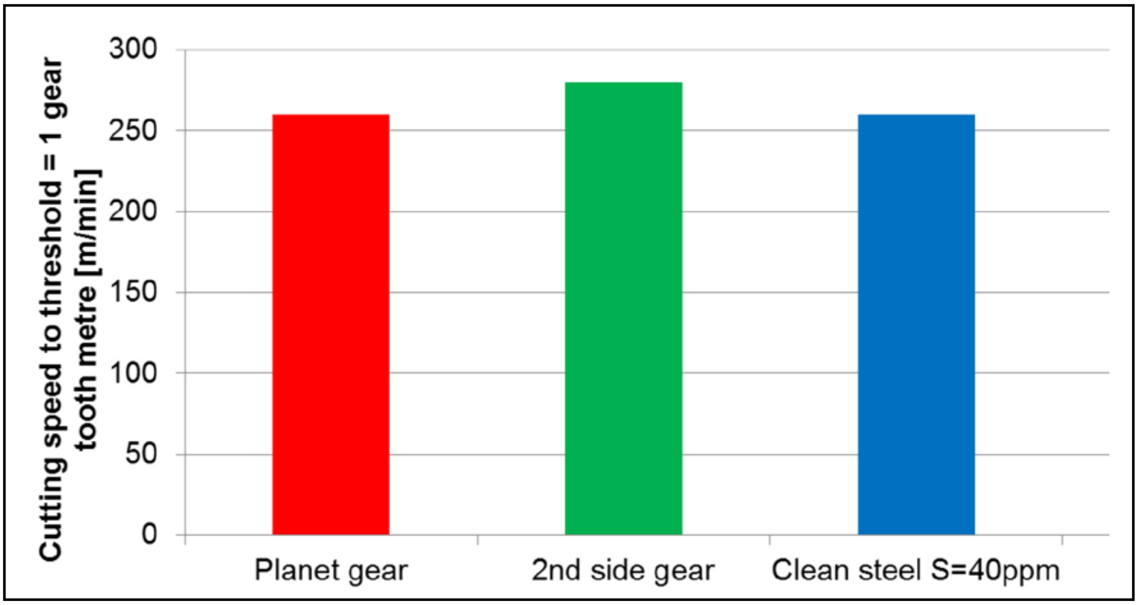

Figure 9 Experimental simulation of the tool conditions in gear hobbing, threshold cutting speed that enables tool life of ONE gear tooth meter in hobbing.

The experimental gear hobbing test (Figs. 7–9) showed that the same service interval of PVD-coated HSS hobs is expected with clean steels as with conventional steels. The cutting tool edge line remains intact longer with the clean steel with respect to abrasive wear of the PVD coating. However, more thermal softening of the HSS substrate was observed with the clean steel.

Based on the studies mentioned, as well as field tests in component machining of clean steels, the following guidelines to machining of clean steels can be derived:

- The same tooling and machine solutions as used in today's production can be used for clean steels as well.
- A rule of thumb in turning is to increase the feed by 15% and to reduce the cutting speed by 15%.
- A rule of thumb in gear cutting is to increase the tooth feed with 20% and to reduce the cutting speed with 20%.
- In hard part turning using PCBN cutting tools, select a PCBN grade with higher toughness than the one currently used. In addition, reduce the cutting speed by 10%.

Experiences from machining field tests of clean steels. To gain enhanced knowledge of machining of ultra-clean steels, more machining trials have been and are being performed. These trials include a larger quantitative study of turning and hobbing, as a continuation on previous trials (Ref. 11), as well as gear and spline cutting with gear milling tools.

The continued quantitative study for turning and hobbing, based on more than 1,000 forged gear blanks of ultra-clean 20NiMo9-7F (158Q), will be concluded later during 2016. The reference is conventional steel in a grade similar to AISI 8620 used in series production for the same planetary gear. Both steels are forged to the same planetary gear ring geometry at the same sub-contractor. The AISI 8620 was isothermally annealed according to the specification, whereas the clean 20NiMo9-7F was subjected to a sub-critical annealing.

Another pre-study uses indexable disc cutters in a profile milling configuration. The work eventually aims at introduction of power skiving using indexable carbide tools as an option to gear hobbing. The study compares the reference AISI 8620 with the ultraclean 20NiMo9-7F.

A 15-tooth pinion of module size 4.233 (DP 6) was profiled using disc cutters (Fig. 10). Both solid HSS cutters and indexable carbide concepts were tested. A DMG Mori, NT4250 DCG, multi-task, 5-axis milling/turning center was used.

