gear TECHNOLOGY®

SEP/OCT 2021

WORKHOLDING

POWDER METAL

GEAR HOBBING

Gear Technology is published by **The American Gear Manufacturers Association**

www.geartechnology.com

Star SU and GMTA have aligned on Profilator Scudding® technology to radically improve on traditional gear production technology

GMTA and Star SU combine the vast experience in gear cutting tool technology for new tool development and tool service center support from Star SU together with Profilator's Scudding® technology for special gear and spline applications.

With Scudding, quality meets speed in a new dimension of productivity, FIVE TIMES faster than conventional gear cutting processes. The surface of the workpiece is formed through several small enveloping cuts providing a surface finish and quality level far superior to traditional gear cutting technology. Scudding is a continuous cutting process that produces external and internal gears/splines as well as spur and helical gearing, with no idle strokes as you have in the shaping process. Ring gears, sliding sleeves and annulus gearing, whether internal helical shapes or internal spur, blind spline, plus synchronizer parts with block tooth features, and synchronizer hubs are among the many applications for this revolutionary technology from Profilator / GMTA.

Star SU   Star   SU SAMPUTENSILI

Phone: 847-649-1450

5200 Prairie Stone Pkwy. | Ste. 100 | Hoffman Estates | IL 60192

gear TECHNOLOGY®

contents

SEP/OCT 2021

A Publication of
The American Gear Manufacturers Association

24

features

technical

Stay Connected

Join the Gear Technology Facebook group at
www.facebook.com/groups/210890932629794/

Follow us on Twitter
twitter.com/#!/Gear_Technology

Connect with us on LinkedIn
www.linkedin.com/groups/3893880/

Subscribe Online
www.geartechnology.com/subscribe.htm

Vol. 38. No. 7 GEAR TECHNOLOGY. The Journal of Gear Manufacturing (ISSN 0743-6858) is published monthly, except in February, April, October and December by The American Gear Manufacturers Association, 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). The American Gear Manufacturers Association 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.

gear TECHNOLOGY®
Vol. 38. No. 7

departments

Cover Photo by David Ropinski

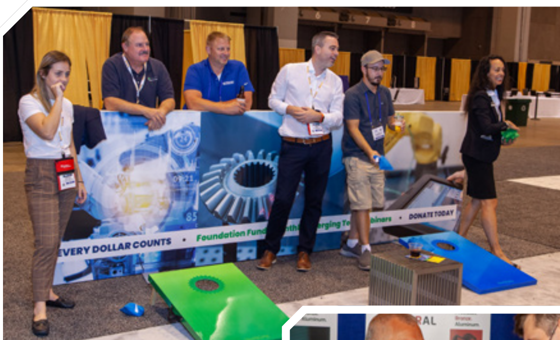
THE GEAR INDUSTRY'S INFORMATION SOURCE

www.geartechnology.com

Motion + Power Technology 2021

Thank you again to everyone that made the trip to St. Louis this year. We're ready to report on your latest and greatest technologies in the coming months online and in print. See you in Detroit in 2023!

www.facebook.com/geartechnology/photos



gear TECHNOLOGY®

AGMA MEDIA
1840 JARVIS AVENUE
ELK GROVE VILLAGE, IL 60007
(847) 437-6604
FAX: (847) 437-6618

EDITORIAL

Publisher & Editor-in-Chief
Randy Stott, Vice President Media
stott@agma.org

Senior Editor
Jack McGuinn
mcguinn@agma.org

Senior Editor
Matthew Jaster
jaster@agma.org

Technical Editors
William (Bill) Bradley, Robert Errichello, John Lange, Joseph Mihelick, Charles D. Schultz, P.E., Robert E. Smith, Mike Tennutti, Frank Uherek

DESIGN

Art Director
David Ropinski
ropinski@agma.org

ADVERTISING

Associate Publisher & Advertising Sales Manager
Dave Friedman
friedman@agma.org

Materials Coordinator
Dorothy Fiandaca
fiandaca@agma.org

CIRCULATION

Circulation Manager
Carol Tratar
tratar@agma.org

ACCOUNTING

Accounting
Luann Harrold
harrold@agma.org

MANAGEMENT

President
Matthew E. Croson
croson@agma.org

FOUNDER

Michael Goldstein founded Gear Technology in 1984 and served as Publisher and Editor-in-Chief from 1984 through 2019. Thanks to his efforts, the Michael Goldstein Gear Technology Library, the largest collection of gear knowledge available anywhere, will remain a free and open resource for the gear industry. More than 36 years' worth of technical articles can be found online at *www.geartechnology.com*. Michael continues working with the magazine in a consulting role and can be reached via e-mail at *michael@geartechnology.com*.

Now Hiring

Publisher & Editor-in-Chief
Randy Stott

Raise your hand if you have a staffing shortage.

Keep it raised if you don't know what to do.

Manufacturers have long been plagued by the difficulty of finding skilled labor. The refrain of the past decade might as well be "I could make more gears if I could hire more qualified machinists." We've been talking about this problem for years.

But it's not just manufacturers anymore. Restaurants, retailers and grocery stores just can't hire enough people to sustain the level of business they're used to. We've all seen the results. I drove up to a major fast food restaurant the other day, and the sign on the window said they were now closed at 7 p.m. instead of the normal 10 p.m. I've walked through the aisles of big box stores and seen piles of merchandise sitting on the floor because there's no one to stock the shelves.

What used to be a problem facing just us in the manufacturing industries is now everywhere. It's not just that no one wants to work in manufacturing anymore. It seems almost as if no one wants to work at all.

I mean, who wants to drive to work every day? Who wants to have a boss? Who wants five days per week of their life dictated by someone else?

We can blame it on COVID. We can blame it on the attitudes of millennials or Gen-Zers who would rather make money (or not) on TikTok than get a job where someone tells them what to do all day. We can blame it on the government. Or we can blame it on the fact that people got used to working at home, and now there's no going back. There's a lot of blame to go around and no single cause. But the phenomenon is real.

Unfortunately, I don't have any answers, and I haven't heard from anyone else who has, either.

But with your help, I'd like to start a dialogue. I want to hear from you about what you've tried, how you've failed, and hopefully a little bit of what's worked. Who have you hired, trained, or convinced to stay? What changes did you have to make? Just as importantly, who has left, and why?

Just as importantly, what are you doing to cope with these issues? Are you losing sales? Are you outsourcing? Are you investing in more automation? What answers have you come up with to keep the gears turning?

Even if you don't have answers either, I'd still love to hear from you. The dialogue starts with an e-mail. Just send me one at stott@agma.org. I promise I'll write back, and if you DO have ideas, I promise I'll share them with the community.

Let's talk.

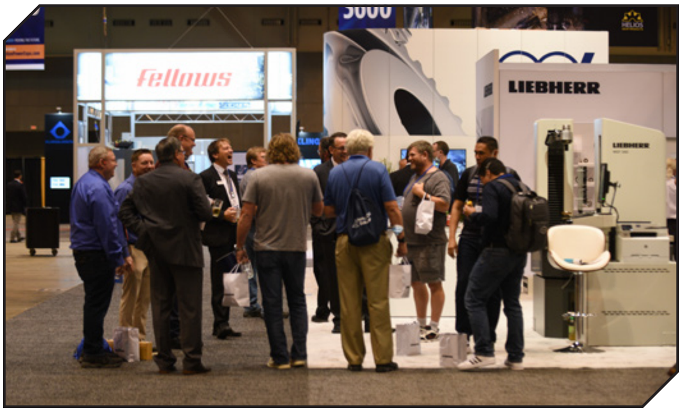
P.S. You can put your hands down now.

MPT EXPO 2021: Moving Industry Forward in Tough Times

Steve Janke, Chair, AGMA Trade Show Advisory Committee
President, Brelie Gear Company Inc.

On behalf of the AGMA Board of Directors, Show Committee and our 123 exhibiting companies—thank you for supporting Motion + Power Technology Expo 2021 (MPT Expo).

We all know this event was not the show we expected, in terms of attendance. There will not be any glowing press release about crowded aisles, overly busy booths, and long days and nights spent with customers. Combined, Heat Treat and MPT Expo drew over 2,000 total attendees—down from our normal 6,500. Those are the facts.



On the other hand—what has always made our show stand apart from other larger shows is attendee quality. One major benefit of MPT Expo is that no one comes to this show by accident. If you aren't focused on gear technology—you don't show up and roam the hall, kicking tires or looking for free food and giveaways.

Even with the decrease in attendance, it was important to hold MPT Expo this year to begin to get back to normal even in the face of the ongoing pandemic, supply chain challenges and other factors making 2021 an abnormal year. I am proud to see the resiliency of our industry and I know that it really only takes one or two QUALITY leads to make MPT Expo a success for most of our exhibitors—and even this year, MPT Expo was able to provide that connection between buyers and sellers.

As a long-time supporter of Gear Expo, and as the Chair of AGMA's Show Committee, I can live with that fact—furthermore, that's the way I like it! Small, 100% focused on power transmission innovation, and affordable for both the big multinationals, and small family-owned open gear shops, like mine—Brelie Gear.

I know many companies managed their expectations, rationalized their spend—and of course, many cancelled due to COVID. But for the leaders that showed up, spent their money wisely, and focused their time on delivering value to their customers—I am confident the show will have a strong return on investment.