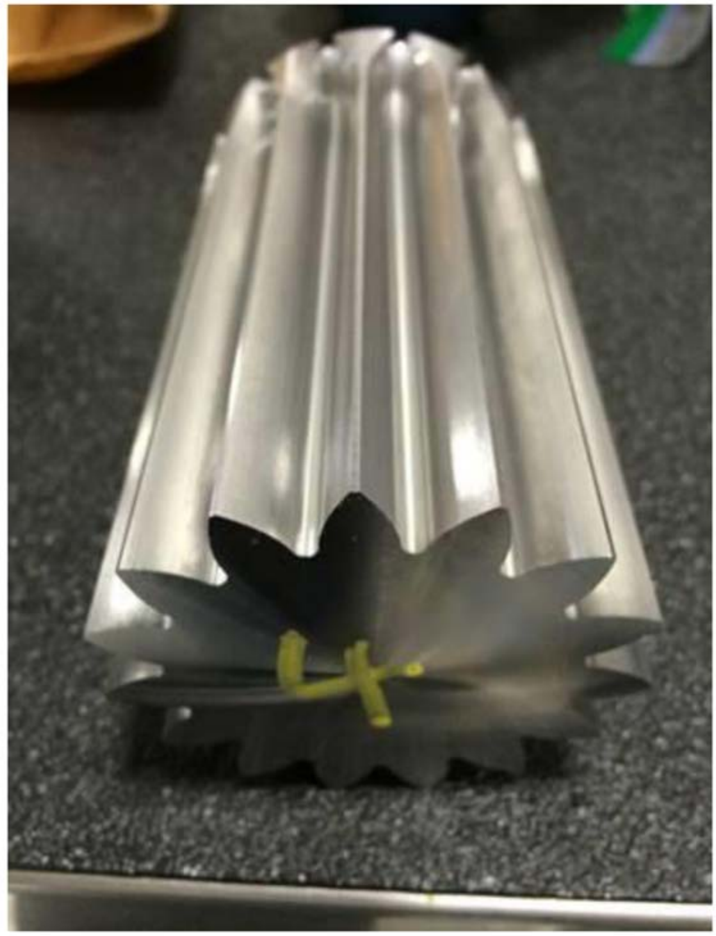

Figure 10 Pinion with 15 teeth produced in profile milling machining tests.

The indexable carbide inserts (ICI) disc cutter was a full profile disc cutter with only one insert, in order to achieve expedient test results. Inserts were Sandvik Coromant Grade GC1030, equivalent to ISO P30 carbide inserts with a PVD TiCN, TiAlN, and TiN multi-layer coating approximately 6 microns in thickness.

Cutting data was chosen according to modern gear industry tooling norms as follows:

- Cutting speed $vc = 280$ m/min
- Feed rate $F = 191$ mm/min average
- Resulting chip thickness was 0.1 mm Hex. All cutting was dry.

Conventional (up-milling) was done according to setup requirements. Results of testing proved a tool life of 40 min-

Figure 11 Rake face of carbide milling inserts after machining tests of AISI8620 (left) and ultra clean 20NiMo9-7F steel (right) (LOM).

utes per cutting tooth. The tool life corresponds to a volume of removed chips of 1.5 gear tooth meter for both steels. Both steels generate micro chipping wear on the rake face of the cutting tools (Fig. 11). However, the tool wear had progressed more with the 20NiMo9-7F steel. The micro chipping probably resulted from high thermal and mechanical loads on the rake face of the cutting tools. A weak substrate makes the wear resistant, yet brittle PVD coating, come off in patches 5–30 µm in size, as observed.

Conclusive remark and outlook. Clean steels can be machined using existing machines and existing tooling. Abrasive wear is minimized thanks to the absence of hard inclusions, primarily oxides; 20–50 µm often present in conventional steels produced by continuous casting. However, clean steels generate more thermal load on the cutting tools. The solution in both rough turning and in gear cutting is to increase the feed by about 20% from the numbers used in today's machining. With a thicker chip, more heat is removed with the chip. In fact, the machinability profile of clean steels may be used to bypass the productivity of conventional steels.

Conclusion

In advanced designs for high-power density applications, conventional steels and clean steels offer completely different possibilities. By making use of clean steel properties, there are ways of making huge improvements in, for example, gearboxes, AWDs, and final drives for both current and future generations. The difference is because of the way conventional steels have been produced, with high S-contents and a higher probability of running into harmful defects, such as macro inclusions, in combination with a relatively low reduction ratio of dimensions from cast to finished product. The results are poor fatigue performance, which for many components is the deciding factor for design. And the performance is at its worst in the transverse loading direction. Clean steels that focus on reducing the probability of finding detrimental inclusions in the loaded volume, through controlling the steel making including sulphur and oxygen content, together with a higher reduction ratio on the other hand, can contribute to impressive improvements. And to make the most of the material, it needs to be part of the design process from the first step through a more holistic approach to powertrain design.

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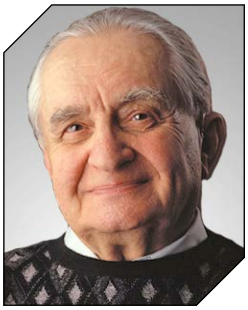
Lily Kamjou is a senior specialist in Ovako's Industry Solutions Development department. In her current role, she focuses on powertrain application development, specializing in clean steel and high-temperature resistance applications. Kamjou joined Ovako in 2008 and is based at the company's headquarters in Stockholm, Sweden. She has held a variety of positions in the automotive sector, including working with the highly demanding market for diesel injection systems. Kamjou has a master's degree in materials engineering from the Royal Institute of Technology (KTH) in Stockholm, Sweden and a bachelor's degree in social science from Stockholm University.

Joakim Fagerlund is a Senior R&D Engineer in Ovako's R&D department. In his current role, he focuses on development related to steel cleanliness and fatigue. He has been with Ovako for more than 10 years and is based at the company's headquarters in Stockholm, Sweden. He has a master's degree in materials physics from KTH Royal Institute of Technology.

Brent Marsh joined Dormer Pramet (a unit of Sandvik Machining Solutions) in March of this year as manager for the company's North Central Region. As an experienced market business development manager with a demonstrated history of working in the mechanical or industrial engineering industry, Marsh possesses valuable skills in sales, negotiation. Value stream mapping, failure mode and effects analysis (FMEA), SolidWorks, and industrial engineering. At Dormer Pramet Marsh will assume responsibility for sales and applications in ten central states including, for example, Illinois, Minnesota, Missouri and Nebraska. Marsh joined Sandvik in 2005 as a productivity team leader, and eventually served as manager of business development for the Americas before assuming his present position. Marsh received a BS in business administration/economics at Missouri Valley College (1983) and an MS/industrial technology at the University of Central Missouri (1986).