That is AGMA's goal—always has been, and always will be.

- For MPT EXPO 2023 – we have already started to deliver on that goal through the following ways:
- For MPT Expo 2021 Exhibitors – we offered a $21 for 2021 special per square foot rate if you signed up during the show. I am pleased to report that we had a 99% renewal rate for the show and are already larger than the 2021 event.
- For MPT Expo 2021 Exhibitors – who signed up, then cancelled due to COVID, we will be offering a special early bird registration through November 30.

We are expanding our Solutions Center offerings in 2023, and will work with speakers who sign up to ensure their onsite presence also includes a digital presence on *geartechnology.com*, *powertransmission.com* or both websites.

AGMA and the Trade Show Committee are also spending the next six months considering how MPT Expo supports the industry. We will be focusing on all aspects of the show—what's working and what isn't along with location, exhibitor make up, partnerships, and what changes to marketing have occurred post-COVID—such that MPT Expo needs to adjust.

AGMA will also spend time discussing how to bring the next generation of buyers to MPT Expo.

None of these challenges is easy to solve, nor will there be a silver bullet to "fix" anything that needs fixing. I am certain not every direction we take will be supported by 100% of our industry. That is also why it is so important to be involved at the committee level. AGMA makes a difference in bringing the industry together, and if you want a say in the direction the show is headed, I encourage you to support the efforts and join in and grab a seat at the table. Share your opinion, your expert knowledge and join your peers to mold the future of MPT Expo.

My message to the entire industry—our machine tool innovators, our materials suppliers, our open and closed gear system providers—EVERYONE—is this: AGMA and its members drive power transmission innovation—and we want MPT Expo to be the platform of choice for both buyers and sellers.

Again—thank you for your support of MPT Expo—I look forward to seeing you in Detroit in 2023.

Get a Grip

Gleason's new Modular Standard Workholding solution puts the exceptional changeover speed of Quik-Flex® into small, medium and large standard modules, readily available for the most common cylindrical gear bore sizes. All are equipped with 'New Blue' Segmented Collets for maximum reliability and wear life.

www.gleason.com/qfp

Total Gear Solutions **Gleason**

Felsomat

IMPROVES PART QUALITY AND CUTS PRODUCTION TIME WITH LASER WELDING LINE

When a leading automotive supplier in Mexico was looking to cut production time and improve part quality for their rear drive assembly (RDU) and power transfer unit (PTU) assembly, they knew just who to turn to — Felsomat USA! The Felsomat USA automation experts used their expertise to create not one, but TWO laser welders for this customer. "We're thrilled that we had the opportunity to show this automotive supply leader the capabilities of our laser welding line, and that the customer saw the incredible benefits of our system," says Daniel Maerklin, president at Felsomat USA. Maerklin continued, "We knew our complete laser welding system would be the perfect fit for the application because of its production quality, versality, and short cycle times. Clearly, the customer saw the benefits too as we just shipped their second complete system!"

The Felsomat laser welding cell is called a complete welding system, because of all of the amazing components it includes. "We wanted the laser welding system to really do it all, essentially be a one-stop-shop for the laser welding of parts. With this system, we've successfully achieved that goal," says Maerklin. And that is absolutely not an understatement. This state-of-the-art complete line includes press, laser clean, and ultrasonic test stations, as well as a robot handling system. By combining all of these pieces, the complete part assembly can be performed in one system, minimizing production times and improving overall part quality.

Showcasing some of its extreme versatility, this laser welding line has an interchangeable laser head and clamp that can be easily swapped for each individual part. "We know that the thought of changing out these pieces can be scary, but we've designed the machine so that it is not only simple to change but can also be done in no time! We know that production time is critical, so we ensure changeover times are minimized," says Maerklin.

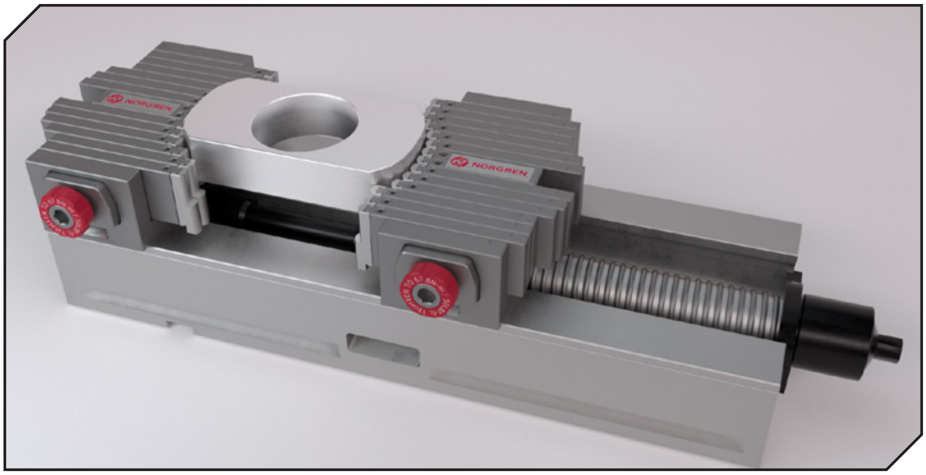
The laser welder is equipped with a 6 kW TRUMPF laser source. "We work very closely with the experts at TRUMPF and are excited to partner with them again for the laser sources in our state-of-the-art laser welders," continues Maerklin. Not only was versatility and power essential for this customer, but so was maintaining consistently high part qualities. "To ensure parts are perfect, every time, our Felsomat laser welder is equipped with a laser seam tracking and weld monitoring system from Lessmueller" concludes Maerklin.

Felsomat recently hosted its Technology Days from October 12–14 at their Konigsbach-Stein, Germany-based headquarters. Throughout this open house, they showcased their e-motor traction motor stator and rotor assembly systems, 2D and 3D hairpin stator bending demonstrations, and Felsomat FHC hobbing and machine demonstrations.

www.felsomat.de

Norgren

LAUNCHES ADAPTIX SOFT JAW



Norgren, part of IMI plc, recently made two key announcements at the 2021 Precision Machining Technology Show (PMTS 2021). One to officially launch Norgren's Workholding business, and the other to preview the Adaptix Soft Jaw, the first product in the new portfolio.

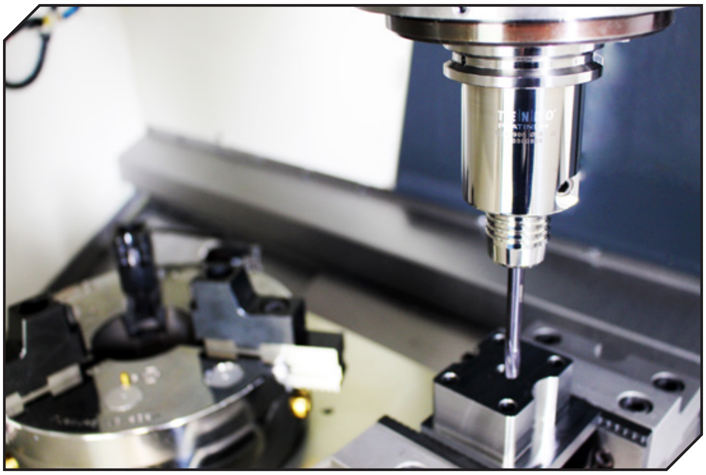
The Adaptix Soft Jaw uses adjustable fingers and interchangeable tips to grip a wide variety of parts or workpieces during the computer numerical control (CNC) machining process. It was specially engineered to be a one-size-fits-all alternative to standard, single-application aluminum soft jaws.

"Single-application soft jaws require a significant amount of time, skill and raw material to construct, even before a single part is milled," said Tom Wood, senior director of growth initiatives at Norgren. "We saw an opportunity to solve several machining problems with just one tool, and so we designed the Adaptix Soft Jaw to grip nearly any part with comparable repeatability and clamping force as single-application soft jaws. This singular innovation in the CNC machining workflow can have a huge impact on several pain points in the industry."

The Adaptix Soft Jaw's adjustable fingers and interchangeable tips are made out of a variety of different materials to match the milling needs of a particular part. The fingers easily mold into place to conform to the shape of the target part and then are locked in place. This configuration process takes minutes, instead of hours, on average, with traditional soft jaws. The soft jaw fits directly onto a vise, and is currently compatible with Kurt and Schunk brand vises, with other vise compatibility planned in the near future.

"The COVID-19 pandemic and the pressure it placed on supply chains, hiring needs, and skills training only exacerbated the existing needs of the machining industry," said Wood. "Adaptix and, by extension, Norgren Workholding were created by Norgren to leverage our commitment to breakthrough engineering to make manufacturing more streamlined and accessible, and to solve several industry bottlenecks. So, we are thrilled to have collaborated with industry experts to create a first-of-its-kind soft jaw for the next generation of machinists."

www.norgrenworkholding.com



Schunk

INTRODUCES HYDRAULIC TOOLHOLDER

Schunk has announced the launch of the new TENDO Platinum V2 hydraulic toolholder. Designed and manufactured in the USA, the TENDO V2 is a culmination of more than 40 years of ongoing research and development in hydraulic toolholder technology to bring manufacturers the most advanced direct clamping toolholder in the industry.

A critically thought out, modern toolholder

With its ergonomic slim outer profile for easy and comfortable actuation, the TENDO Platinum V2 is specifically designed for direct clamping the tool. Imbalance correction goes unnoticed and is carefully designed into the body profile. Constructed of durable hardened tool steel, the V2 improves stability, stiffness, and clamping force to give you a toolholder with longer sustained accuracy throughout its life.

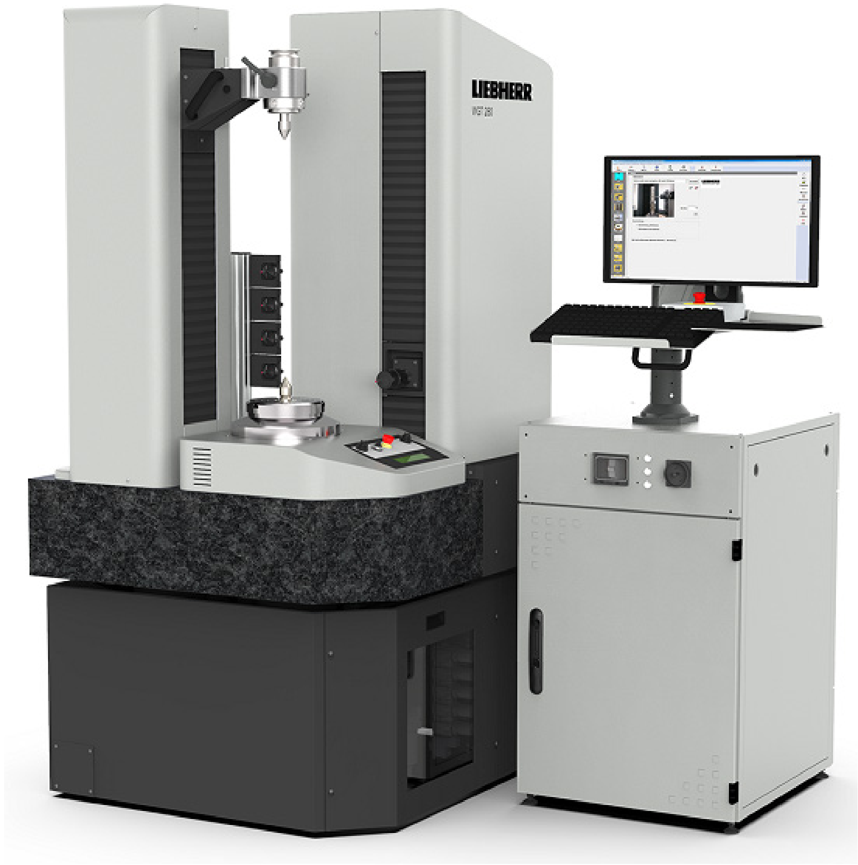
Innovative since the beginning

The TENDO Original with three rings was developed in 1978 and was the first in the market to feature a run-out/repeat accuracy greater than or equal to 0.003, balance G2.5 25,000 rpm, and no risk of damage when clamped without the tool. SCHUNK continues to bring technological advances to the world of toolholding with the release of the TENDO Platinum V2.

Schunk.com

Liebherr

OFFERS LHINSPECT SOFTWARE FOR WGT SERIES



After acquiring the highly efficient software from metrotek, Liebherr will be offering it under the name LHInspect for use on the WGT series of high-precision, four-axis inspection machines.

LHInspect offers a unique range of functions and will be used in conjunction with the WGT series of machines for inspecting all types of gears, gear cutting tools and shaft-type workpieces, including size and position determination. LHInspect also supports the manufacturer-neutral GDE interface for exchanging geometrical and measurement data between gear inspection machines and gear cutting machines as the basis for automated correction of setting data (LHOpenConnect).

The easy to operate and user-friendly WGT gear inspection machines with LHInspect, are the result of decades of experience in gear inspection technology.

In the future, Liebherr Verzahntechnik GmbH will continue to develop LHInspect while focusing on the needs of customers.

www.liebherr.com

TCI Precision Metals

INSTALLS WATERJET MACHINING CENTER FOR MACHINE-READY BLANKS

TCI Precision Metals has announced the installation of its second OMAX 80X waterjet machining center. The new machine is the second waterjet added in the last twelve months to keep up with growing demand for precision Machine-Ready Blanks and other specialty parts.

TCI has standardized on the OMAX 80X for its speed and more accuracy compared to other abrasive jet waterjets in the industry, which will help TCI Precision Metals maintain its excellent customer lead times even the face of growing demand.

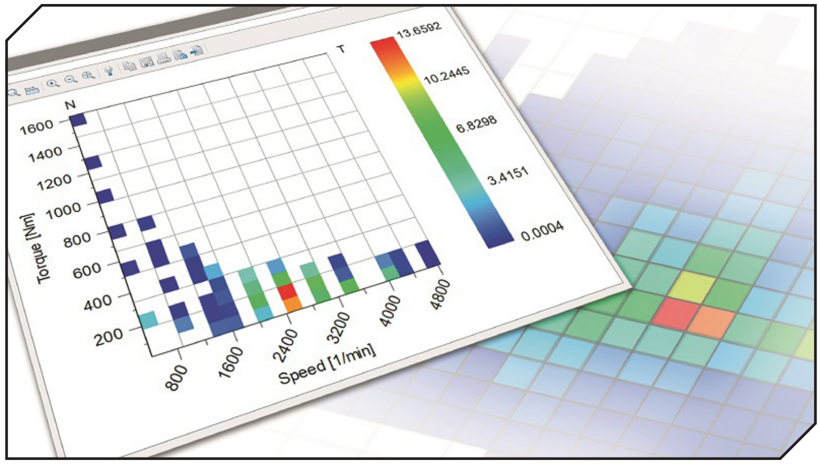
"Our recent investments in both sawing and waterjet cutting equipment have paid off big for our customers by helping us shorten lead time and improve on time delivery. Most of our Machine-Ready Blanks orders are for either aluminum or stainless steel alloys. For our aluminum customers we previously installed a new Schelling fm8 plate saw, capable of cutting aluminum and other nonferrous metals up to 6-inches in thickness at speeds up to 100 ft/min. We then added our initial OMAX waterjet machine, and now our second one, capable of cutting stainless steel alloys and other ferrous materials that are up to 8" thick on 15'0" × 7'5" table. This allows us to maintain complete control over managing our customer's expectations when it comes to special needs and on time delivery," said Ben Belzer, president of TCI Precision Metals.

OMAX waterjet machining centers are recognized as being highly accurate, flexible, and efficient. With its Tilt-A-Jet cutting head technology, the model 80X produces high precision, finished edge cuts that are square, with no edge tapper, which is a problem with many other waterjet matching centers.

www.tciprecision.com

KISSsoft

EXAMINES GEAR STRENGTH CALCULATION WITH LOAD COLLECTIVES

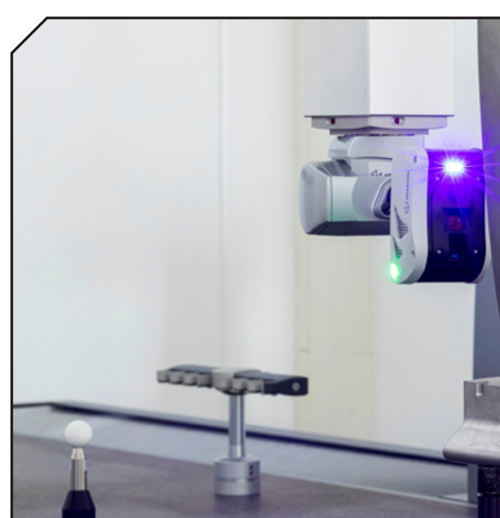


Load spectra can be derived from time series - a measured time-torque-speed curve or one derived from simulations. For time series with only positive torque, the "Simple Count" method is used to obtain a load spectrum with torque-speed bins. The refinement of the resolution in load spectrum bins (grid) can be specified.

The procedure is more complicated for time series with positive and negative torques since the tooth root is then subjected to alternating loads. First, the "Rainflow" method is used to find all significant torque changes over time. A load spectrum, which also contains alternating bending factors YM, is then derived from the resulting Rainflow triangular matrix. In addition to extended reports on the calculation details, graphical displays are now available in matrix form for torque and speed distribution with frequency. The same display can also be used for the direct input of load spectra. The evaluation and control of the collective are thus much clearer.

Dr. Ulrich Kissling will give an (online) presentation (in English) on "Use of duty cycles or measured torque-time data with AGMA ratings" at this year's AGMA Fall Technical Meeting (Nov 1-3, 2021) in the United States.

www.kisssoft.com



Hexagon's Manufacturing Intelligence

INTRODUCES NON-CONTACT LASER SENSOR FOR CMMS

Hexagon's Manufacturing Intelligence division has announced the HP-L-10.10, a genre-busting non-contact laser sensor for Coordinate Measuring Machines (CMMs) that offers manufacturers the ability to perform dimensional measurements at comparable accuracy to tactile probing and inspect almost any surface in a fraction of the time. Manufacturers using CMMs for critical part measurements have become accustomed to trading speed for accuracy. The HP-L-10.10 sensor utilizes Hexagon's latest cross-platform laser line scanning technology to offer similar repeatability and performance compared to tactile measurements executed on the same CMM. Furthermore, it can measure 600,000 individual points per second with a probing form error of just 8µm, rapidly capturing a complete high-resolution digital representation of a part that is valid for both surface and detailed feature inspection. While laser scanning has been possible on CMMs, the HP-L-10.10 is 7 times faster than its predecessor and introduces high precision scanning.