Thomas Björk holds a Ph.D. in materials science. He currently leads the group in Cutting Technology at Swerea KIMAB. The research is focused on machinability and machining processes of steels for components, transmissions, tool steels and aerospace materials. Studies of the cutting tools used and tool wear mechanisms are critical in explaining and differentiating machinability behavior. As Research Leader in Cutting Technology he also serves as secretary of the Member Research Consortia in Cutting Technology at Swerea KIMAB. He is the Institute's representative of the International Academy for Production Engineering (CIRP).

Faydor L. Litvin 1914–2017



Dr. Faydor L. Litvin, a living legend in the gearing industry, died April 26 at age 103. Credited with 25 inventions, three patents and some 300 publications, including (and still in print, see Amazon) Noncircular Gears — Design and Generation (with Alfonso Fuentes-Aznar); Gear Geometry and Applied Theory (Fuentes); and Face Gear Drive with Helical Involute Pinion — Geometry, Generation by a Shaper and a Worm, Avoidance of Singularities and Stress Analysis (NASA Technical Reports).

Dr. Litvin's prolific output was matched only by his genius. Of his patents, it is for "Apparatus and Method for Precision Grinding Face Gears" that he is perhaps best known. His "method" provided a way to reduce the weight of helicopter transmissions by 40 percent — in turn leading to fuel savings, reduced emissions and lower seat prices.

Indeed, Dr. Litvin's patented method revolutionized the grinding of hardened face gears without sacrificing the level of safety typically found in spiral bevel gears. It enabled use of such low-cost, high-capacity gears in applications specific to aerospace, automotive, and shipping manufacturers.

Significantly, Dr. Litvin was equally celebrated for his academic career as a professor teaching the analysis and kinematics of mechanisms; theory of gearing and applications; advanced theory of gearing; dynamics of machinery; analysis and design of manipulators; and special topics in advanced kinematics and dynamics of mechanisms. A Professor of Mechanical Engineering at the University of Illinois at Chicago since 1979, he also served as Director of the university's Gear Research Center. In that role he supervised the research of 84 Ph.D. students.

His academic and research careers both began in his native Russia — beginning with St. Petersburg State Polytechnic University (1947–64) and later at St. Petersburg Institute of Precision Mechanics and Optics (1964–78), where he was professor and department head of mechanisms theory and machine elements.

A partial listing of honors bestowed includes: ASME Fellow; 12 NASA Tech Brief Awards (1984–2004); Inventor of the Year 2001 from the University of Illinois at Chicago; and the Thomas Bernard Hall Prize Award (2002) from the Institution of Mechanical Engineers, U.K. Dr. Litvin also served as associate editor of Computer Methods in Applied Mechanics and Engineering, was a member of the honorary editorial advisory board of the journal Mechanism and Machine Theory, and served on the editorial board of Gearing and Transmissions.

Dr. Litvin was husband of the late Shirfra Litvin, and is survived by two children, four grandchildren and seven great grandchildren.

Reacting to the news of his passing, Dr. Robert F. Handschuh, Chief, Rotating and Drive Systems Branch NASA Glenn Research Center said, "This is very sad news for me as Dr. Litvin was like a 'Technology Father' to me. Part of my Ph.D. was based in using his methodology for gear geometry development. I managed his grant work with NASA/Army over a 25-year period and therefore talked to him very frequently and visited U of I at Chicago a multitude of times. His USA-trained students have now found prominent places to further impact the gearing industry. Many of his ideas are flying today in our latest military and civilian rotorcraft and (in so doing) has made a substantial impact to the gearing industry. Dr. Litvin was a very special person, both professionally and personally. Even though he was from Russia, he became a real American."

Michael Goldstein

RECEIVES AGMA DISTINGUISHED SERVICE AWARD

Dean Burrows, president of Gear Motions, Inc. and chairman of the AGMA Board of Directors presented the Distinguished Service Award to **Michael Goldstein** at the AGMA Annual Meeting, April 1, in Palm Springs, California.

The Distinguished Service Award is bestowed only upon an individual who has advanced the state of the gear industry throughout their notable career, who has advanced the state of the gear industry through many years of dedicated work, and whose efforts and achievements have significantly benefited the gear industry and its end users.

The 2017 recipient is Michael Goldstein, of Goldstein Gear Machinery, publisher and editor-in-chief of both *Gear Technology* magazine, and *Power Transmission Engineering* magazine.

"Michael has been a longtime member and supporter of AGMA, but also importantly he has focused a great deal of energy in helping the gear industry through his publications,"

Left to right: Michael Goldstein, Dean Burrows

Burrows said. "Michael began his career in the gear industry in 1964 when he joined his father at Cadillac Machinery Company. He started *Gear Technology* over 30 years ago, bringing a platform for the gear community when none existed previously. In recent years, this publication has also been preserved in digital form with the *Gear Technology* Library, featuring a searchable database of over 2,100 technical articles published over the life of the magazine. Michael started *Power Transmission Engineering* magazine in 2008.

"In addition to his work with the gear industry, Michael has held leadership positions in the Machinery Dealers National Association and the European Association of Machine Tool Merchants, where in 2003 he was honored as Fellow—only the second non-European to have been given that award."

Upon receiving the award, Goldstein made the following remarks:

When I was a very young boy, my father impressed upon me the idea that we all have an obligation to give back to society. He used to tell me that we would live in a very bleak world if everyone was just a taker. As I grew up, I took note of many individuals who gave generously of their time, knowledge and experience to contribute to various venues in our society.

When I joined my father in the used machinery business in 1964, I immediately started to follow in his footsteps by contributing to our association, the Machinery Dealers National Association (MDNA). My father was a past national president of MDNA. After doing work on the chapter level, I quickly went to the national level and joined MDNA's for-profit publishing subsidiary, which published a directory of available used metalworking equipment, called The Locator. *The Locator looked like a telephone directory and had had listed over 32,000 used machine tools being for sale, with approximately 5% of which were added or subtracted every month. We printed and mailed 120,000 books every single month. This product still exists today in digital form. Through the years that I was on* The Locator's *board, and then eventually moving through the chairs as an officer, jobs came up that no one else wanted. When we had to buy a new mini- computer (the PC had not yet been invented), I did the research with our executive director and bought a DEC computer. When we needed a new computerized typesetter, again with our executive director I did the research and bought one. When we needed to negotiate a new printing contract, or a contract for paper, I was, again, the volunteer.*

With these experiences, I felt I was being trained for something, though at the time I didn't quite know what it was. I was just following my father's standard, volunteering because I recognized an obligation to do so.

In the early 70s, I worked for a company called Daldi & Matteucci (DEMM), first in Milan and then, living in Bologna and working in Porreta Terme, up in the mountains between Bologna and Florence. Also, throughout my early career as a used machinery dealer, specializing in gear equipment, I traveled all over the world to inspect and buy inventory and visit customers.

During that time, I became aware of and saw important technical writing being done and presented at AGMA's Fall Technical Conferences and in technical magazines and conferences all over the world. However, I recognized that the information presented at those conferences was never widely disseminated. The owner, plant manager or VP of Engineering would attend these events for three days, come home with a large blue binder containing all the technical papers, and return to his desk with three days of work piled up. The blue binder would be put up on the shelf and *no one but the attendee would ever know the contents.*

When I came out of the presidency of The Locator, *in '83, I had the idea that this technical information was extremely valuable to more than just the attendees and, with my publishing background and experience, I thought that this information could be the basis of a magazine for the gear industry, worldwide. This is when I first started to think about the concept of obligation really being an opportunity.*

Although I continued on MDNA's board of directors, I started to realize that there were many other benefits that I could see by being involved and active in our association. First, you get to meet a lot of people from all over, all of whom are in the same business as you, but who think differently and react to problems differently. Not better, not worse, but different!

It opened my eyes to how different people solved similar problems in a different way. Also, I got to meet people with expertise in aspects of the used machinery business in which I had no experience or insight (i.e. leasing, financing, etc.). My father had an expression "You don't know what you don't know," and working with a myriad of people in your own industry makes this abundantly clear. Because of the nature of working in an association, you often have to speak in front of groups, whether it's committees or boards or the association itself, which gives you practice in public speaking, a difficult task for everyone. Even Johnny Carson said near the end of his career that he got butterflies before the curtain would open.

When I started, I was newly married and had a child and was trying to build a business just like every young person in industry and I didn't know where I would find the extra time for my association activities. But I found that I quickly became a better time manager. In a short period of time, I was able to include the association activities into my routine without overlooking or denying any other responsibilities.

But I think the most valuable quality that you can learn from association work is people skills. When you have to work with a lot of volunteers, each with distinct personalities, needs and goals—and any one of them can tell you to go stuff it—you're forced to develop the skills necessary to point everybody in the same direction and to work as a team. Those skills translate extremely well when you go back to your company. You're able to direct your people effectively—not because you're the owner or the boss, but because you are a good leader. I believe there is no better place for you to acquire those skills than in association work.

Some years ago, I discussed this very same concept with Dr. Phil Terry, who was then head metallurgist at Lufkin Industries and Buzz Maiuri's predecessor as head of the AGMA Technical Division. He relayed a story about Lufkin's VP of Engineering, who had joined one of the AGMA technical committees as a very young man. At the time, the committee was populated with substantially older and more experienced volunteers. As the youngest guy there, they often gave him the dirty jobs: "research this," "find out that," "write this proposed standard," etc., but he persevered and eventually headed that committee. I asked Phil, "If this young guy did not have those experiences doing the research, writing the standards and dealing with substantially older and more knowledgeable people, is it possible that he would not be the VP of Engineering of Lufkin Industries today?" Phil remarked, "I've never thought of it that way," thought a second and then said, "Probably not." An obligation that turned into an opportunity.

I was on the board of MDNA for over 40 years. During that time the U.S. representative to the European Association of Machine Tool Merchants (EAMTM) was set to retire and asked if I would work with him on the council and eventually replace him, representing all of the non-European members to the council. Again, I saw an obligation that could turn into a potential opportunity. While I continued to develop my people skills, my speaking skills, etc., and this also gave me an opportunity to see a much broader aspect of the used machinery business and to better understand how the English don't think like the Germans, who don't think like the French, who don't think like the Italians, and who don't think like the Scandinavians, etc. In my case, I represented mostly Americans but also Japanese, Koreans, South Africans, South Americans, an Israeli, etc., which was a whole new experience. Further, my wife, Marsha, and I were required to attend their annual conferences in such places as the Canary Islands, Estoril, in Spain, Santa Margarita, Scotland, Paris, Cannes, Berlin, Villa d'Este in Como, Monte Carlo, Stockholm, Florence, Marbella, Lanzarote, Malta, Barcelona, Jersey, Sorrento, Naxos, Rhodes, Budapest—yes-a tough job! I served on their council for 21 years and was honored as a Life Fellow of the Association, only the 15th recipient and second non-European since 1940. An obligation that became an opportunity.