The new sensor employs Hexagon's unique SHINE (Systematic High-Intelligence Noise Elimination) technology, making it possible to scan almost any part surface or finish at maximum speed and accuracy without user intervention.

"We believe this laser-line scanner is game-changing because it offers speed, flexibility and accuracy without sacrificing one crucial inspection need for another," said Patryk Wroclawski, product manager non-contact and laser triangulation. "The HP-L-10.10 redefines what can be achieved with a single piece of equipment, so that our customers can utilize comprehensive measurement data for actions beyond final part quality, whether that be within new product development or continuous improvement initiatives."

The HP-L-10.10 complements Hexagon's extensive offering of sensor solutions for CMMs, providing manufacturers greater flexibility projects with confidence that their CMM investment can take on the broadest range

of measurement applications from larger sheet-metal parts to intricate electric vehicle components. Available for the GLOBAL S productivity line and GLOBAL Advantage CMMs.

Developed in close collaboration with the device, Hexagon's PC-DMIS inspection software enables users to automatically produce efficient laser-scanning paths by automatically generating the tips, scans, and motions needed for measurement. The software can capture a single point cloud with variable point cloud density within one motion that is valid for both surface and detailed feature inspection. Users can easily visualize surface imperfections, fully exploiting the scanner's multi-faceted capabilities to identify perceived quality issues, imperfections to feed continuous process improvement.

When measuring large parts or remotely programming the CMM, the user's experience is greatly enhanced by an integrated Overview Camera (OVC), that provides a clear view of the work area with visible guides on the part that indicate the measurement range. The visible guides help to warn the Quality technician when the measurement range is exceeded, allowing for easier routine creation and inspection through PC-DMIS software. The overview camera also improves productivity and collaboration during inspection, for example photographing a part surface that is out of tolerance to so the operator and production colleagues can quickly locate the problem.

The HP-L-10.10 laser-line scanner is now available worldwide. Visit Hexagon's new Can I Measure It? micro site for resources explaining how measurement challenges are overcome with effective strategies and the best use of CMM and sensor technologies.

Hexagonmi.com

Mercury Marine

ADVANCES HEAT TREAT PROCESSES WITH ECM TECHNOLOGIES VACUUM FURNACES SYSTEMS

Mercury Marine of Fond du Lac, Wisconsin, recently launched a plan to upgrade its heat-treating capabilities with a move to the low-pressure carburization and high-pressure gas quench system. Partnering with ECM Technologies, the new plan incorporates completely automated Nano vacuum heat treating systems. The innovative Nano system incorporates 20 bar nitrogen gas quenching along with Low Pressure Carburizing (aka vacuum carburizing). The Nano, with its versatile configuration, will operate several different carburizing, hardening, and spheroidizing processes simultaneously. This change marks a departure from Mercury's traditional atmospheric carburization and oil quench system while benefiting from advantages that come with vacuum processing:

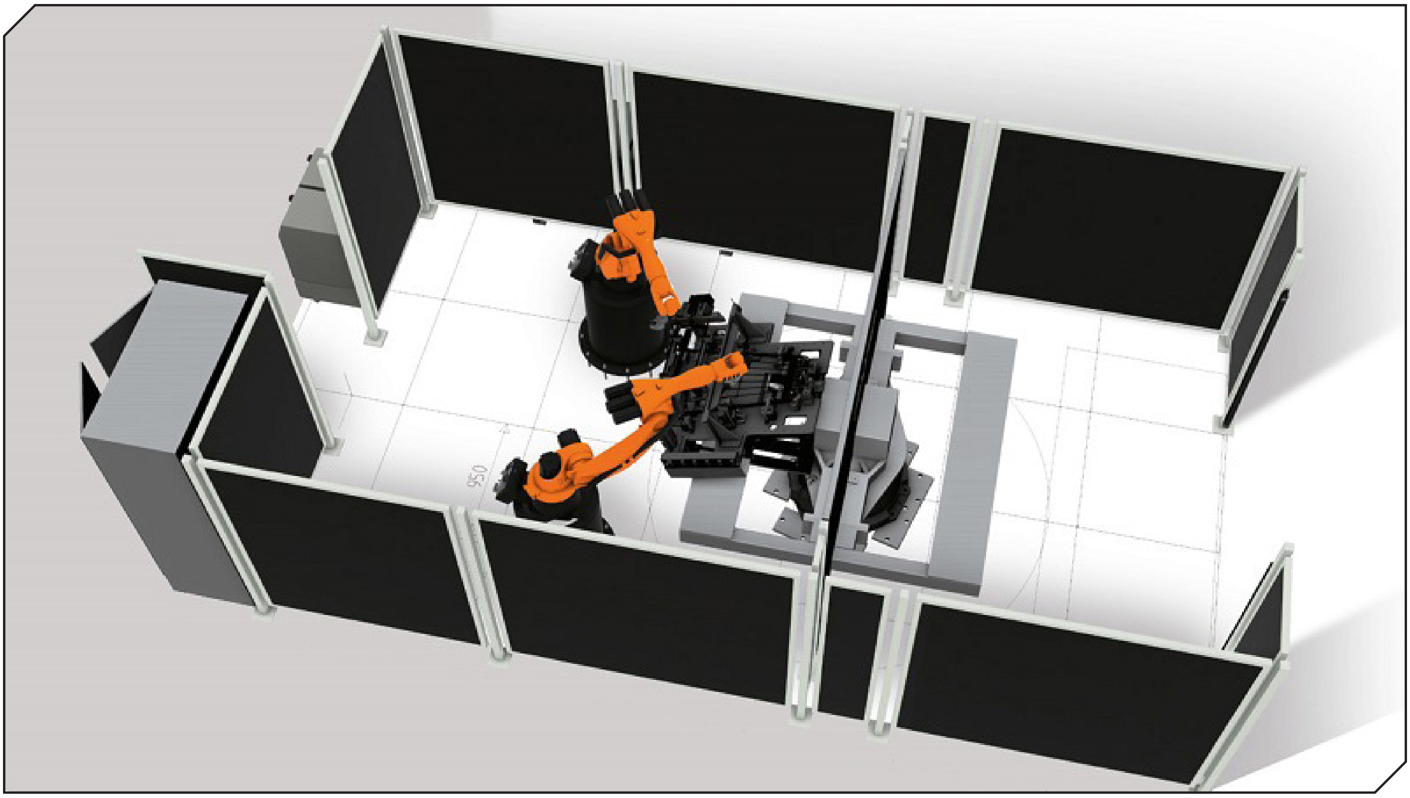
- Innovative vacuum heat treating in lieu of traditional atmosphere (elimination of intergranular oxidation & highly repeatable process with consistent results
- Employs preventive maintenance planning, remote system status access and facility information systems integration
- Relocates heat treat from a secondary location to the clean, controlled environment of the machining centers
- Converts to Small Batch processing principles to maximize process efficiency
- State-of-the-art growth with ECM's advanced system automation and robot capability with load building and breakdown
- Controls downstream operations by matching incoming dunnage with exiting workpieces
- Takes advantage of vapor and vacuum-based pre-cleaning technology to remove multiple machining lubricants
- Incorporates cryogenic and tempering processes within the automated system

The system uses all CFC workload fixtures and ECM's advanced automation fixture tracking to maintain a precise cycle count to know fixture life. This improvement for Mercury significantly reduces energy consumption and process cost per piece. Additionally, the vacuum process takes their heat treatment to a near-zero emissions for drivetrain components processed within the system.

Headquartered in Fond du Lac, Wisconsin, Mercury Marine is the world's leading manufacturer of recreational marine propulsion engines. A division of Brunswick Corporation (NYSE: BC), Mercury provides engines, boats, services, and parts for

recreational, commercial and government marine applications. The company empowers boaters with products that are easy to use, extremely reliable and backed by the most dedicated customer support in the world. Mercury's industry-leading brand portfolio includes Mercury outboard engines, Mercury MerCruiser sterndrive and inboard packages, Mercury propellers, Mercury inflatable boats, Mercury SmartCraft electronics, Land 'N' Sea marine parts distribution and Mercury and Quicksilver parts and oils.

www.ecm-usa.com
www.MercuryMarine.com.



KUKA Robotics

LAUNCHES LATEST DIGITAL SIMULATION SOFTWARE PACKAGE

KUKA Robotics has launched KUKA.Sim 4.0, a major enhancement of its modular digital simulation software package. This latest version facilitates accurate planning, programming, safety configuration and more through digital twins of the automation processes.

The KUKA.Sim software enables manufacturers to test and validate robotic installations before equipment arrives, minimize the footprint of cells with 3D visualization of safety spaces, then transfer applications with 100% accuracy to an actual robot controller. In addition, KUKA.Sim 4.0 can program robots offline, analyze cycle times and expand with new functionalities through add-on modules.