When I first came up with the idea of starting Gear Technology *magazine, there were three people/companies that were important in supporting me and my idea, which I would like to acknowledge. First, Marty Woodhouse, Sales Manager at Star Cutter Company was on board before I even had a chance to give him my whole pitch. I said "Marty, don't you want to hear my all my ideas?" He replied "I like the idea, the industry needs this information and you can count on Star Cutter Company for a one-page ad." The second was Henry (Hank) Boehm, President of Liebherr America, which has been a continuous advertiser from day one. The third is David Goodfellow, who at that time was the president of American Pfauter, who has also been an advertiser from our first issue, first with American Pfauter and now with Star SU, and we are and have been David's sole advertising venue to the gear industry, for 34 years.*

With what we've heard earlier in the conference about the upcoming challenges of IoT, participating in your association is an efficient and valuable way to, together, learn about these new technologies. We also had a speaker talk about the difficulty in the challenges of engaging millennials, who were born and raised with electronic devices and it's a perfect way to get them interested in our industry, by getting them involved in the association's upcoming IoT offerings, so that they can start in areas that they know and that challenge them so that they can grow into the mechanical parts of the gear manufacturing and bearing industry, as they grow and mature.

I would like to thank and acknowledge my wife, Marsha, as we just celebrated our 50th anniversary of our journey together, and she too has always had the same attitude toward obligation being opportunity, and my accomplishments often pale compared to hers.

I have found that obligation and opportunity are often two sides of the same coin and, in life, when you flip a coin with obligation facing up, more often than not, the coin will come down on the side of opportunity.

Kapp Technologies

ANNOUNCES PERSONNEL CHANGES

Michael Ruppert joined the Kapp Group in Germany in 2005 and moved to the Boulder, Colorado operation in 2007 to run the tool manufacturing business reporting to Jim Buschy. Ruppert was recently promoted to vice president and general manager. Bill Miller joined Kapp as regional representative in 2000 and was promoted to vice president sales in 2007. Miller has recently been promoted to vice president of sales and service.

Buschy retires after 26 years with the company. The last 10 years he served as vice president and general manager. Buschy's leadership, technical knowledge and experience have been a sustaining force in the growth of the company. Under his guidance a new generation of employees has joined the company and learned the company culture set by his example. No task is beneath anyone including himself in service to customers. Customers know they can count on Kapp to respond in all cases.

Left to right: Michael Ruppert, Jim Buschy, Michael Kapp and Bill Miller.

"It is just what we do when called upon," said Buschy. The old cliché that "they threw away the mold" after Jim was born, is said of him by longtime customers. Miller and Ruppert lead a great team that will carry on in the same tradition.

Buschy looks forward to enjoying time with his family - especially as his grandchildren are in their formative years. The grandkids are, he says, his most important legacy. He is modest. (*www.kapp-usa.com*)

LMC Workholding

RECEIVES GOVERNOR'S CENTURY BUSINESS AWARD

LMC Workholding received the Governor's Century Business Award honoring its 100 years in business and was one of eight Indiana companies recognized by Governor Eric J. Holcomb with such an award. During the ceremony on March 27, 2017, a total of 34 companies were honored, including those receiving the Governor's Half Century Business Award. These awards recognize businesses that have remained in operation for a minimum of 100 or 50 consecutive years and have shown commitment to its employees, community and state.

"Today, we honor Indiana businesses that have withstood the test of time, helping to drive Indiana's economy forward," Governor Eric J. Holcomb said. "I am thrilled to celebrate this year's honorees and their integral role in building one of the nation's best business climates. Together, I'm confident we will continue to take Indiana to the next level, ensuring Indiana is the best place to start a business, grow a business and get a job."

LMC Workholding celebrated its 100^{th} anniversary in 2016, having provided quality products, services and solutions to the workholding industry for a century. LMC Workholding is the present entity of the Logansport Machine Company which from 1916 to the present has built a reputation for engineering and manufacturing of power chucks, cylinders and special workholding products in Logansport, Indiana. (*www.lmcworkholding.com*)

The AGS Gear Industry Training Series

An Introduction to Gear Process Engineering

Matthew Jaster, Senior Editor

With the number of contacts Joe Arvin has in the gear industry, the logical next step in his career was to start a consultancy business. He started Arvin Global Solutions two years ago, and began this next chapter in his career by asking about the most relevant challenges facing gear manufacturers today.

While some answers dealt with topics such as incorporating new technologies, staying relevant in a competitive environment and increased foreign competition, one challenge, in particular, kept coming up in these initial discussions—the lack of well-trained, knowledgeable gear process engineers.

"This came up time and time again," Arvin said. "The demand for gear process engineers led my business partner (Scott Newton) and myself to consider establishing a recruiting arm as part of AGS. Unfortunately, the lack of training programs available to the gear market was the first issues that needed to be addressed."

With his experience and growing list of gear contacts, Arvin changed his focus from recruiting to establishing a training program that could introduce some of the basic elements of gear processing to industry professionals. The first in the AGS Gear Industry Training Series: An Introduction to Gear Process Engineering took place March 7–9 at the Northern Illinois University (NIU) Naperville Conference Center.

Conversational Instruction

A prerequisite in developing the training seminar was to keep it conversational and educational, void of the pitfalls that can certainly dominate highly technical, engineering presentations.

"I didn't want this to be another typical monotone presentation where someone stands at a podium and delivers a great deal of information while the audience occasionally nods off," Arvin said. "We wanted it to be a forum to share ideas, offer suggestions and create a lot of back and forth between our presenters and our attendees."

For the first training seminar, Arvin invited a diverse group of presenters that included Ron Green, Matt Mondek, Bruce Roberge, Chuck Schultz, Mike Steele, Al Swiglo and Kevin Walsh.

Topics included "What to Look for When You Open Up a Blueprint?" "Turning, Milling and Drilling," "Gear Cutting," The Impact of Heat Treatment," "Surface Temper Etch and Magnaflux," and more.

One of the highlights of the program was the heat treat section, where attendees spent five and a half hours discussing heat treat distortion. Swiglo gave attendees insight into heat treat practices and offered ideas and suggestions they may not have considered previously.

"The greatest compliment was hearing how many of our attendees went back to their shops with new ideas and new ways at looking at heat treat distortion," Arvin said. "I think it was extremely beneficial to let our presenters like Swiglo share past experiences and anecdotal stories that really complemented the questions being asked."

Another highlight was when the attendees went through a step-by-step procedure to process a 22-inch shaft (6 in. diameter) with a helical gear in the middle. A panel of judges examined the work, offered alternatives and suggested how they could process the part differently. This again opened up a great bit of dialogue between presenters and attendees.

Overall, attendees were thrilled with the content presented. Mike McKernin, president at Circle Gear, wished a conference like this existed 30 years ago when he was first starting out in the industry.

"Joe Arvin is a really well connected and creative individual. I am sure he will continue to bring together our industry's most experienced professionals to pass their knowledge to the up-and-coming engineers," McKernin said. "I believe this conference was exceptional for the initial offering. I also believe the conference will improve with each future seminar."

Planning Future Installments

AGS plans to present the same seminar again in June and is also prepping an Advanced Gear Processing Course based on feedback he has received from his contacts in the gear industry.

"The advanced course will go more in-depth on heat treat distortion, how to control it, and determine what it has done to your gear teeth, etc.," Arvin said. "We'll take a closer look at heat treat distortion through various heat treating procedures."

There will also be more in-depth discussions on gear cutting. Arvin reiterated that the process engineer doesn't need to know how to set up a Höfler gear grinder, for example. "They need to know what's important once the gear blank reaches that Höfler gear grinder," he said.

The Advanced Gear Processing Course will also look at high-volume commercial gears for industries such as aerospace, energy and mining. After the successful workshop on processing a part in the first course, the Advanced Course will include three different parts for the attendees to process. "I'm looking forward to this section of the seminar and hearing what our judges have to say about the work our attendees present," Arvin added.

Skills Remain Top Priority

While the skills gap continues to plague the gear industry, manufacturing, in general, is still playing catch-up. According to Arvin, the industry is well aware of the problem, but they're still not where they need to be in terms of training the young engineers that will eventually lead the gear industry into the future.

"I can't tell you how many conversations I've had about the amount of experience that is disappearing on factory floors today. One gear manufacturer lost a bulk of his skilled labor in a three-week time span. This is where we come in."

The "we" Arvin is referring to includes many gear industry veterans that are retired, but want to stay in the game, so to speak, on a limited basis.

"These people have the knowledge and experience to share with the next generation of gear engineers, and more importantly, they *want* to share this information."

Arvin was skeptical when talk of his own retirement surfaced. He thought he might go crazy not being involved in the day-to day-minutia the gear industry offered.

"I called up five guys that had retired from the gear industry in the last two years to ask what they thought about retirement. Many of them said it was just okay and that they missed being in the fray. They also said they didn't want a job if that was the reason I was calling!" Arvin said.

Some of these same retirees, however, were very interested in participating in the gear seminar as a way to share their experiences and help the next generation coming up. And it was a way for them to continue participating in the gear industry on their own terms.

Schultz (a presenter at the event) discussed this sentiment in a recent blog on the *Gear Technology* website (*www.geartechnology.com/blog/why-not-teach/*).

"I was fortunate to have the opportunity to attend AGMA committee meetings from a relatively young age. The insights of the esteemed engineers at those gatherings were like a graduate school seminar," Schultz said. "If only I could go back and ask them the questions that have come to mind in the years since! My own work in this very public sphere is a small way of repaying the kindness shown to me back then."

For more information:
Arvin Global Solutions (AGS)
Phone: (800) 815-2303
www.arvinglobalsolutions.com

The next session of "An Introduction to Gear Process Engineering" takes place June 20-22 at Northern Illinois University. For more informatio, visit *www.arvinglobalsolutions.com.*

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June 6–8—Western Manufacturing Technology Show 2017 Edmonton Expo Center, Edmonton, Alberta. As the most important manufacturing technology event in Western Canada, the Western Manufacturing Technology Show is a venue for the manufacturing community to come together as one, whatever the current manufacturing environment. Leading-edge machine tools, tooling, metal fabrication, design engineering and advanced manufacturing equipment wall all be on display under one roof. With keynotes, panel discussions and interactive technology exchanges on the event floor, participants can be sure to connect with other stakeholders on timely topics including sourcing the future workforce and government programs driving innovation along with updates on energy forecasts and impacts to the region. For more information, visit *www.wmts.ca*.

June 12–14—AGMA Gear Failure Analysis Big Sky, Montana. Learn the skills necessary to diagnose gear failures and prescribe remedies. Study six classes of gear tooth failure: overload, bending fatigue hertzian fatigue, wear, scuffing, and cracking. Examine each failure mode as illustrated by color slides and field samples because of the magnification inherent in slide projection. Engage in group activity and discussion in a hands-on practical exercise using field samples and a case study. Recommended preparation for Gear Failure Analysis is the archived AGMA webinar, Metallurgy of Gear Materials, presented by Dr. Phil Terry. This webinar is excellent especially for those with no training in metallurgy. The webinar is available by download free for members and $159 for non-members. Gear engineers, users, researchers, maintenance technicians, lubricant experts, and managers should attend. Instructors include Robert Budny, Robert Errichello and Jane Muller. For more information, visit *www.agma.org*.