KUKA.Sim 4.0 checks reachability and detects collisions in virtual space to ensure foolproof implementation of programs and cells, minimizing the time and costs of planning tasks as well as actual production downtime. Through a digital twin that matches the physical process, 3D simulation covers the full planning process from design and verification through PLC code, eliminating bottlenecks with full consistency for advance testing and optimization. For system integrators, KUKA.Sim 4.0 saves time and increases project success with solutions that translate directly to customers' production lines.

In industries from consumer goods to electronics and automotive, KUKA.Sim 4.0 makes automation planning easy with a new KUKA Robot Language (KRL) editor that includes expert and beginner onscreen views with a visual program tree that facilitates ease even without previous KRL experience. Drag-and-drop configuration of an extensive library of smart components enables quick investigation of design ideas with accurate calculation of cycle times. Export options include 3D PDF files, detailed 2D mechanical commissioning data and presentation/simulation results for use on virtual-reality hardware or the Mobile Viewer app for smartphones and tablets.

Modular add-ons expand the flexibility and power of KUKA.Sim 4.0 and enable customers to acquire only the level of functionality they need. The Modeling add-on enables users to build a customized library based on the CAD data from the kinematic systems, sensors, material flow and physical behavior of their own robotic installations. The Connectivity add-on commissions robot cells virtually for accurate planning and implementation. The Arc Welding add-on defines robot approach positions and optimal orientations to speed up offline programming.

The my.KUKA customer portal handles new and existing licenses, provides updates and enables prospective customers to obtain a free trial of KUKA.Sim 4.0. The portal also processes software license purchases.

www.kuka.com

LK Metrology

RELEASES LATEST VERSION OF CAMIO CMM SOFTWARE

LK Metrology has announced the release of the latest version of its measurement, programming, analysis and reporting CMM software. Now called CAMIO 2021, the software has been significantly improved in numerous key areas, helping to increase inspection productivity, improve the quality of data collected and gain better insight into the components being measured.

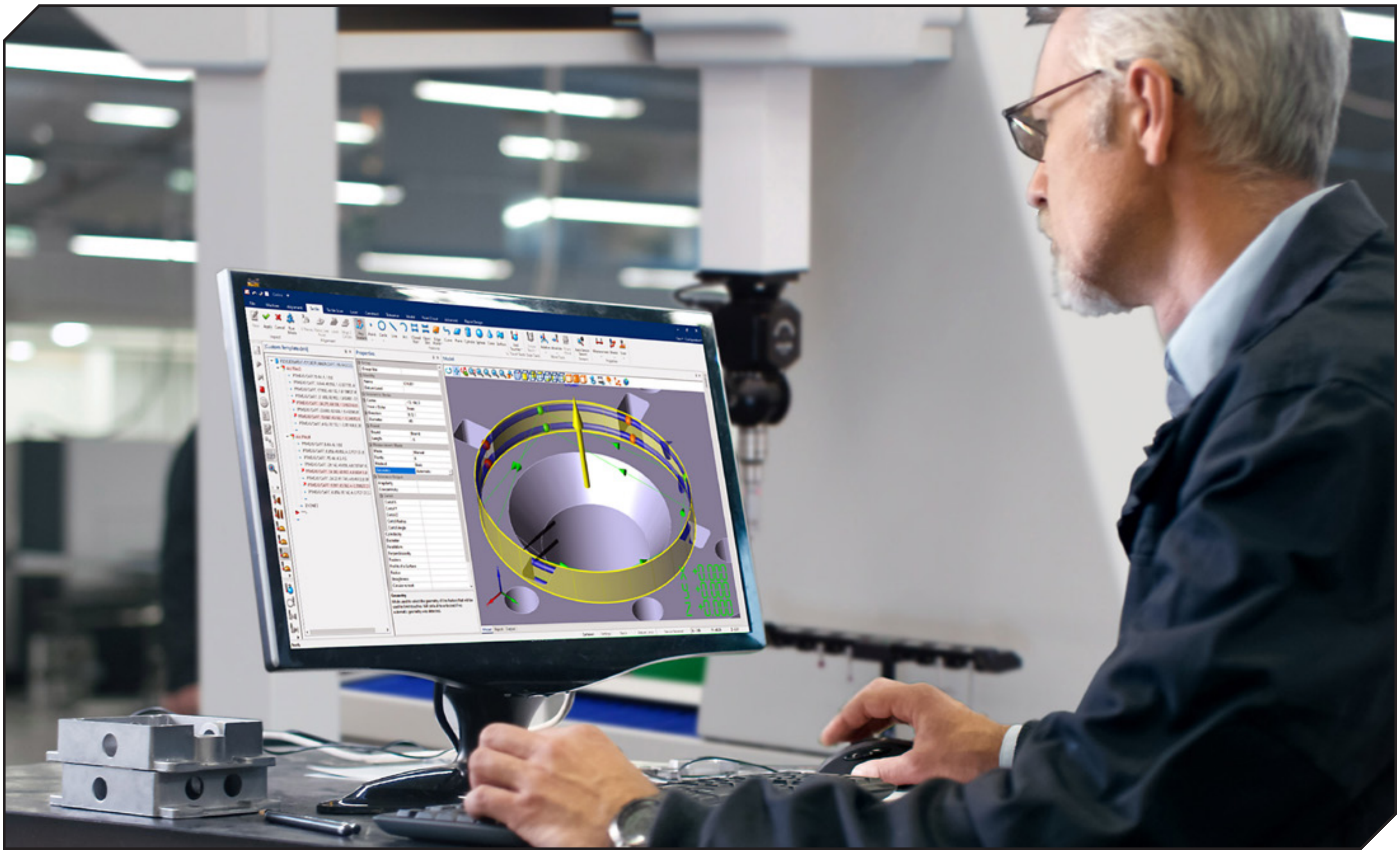
CAMIO 2021 Geometry Validation reduces the time taken when preparing new inspection programs by automatically detecting which surfaces of the CAD model should be used to measure the feature. It ensures that all measurements are taken on suitable surfaces automatically and at the same time provides the programmer with the option to modify the default settings and selections. While the feature is being programmed, the CAD simulation highlights the geometry used for the validation and previews the measurement sequence. This combines with the Teach Path view to provide a full visual and numerical evaluation of the programming sequence prior to executing the touch points or scanning sequence, enabling the programmer to get the inspection sequence right first time when programming online or offline. Other improvements have been made to the programming workflow by extending the advanced picking function to touch points and scan paths on a CAD model and to indicate the selection of existing measured features.

New for CAMIO 2021, probe self-centering allows the center point of a V-groove to be automatically located and measured using a scanning probe. This replicates hard gauging and measurement using gauge-balls, typically used for gear tooth inspection and measuring countersink depth. Probe self-centering responds to the continuous deflections of an analogue probe in real time to locate the mid-point between two surfaces.

CAMIO 2021 Orientation Tolerancing automatically determines the appropriate relationship to a secondary datum based on the nominal feature definitions. Any manually specified relationship is ignored, except in cases where a relationship cannot be determined automatically. Tolerance zone shape and relationship to the secondary datum outputs have also been added for enhancing the output of orientation tolerances. Perpendicularity, parallelism and angularity checking have been enhanced with improved validation, evaluation and user feedback for geometric dimensioning and tolerancing (GD&T).

For CAD users, the CAMIO 2021 exchange file versions have been updated to the latest release of Spatial's InterOp. The interoperability software is an industry-leader in CAD data translation that allows users to import, interact with, share and export 3D data easily across CMM platforms and manufacturing sites. The Select Components dialogue box has been extended to reserve stalls in the ACR3 change rack for any CMM laser scanner, including all those from Nikon Metrology. Lastly, the NmAPI interface that enables deployment of Nikon Metrology laser scanners on a CMM has been updated to version 4.6.

www.lkmetrology.com



Klingelnberg

PRESENTS FLEXIBLE ROLL TESTING ON THE R 300

The Höfler Cylindrical Gear Roll Testing Machine R 300 is the latest machine development from the engineering company Klingelnberg in the area of cylindrical gear technology. Designed for all five roll testing methods, this compact machine is the ideal solution for anyone who wants to combine inspection cycles and reduce disassembly costs while benefiting from a user-friendly design.

Due to the increasing outsourcing of part and component production in large-scale transmission manufacturing, some transmission and vehicle manufacturers now require a certificate of quality for all gears installed in the powertrain. A further driver of ever-higher inspection levels is e-mobility. With the elimination of the combustion engine, there is an even greater focus on the noise behavior of the transmission than before, since the electric motor has a comparatively low masking effect on gear noise. To meet this challenge, Klingelnberg is building on roll testing technology, a familiar method from the bevel gear industry that is now moving into the world of cylindrical gears.

Only with a flexible test machine can the many quality control requirements for gears be met. Depending on the configuration, the R 300 provides the option of using all five roll testing methods. These include the single flank test, the structure-borne noise test and torsional acceleration test, the double-flank test, and the helix roll test. Thus the R 300 can be used at every point in the production process chain for cylindrical gears – from monitoring the soft cutting to checking the hardening distortions, to evaluating the noise behavior of the installation-ready gear.

Modular Machine Design

In terms of axis traversing paths, the Höfler Cylindrical Gear Roll Testing Machine R 300 covers the same component spectrum as the tried-and-tested Höfler Cylindrical Gear Generating Grinding Machine Speed Viper. Gear components up to an outside diameter of 300 mm can be tested, for example. In conjunction with the optional counter support, shafts up to 800 mm in length can be analyzed to determine their running performance and noise behavior. With a minimal footprint of 2 m2, the machine's compact design also saves costs since it requires very little expensive floor space.

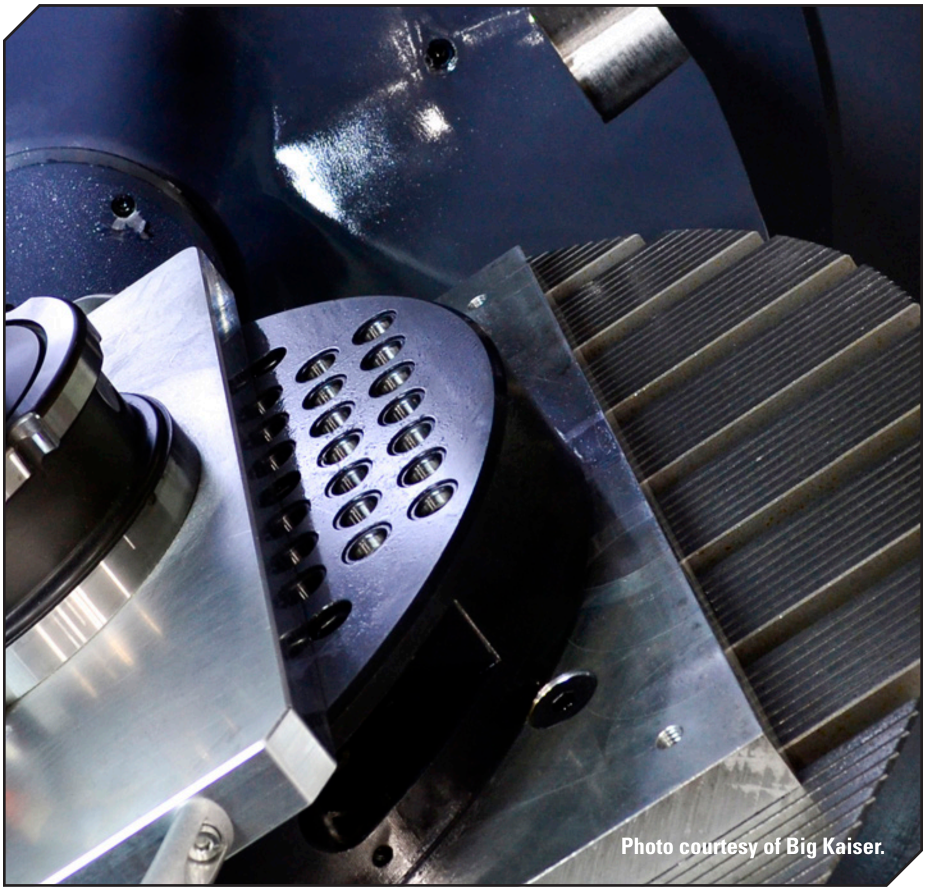
Convenient, User Friendly Design

The tried-and-tested design of the human-machine interface (HMI), familiar from the cylindrical gear and bevel gear processing machines, also ensures optimal user-friendliness in the R 300. The HMI is equipped with a 19-inch touchscreen, and important functions, such as "Clamp and release workpiece", can be initiated via hardware switches. To make the user navigation as easy as possible, the operator is guided via a process-oriented menu structure to only those windows that are necessary for the specific test task at hand. This contributes significantly to the prevention of input errors and shortens the time required to train new employees.

www.klingelnberg.com

The Next Era of Workholding

Matthew Jaster, Senior Editor



We asked what the future holds for workholding and the industry did not disappoint. All the machining trends such as automation, robotics, sensors, 3D-printed parts, etc. are finding their way into workholding equipment. The end game is saving money, conserving energy, mitigating the skills shortage, and highlighting flexibility and consistency in machining.

Gleason Examines Fast-Changing World of Workholding

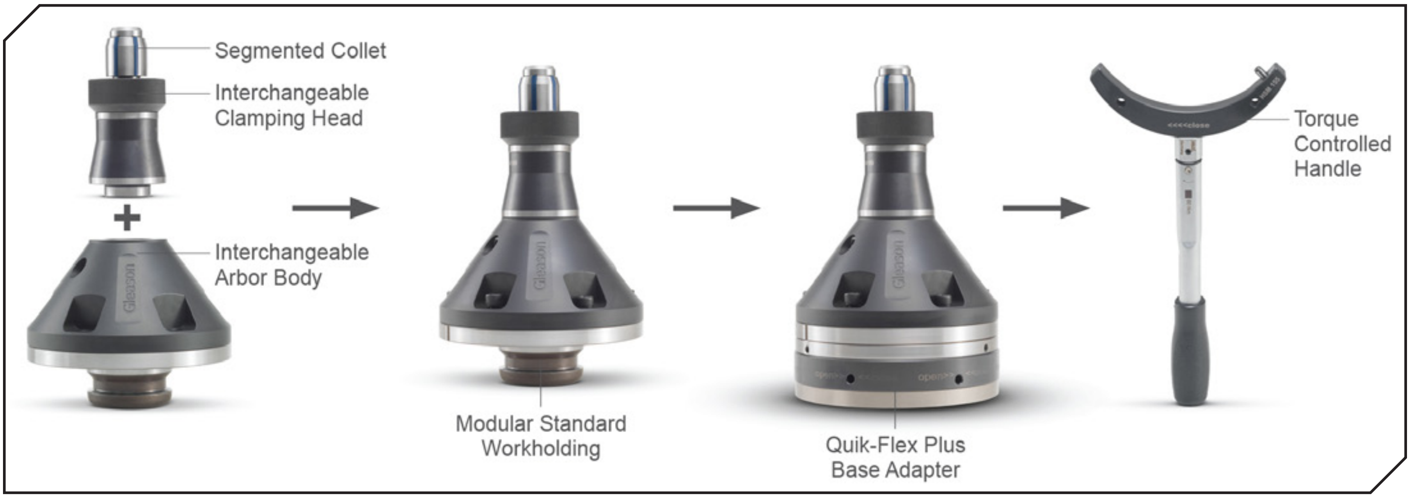
In the brave new world of smart factories, Internet 4.0 and highly automated machines and cells, workholding rarely gets top billing. Fortunately, most gear manufacturers are taking notice, as a new generation of these under-appreciated components that do the 'dirty work' prove their worth. Today, new workholding solutions are having a profound impact on reducing cycle times, scrap and, ultimately, cost per workpiece.

The Arrival of Quick-Flex—and Quik-Flex Plus

"For many of our customers, just-in-time production of smaller batch sizes requiring frequent part changeover is now the rule rather than the exception," said Paul Spencer, manager, new products, workholding at Gleason Corporation. "It was only a few years ago that traditional workholding required 20 or 30 minutes for changeover and considerable operator experience."

Fortunately, the arrival a few years ago of Gleason's Quik-Flex and Quik-Flex Plus systems have revolutionized workholding changeover for small and medium size cylindrical gears with a system of modules that can be installed on a base arbor that's permanently mounted in the work spindle with just the twist of an activation handle.

Now, accommodating a changeover for different workpieces can be done with a new module that's installed and



Gleason's new Modular Standard Workholding puts the performance benefits of Gleason's tool-less quick-change workholding solutions into a system of standard, interchangeable modules for the most common cylindrical gear bore sizes to greatly reduce lead times.

removed in just seconds, with only a single tool, and by even a novice. (Quik-Flex is so simple and effective that even non-operator contestants in our tradeshow demonstration challenges have routinely removed and installed Quik-Flex in under 10 seconds.)

For a gear manufacturer running small batch lots throughout the day, this can mean a savings of an hour or more in spindle time as compared to the old technology. Plus, the speed and ease of changeover when utilizing these new quick-change workholding systems can greatly minimize the need for skilled machine operators and toolmakers, which in this industry are becoming harder to find.


Gleason hydraulically actuated expanding and contracting workholding solutions are an increasingly attractive alternative to traditional mechanical systems. They're ideal for multi-stacking and thin-walled parts, with the added benefit of being sealed against contamination for greater reliability.

Quik-Flex Goes Modular, and Arrives Faster

"Most recently, we've raised the quick-change bar even higher, with introduction of a system of Modular Standard Workholding that puts Quik-Flex performance into a system of small, medium and large standard interchangeable modules that span the most common range of cylindrical gear diameters," Spencer said. "If Quik-Flex results in shorter cycle times chip-to-chip, then Modular Standard Workholding does it one better: shorter *ship-to-chip* time. Now, there's an in-stock, off-the-shelf solution available to users almost overnight to meet the workholding requirements of many of the most common cylindrical gear bore sizes and diameters."

This results in the elimination of many weeks of waiting, and the inherent cost, for special tooling whenever a new application arises. Instead, manufacturers can meet most, if not all, of their needs with any of a family of just eight standard modules covering bore diameters ranging from 18 mm to 100 mm. Compare that to the costly and time consuming 'start from scratch' approach that you often must take to either make, or source, workholding for completely new, and increasingly complex, gears.

"Now, a gear jobber, already stretched thin for time and resources, can assemble most, if not all, of the necessary workholding right off the shelf. In most instances, adaptation, if any, is minimal, requiring the machining of a simple backing ring," Spencer added.

How does it work?