June 13–16—PowderMet 2017 Las Vegas. The International Conference on Powder Metallurgy and Particulate Materials will present leading companies featuring the latest PM equipment, powders, products, and services. Over 200 worldwide industry experts will present the latest in powder metallurgy, particulate materials and metal additive manufacturing. Additionally, the program for the fourth annual Additive Manufacturing (AM) with Powder Metallurgy (PM) conference, AMPM2017, is available online. Featuring worldwide industry experts presenting on the latest developments in the fast-growing field of metal additive manufacturing, the conference will be held June 13–15, 2017, at the Bellagio Hotel, Las Vegas, Nevada. The technical program is more robust than ever before with over 70 technical presentations. AMPM2017 shares several events and an exhibit hall with the co-located PowderMet 2017. For more information, visit *www.powdermet2017.org*.

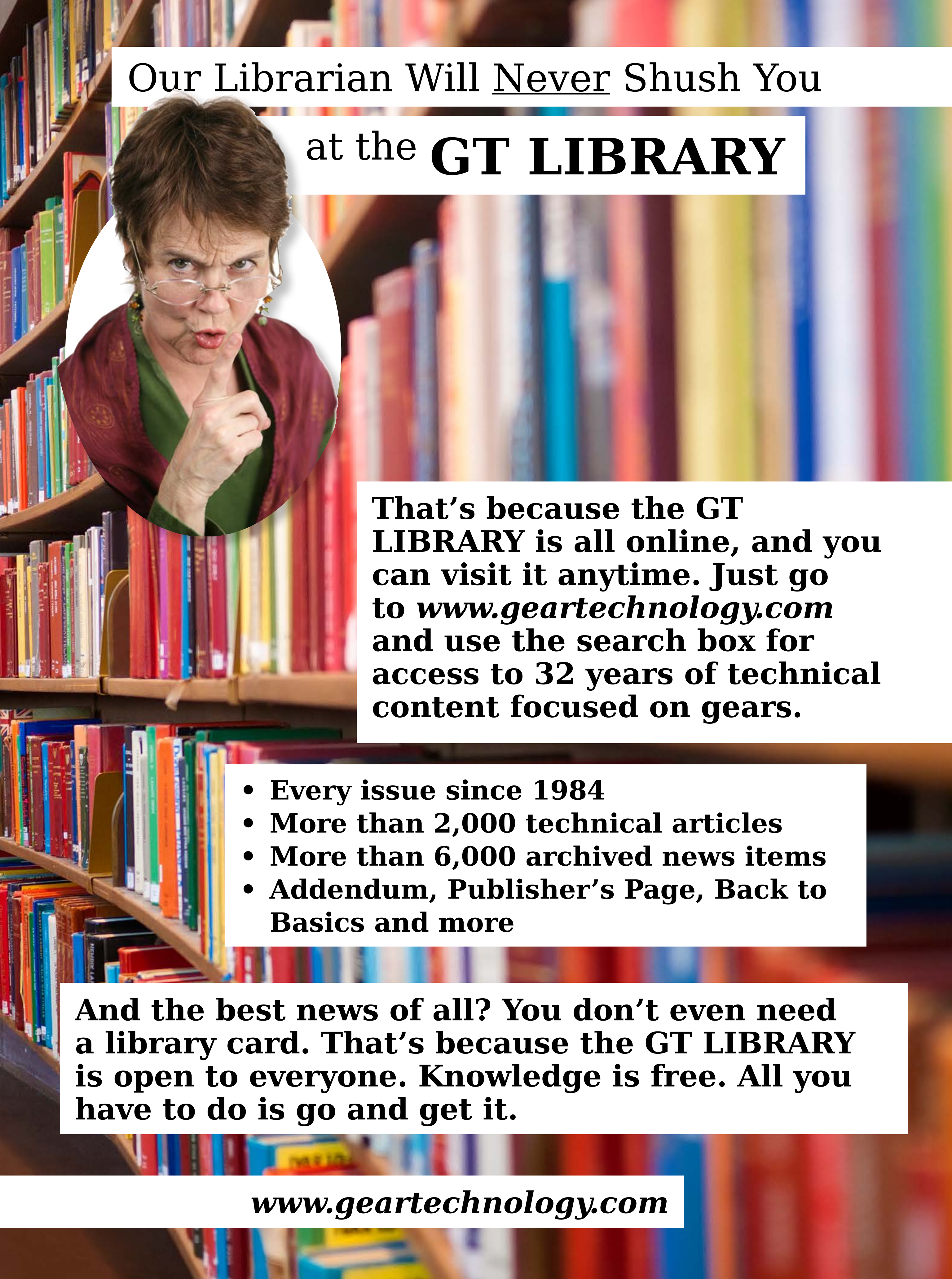
June 13–16—HxGN Live 2017 Las Vegas. Professionals from around the world attend this four-day event showcasing the latest data-driven developments enabled by Hexagon's newest metrology and manufacturing solutions for the Smart Factory. This year's theme, "The Shape of Potential," sets the stage for attendees looking to re-engineer product development from concept to reality in a connected world where data informs the process every step of the way. The conference's centerpiece is The Zone, which displays more than 50,000 square feet of Hexagon technologies and more than 60 exhibiting sponsors. For more information, visit *www.hxgnlive.com*.

June 20–22—AGMA 2017 Gear Manufacturing and Inspection St. Augustine, Florida. Learn key factors in the inspection process that lead to better design of gears. Develop a broad understanding of the methods used to manufacture and inspect gears. Discover how the resultant information can be applied and interpreted in the design process. (Please Note: This seminar is not a tutorial in the mechanics of machine operation; rather, the content addresses the relation between the manufacturing/inspection sequence and the detailed gear design process.) Gear design engineers; management involved with design, maintenance, customer service, and sales should attend. The course is instructed by Raymond Drago. For more information, visit *www.agma.org*.