"Simple. Each of these small, medium and large modules consists of an interchangeable upper module connected to an interchangeable arbor body, both of which come in a variety of sizes to form a multitude of standard combinations to fit the user's part-specific application requirements. These modules interface with a base adapter that's permanently mounted in the work spindle. The modules can be installed, and removed, in just seconds with just a quick twist of the system's simple, removable, activation handle. No other tools are required, nor any of the usual mounting bolts, set screws or ejector screws to deal with," Spencer said.

Workholding Gets Smarter

Since customers are increasingly in need of the ability to track critical data, Gleason is incorporating 'Gleason 4.0' and gTools technology into its workholding. Benefits to the customer are significant.

"In the case of our latest generation of workholding, gTools will give users the option to use RFID chips or data matrix codes to ensure that the workholding system is assembled correctly with the right components, and track how many times components have cycled," said Brian Baldeck, manager design engineering and assembly, at Gleason Corporation. "This is critically important in a busy tool room where collets and arbor bodies with various 'miles' on them are mixed and matched, thus increasing the potential for poor runout or a failure downstream. Data provided by gTools can optimize the assembly process, help the customer to determine when preventive maintenance is required, and trigger reorder points for wear parts such as collets."

One Solution Doesn't Always Fit All

As awareness of workholding's importance has grown, so too have customers' willingness to explore alternative clamping solutions. Hydraulically actuated workholding solutions for bores and shanks, for example, are now available from Gleason for applications once considered strictly the domain of traditional mechanical clamping systems. Most recently, Gleason has developed hydraulic workholding systems for applications ranging from hobbing automotive transmission gears in high volumes, to Power Skiving large internal gears, in lots of one or two, to high-precision hob sharpening operations. These systems are capable of performing as well or better than their mechanical counterparts. Most importantly, they offer a host of characteristics unique to hydraulic systems that are increasingly desirable.

Some examples:

More Flexibility: Hydraulic workholding offer attractive benefits to manufacturers producing parts with various bore or shank diameters, and/or producing multiple parts in a stacked configuration. The new-design Gleason hydraulic production expanding arbor is available for, but not limited to, the most common size range of automotive cylindrical gears from 12 mm to 100 mm in diameter. It delivers a very powerful and consistent clamping force when hydraulic fluid pressure is applied to a thin-walled expansion sleeve, precision-machined out of tough tool steel. The sleeve expands as required by the application uniformly over its entire chucking length. This gives a single arbor the inherent flexibility to meet the requirements of a variety of parts with different bore diameters.

The ability to produce uniform clamping force across the entire length of a gear's bore also makes it an ideal solution for the machining of both thin walled and multiple-stacked parts. In the case of multi-stacking applications, the sleeve can be designed with multiple expansion zones so that even parts with different diameters can be stacked together and clamped with great precision.

Greater Reliability: These hydraulic workholding systems apply clamping forces in a completely enclosed system that's impervious to the contamination that can plague much more exposed mechanical systems. In high-volume, dry-cutting operations, the periodic downtime required for routine maintenance, cleaning and lubrication can be an enormous burden. The same problems exist in large-part production as well, and particularly so with internal gears where effective chip evacuation can prove more difficult.

"Additionally, Gleason's use of new FEA design tools, precision machining and heat treat resources, and our extensive workholding 'know-how', have enabled us to manufacture hydraulic workholding for greater reliability and extreme accuracy. Our standard hydraulic production expanding arbors, for example, deliver the standard accuracy and repeatability levels — 5 microns (0.0002") TIR — of their mechanical counterparts, but can also be designed for applications where the quality bar is even higher," Baldeck said.

Fast and Economical: Finally, hydraulic workholding can offer attractive economies. Meeting on-going new-part clamping requirements often requires production of new, high precision mechanical collets that are both expensive and require lead times of many weeks or months. In the case of a large-part Power Skiving application, Gleason's hydraulic workholding system was the perfect solution to meet the needs of the customer's ambitious multipart family production requirements. Just two large chucks, with adapting sleeves, accommodate a range of workpiece diameters from 200 to 400 mm. They can operate with less maintenance required as well, sealed against all the chips and swarf produced in this highly productive Power Skiving environment.

Going Beyond Gear Machines

"Increasingly, we're playing a role in providing workholding for machines on the periphery of the gear making processes — upstream, for example for the turning centers and 5-axis machining centers used to produce precision gear blanks. What works for gears on a gear machine also holds true for the blanks. Our new segmented collet, for example, is an exceptionally reliable and accurate bore clamping solution that can be easily adapted to a lathe or machining center with just a change in the base tooling," Baldeck said. "And, from a purely logistics standpoint, single-sourcing workholding where possible translates into more economic inventories, and easier training of a less experienced workforce for workholding that have common designs and functionality."

www.gleason.com

Smart workholding provides levels of control, consistency and safety that are in ever-increasing demand. **Photo courtesy of Big Kaiser.**

The Art of Clearance with Big Kaiser

The modern manufacturing plant is evolving.

"Gone are the days of all work being done in a vise one part at a time as most medium-size production customers are embracing palletization," said John Zaya, product manager, workholding at Big Kaiser. "We can support this with blank UNILOCK pallets the customer can customize to his requirements, or he can buy standalone UNILOCK retention knobs to attach to any pre-existing fixtures. For those that still need their vise, we can palletize them as well in those cases where knobs cannot be attached directly."

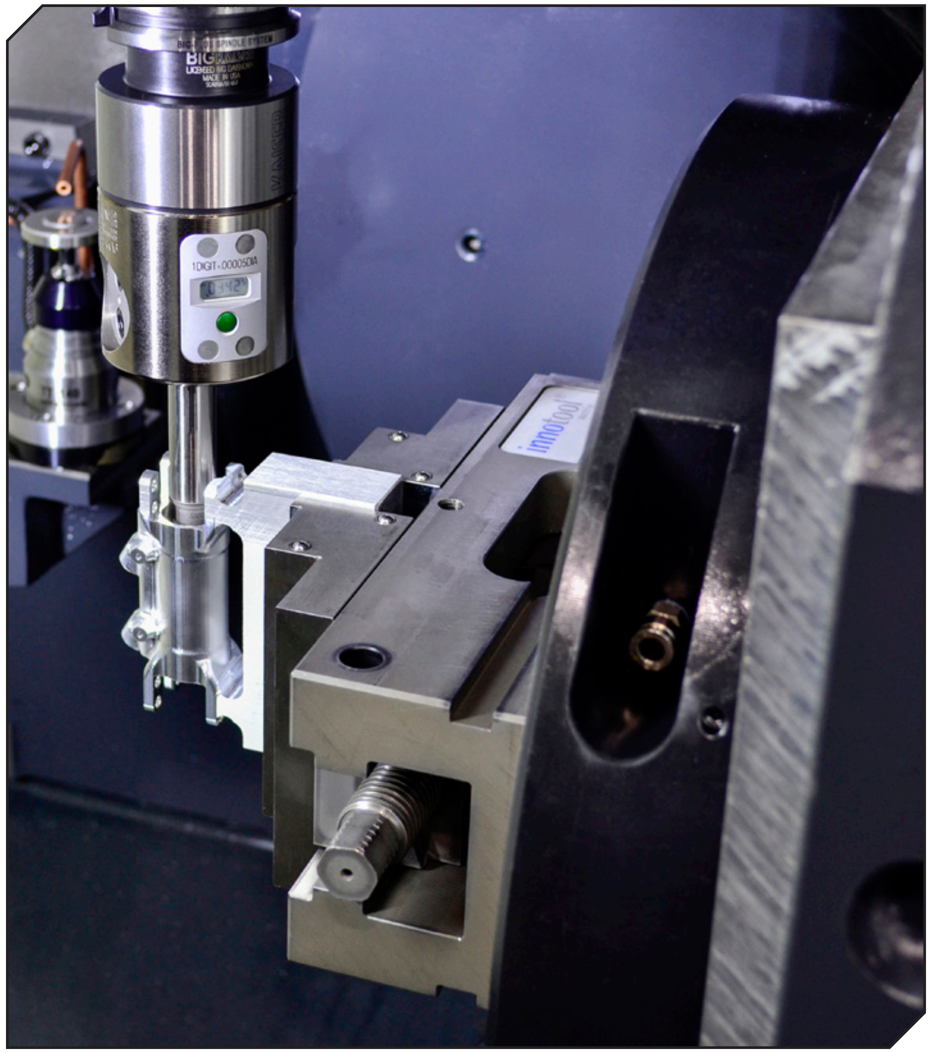
Zaya said that workholding has long had a stigma of not being as intelligent as the machine. However, in past years clamping pressure sensors and part presence sensors have been integrated to allow communication between the machine controller and the workholding system or the operator. This provides levels of control, consistency and safety that are in ever-increasing demand.

The challenges in workholding today start with clearance.

"Much like the real-estate sales mantra 'location, location, location,' in the 5-axis workholding market it's 'clearance, clearance, clearance.' Elevating the part up off the table to provide spindle-to-table clearance is the main goal with any workholding system. Next is clearance of the toolholder to the workholding system so many systems try to limit the amount of material they hold to the bare minimum. They also try to get entirely under the part in order to provide full access to the faces," Zaya added.