June 27–29—Power-Gen Europe 2017 Cologne, Germany. Power-Gen Europe and co-located Renewable Energy World Europe, is where a rapidly-evolving power industry meets to gather information and compare views on shared opportunities and challenges. Attracting a worldwide audience, it is a key event for advancing Europe's energy future. Featuring the leading suppliers, sub-suppliers, service providers and end-users across the entire power generation value chain, the trade show encapsulates all aspects of today's centralized and distributed power generation sector. Together they combine strategic and technical presentations with the largest trade show exhibition of power equipment and services in Europe. Conference topics include renewable energy, energy storage, plant management, digital tools, and strategies for change. For more information, visit *www.powergeneurope.com*.

July 5–6—International VDI Congress-Drivetrain for Vehicles Bonn, Germany. The electrification of the powertrain implies one of the mega trends in transmission development. This technical advancement has impacted the entire automotive industry and affects everyone from the manufacturers, the suppliers and subcontractors up to the drivers themselves. This conference examines the predicted impact and influence of the new electric and hybrid vehicles on the market in terms of suitability for mass production. Here the focus is placed on the requirements that electrified drive systems have to fullfil and how they inspire manufacturers and suppliers in engineering and mechatronics to propel innovative developments to new heights. For more information, visit *www.transmission-congress.com*.

July 17–21—Coordinate Metrology Society Conference Snowbird, Utah. The eminent membership association for 3-D measurement professionals gathers annually to learn about technology achievements, network with industry experts and get a pulse on the metrology industry. Weekly registration includes entry to more than 20 technical sessions, workshops, the ever-popular Measurement and Education Zone, CMSC Exhibition Hall and networking events, as well as post-conference access to all technical papers and presentation materials. CMSC 2017 affords an educational opportunity for anyone interested in 3D measurement and inspection solutions utilized in manufacturing, research and development, and various scientific fields. For the 33rd year in a row, the CMS has connected with metrologists through education and technology. For more information, visit *www.cmsc.org*.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5 → My company's principal product or service is:________________

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

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The Guy Who Put the Gearbox Up Front

Charles Schultz, chief engineer, Beyta Gear Service and *Gear Technology* technical editor and blogger

As the Indianapolis 500 begins its second hundred years, it is a good opportunity to recall the guy who put the gearbox "up front." Harry Arminius Miller, native of Menomonie, Wisconsin, lead a team of engineers, designers, and craftsmen that created winning equipment for the Greatest Spectacle in Racing. From humble beginnings as a mechanic in a lumber yard, he rose to the top levels of motorsport by building finely crafted machinery.

His first breakthrough was in carburetors, and booming sales allowed him to build a well-equipped machine shop before The Great War. An extensive re-build on a Peugeot racing engine led to more custom engines for auto, boat, and even aircraft use.

A custom-built Miller engine sold for the princely sum of $4,000 in 1916 (approx. $96,000 in 2017 dollars). It was completed in less than seven months — seven months from starting the drawings to delivery, including pattern making, casting aluminum parts, machining, assembly, and dynamometer testing; an unheard of performance then and now.

Not content to just supply engines, Miller and his company were soon building complete racing cars for the most famous drivers in the country. The early 1920s saw Miller and Duesenberg battle for supremacy at Indianapolis and races around the country. Always looking for an edge, Miller saw an opportunity to lower the car's center of gravity by eliminating the driveshaft and sending power to the front wheels. The seat bottom was nine inches closer to the ground — a significant change, even with a very light driver. Front wheel drive was not a new idea, Walter Christy had built a monstrously huge racer for Barney Oldfield in the early days of the sport that even featured a transversely mounted engine like today's passenger cars.

Miller chose to simply turn his compact supercharged 91-cubic-inch, straight-eight around and connect it to a custom-built transmission that also served as part of the chassis. It evolved over a period of years to have inboard drum brakes, a semi-independent de Dion axle, and the latest in universal joint technology. As with all Miller Engineering products, the front drive unit was "finished all over," as befit the "jewelry on wheels" reputation Miller enjoyed.

Happily for gear enthusiasts, many of the Miller racing cars have been restored and, surprisingly, the detail drawings of many components have also survived. Longtime Miller collaborator Leo Goosen was active in racing into the 1980s and he kept track of his prints.

So just how good was the Miller FWD unit? With the assistance of G. E. White, auto racing consultant to the Smithsonian Institution, we obtained detail drawings of the reduction gears of the 1929 version of the Miller front drive gearbox. The photograph is from Mr. White's 2004 book, *The Marvelous Mechanical_Designs of Harry A. Miller*. If you look closely you can see that the gear teeth are badly damaged after just 91 laps at The Brickyard. While the car exited the event due to an engine problem, these gears do not look long for the world.

According to the drawings, they were made of SAE #6145 steel with a "desired carbon" of "45 to 50". The teeth are Fellows 6/8 NDP with a 20 degree pressure. If you trace the power flow through the transmission, you see that the shiftable gears are on the low-speed/high-torque side of the device. The generously sized [10" pitch diameter] bevel set has a 3:1 ratio; a 1.1 ratio spur set transfers the power to the shifter gears. The supercharged 91 developed as much as 154 horsepower at 7,000 rpm; 103 horsepower-per-liter is still an impressive number today.

Modern gear rating calculations reveal the cause of the pictured tooth flank damage: contact stresses are as high as 490,000 psi and bending stresses approach 170,000 psi on the most heavily distressed component. The carburized bevel set's stresses are well within current values, perhaps reflective of the rapid advances the auto industry was making with rear axles. Some current open wheel race cars use bevel gears based on 1928 Ford Model A geometry.

Modern Indy cars use a highly developed, transversely mounted transaxle but, unlike the Miller design, the shiftable gears are located on the high-speed end of the system. Peak stresses might approach the levels Miller experienced, but the gears are now carburized, hardened, ground, shotpeened and superfinished. Race retirements for gear failure are infrequent because of these improvements.

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