For customers looking for lights-out production or medium-to-large-scale production, robotic loading/unloading of parts is a key requirement. Robots can handle the fast rate of part picking and placing that is often required. The key to successful automation is how much is customized vs. standardized, Zaya said.

"Many machine builders are doing their integrations in order to provide a one-stop-shop instead of relying entirely on aftermarket integrators. They choose to offer turnkey solutions for machine tending that rely mostly on billets of material. The other end of the spectrum requires many special parts that allow for the customer to deal with a variety of parts. They end up using a pallet-based system that will have semi-standardized blank pallets that can be loaded up with different workholding based on the various workpieces."



The UNILOCK system allows for fast, consistent and accurate changeovers.
Photo courtesy of Big Kaiser.

And does this mean that special fixturing or customized equipment is becoming more mainstream today?

Zaya said in some cases, yes—and in other cases—no.

"Those that recently saw much of their workforce laid off are looking at alternatives to have a warm body sit in front of just one machine. This is where automation of part load/unloading has risen," Zaya said. "For those companies deemed essential and who did not have to let go of workers are so busy they do not have time to consider specials. They are forced to work with what they have already."

Several factors will determine the efficiency and effectiveness of workholding equipment in the future, according to Zaya.

"The use of pallets that can be customized for holding both raw billets, partially processed parts, and 3D printed parts will allow for the greatest flexibility and efficiencies. Vises, grid plates and the like can do this in some cases. So having a common interface, like the UNILOCK Zero Point system, that allows for fast, consistent and accurate changeovers will lead to higher spindle up time and lower costs," he said.

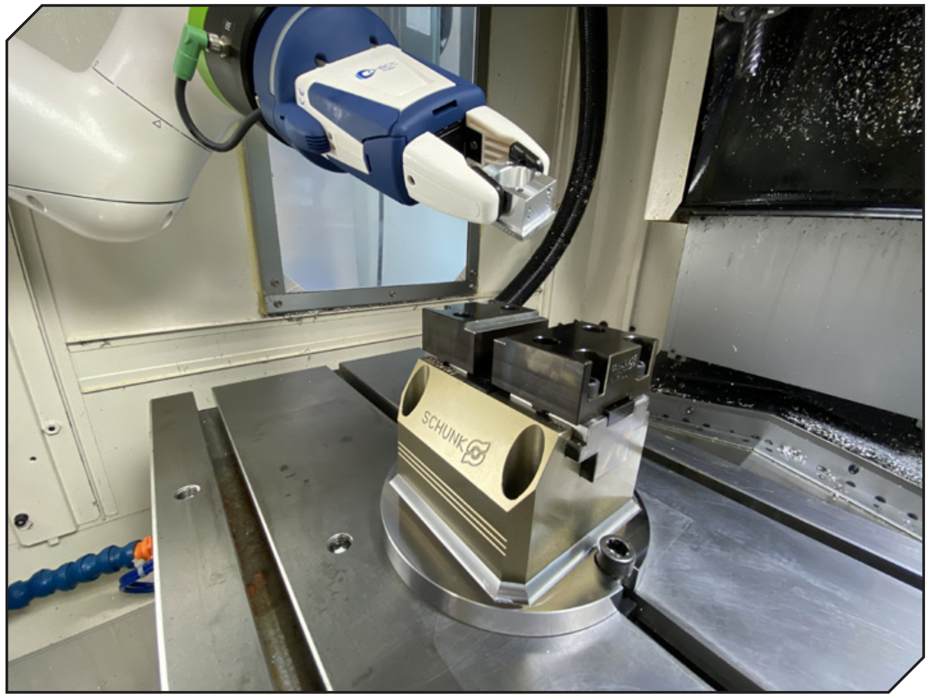
Quick-change products, such as modular stacking systems, allow flexibility to be provided within the system's capabilities and may include a variety of bases, extensions and reductions, all of which can have various diameters and height combinations.

As workers retire, they are being

replaced by a younger generation with a different approach to methods, processes and concepts.

"This will open new avenues to find higher levels of efficiency in all sectors of the economy and manufacturing," Zaya said. "The biggest area that will see most growth is the 3D printing sector. The ability to eliminate waste from the machining process by moving from substrative to additive will have a huge impact."

www.bigkaiser.com



The PGS3 is a compact pneumatic clamping force block for automated metal cutting of small components from Schunk.

Schunk Offers Specialized Workholding Solutions

Automation is the name of the game for Schunk's customers.

"This means confirmation of clamp/un-clamp functions, sealed systems that require less maintenance, fail-safe mechanisms. Not only automation, but automation with reduced lot sizes. In other words, flexible automation. This requires challenging and modern technologies that automate more than just part clamping. It now becomes necessary to automate changeover for handling a variety of workpieces, etc.," said Michael Gaunce, vice president of sales, tooling and workholding at Schunk. "This means continuous monitoring of the systems/processes — more than just success or failure, but a more granular view on spindle loads, tool-life, and even predictability."

For gear manufacturing, it depends on the part, but for first operations using aggressive gripping jaws (impact series claw jaws) can significantly increase machining parameters which means reduced part cycle time. Additionally, quick-jaw change chucks allows for fast repeatable changeover (THW3) and precise hydraulic arbors for finishing operations. These all play a role in smart workholding solutions.

Flexibility is the greatest challenge, according to Gaunce.

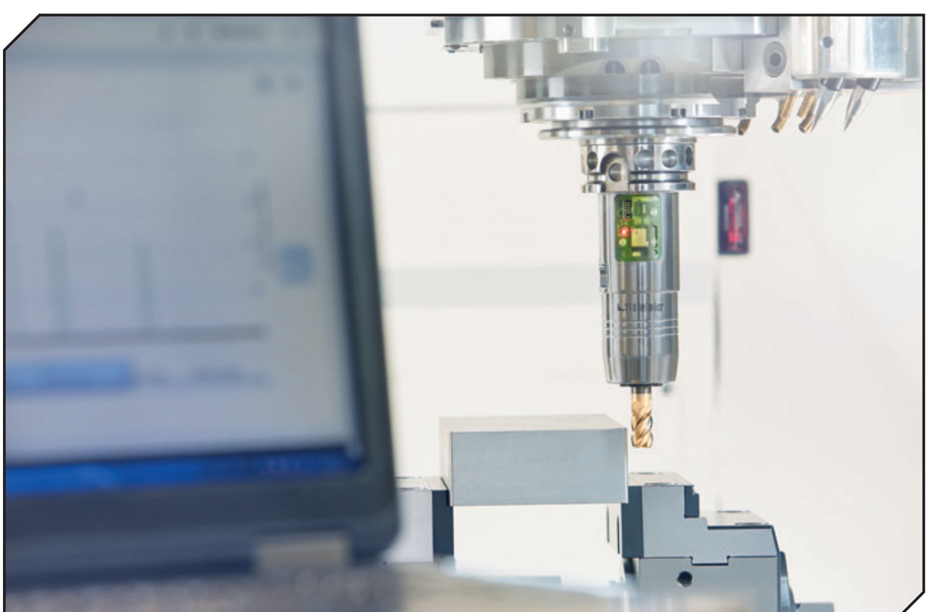
"Five axis machines are incredibly capable. You need to make sure your workholding can match the machine capabilities. Mill-turn machines are more and more common place. A quick-change pallet system (VERO-S) to make the changeover with workholding fast and repeatable. That can save hours of machine time per day," Gaunce added.

No matter the shop size, robotics and automation are the new norm for all machine tools.

"If you're doing nothing but one-off prototyping, you're an exception… otherwise, start automating the part loading aspect of the machining process. Think about it… everything else in the machine tool is automated (tool changer, simulation/verification of machine programs, tool presetting, etc.) Time to automate the part loading as well," Gaunce said.

Schunk finds plenty of value in focusing on specialized solutions. Many specialized solutions are simply just extensions of the company's standard products, but they're tailored to a specific application.

"Also, many times with end-users who are just starting to familiarize themselves with new technology, a special



With the new iTENDO, an intelligent toolholder, Schunkis setting a milestone when it comes to digitalization in the metal cutting industry. Due to the real-time capable data communication, Schunk offers for the first time an autonomous process optimization in the form of a toolholder.

solution is a great start. A tailor-made solution shows the potential of our standard products, and once this is clear to the end-user they will many times start developing their own customized solutions with our standard product," Gaunce said.

On the flip-side, companies like Schunk are also developing more and more off the shelf products that incorporate more automation functionality particularly with regard to integrated software that allows for easy integration.

And what about the future of workholding as these systems evolve?

"This might be a little out there, but most workholding products rely on simple mechanics which ensures rigidity and reliability in automation," Gaunce said. "I could see in the future the possibility of more electrical components being incorporated to allow for more data/information, and more flexibility."

"Flexibility/versatility is key moving forward… You can see the same trend in all aspects of our economy. You need to be flexible, adaptable, and ready to pivot," he added. "Same with your workholding. Find a way to implement lean automation which allows for high productivity while also maintaining that ability to adapt."

Schunk.com

Optimizied Workholding Makes Smart Use of Machine Tool Capabilities

David Jones, Precision Workholding Product Manager, EMUGE-FRANKEN USA

Utilizing machine tool capabilities is helpful for optimizing workholding solutions, whether a mechanical, pneumatic or hydraulic clamping design. Let's start with drawbar driven machine solutions, which are commonly used. A drawbar can be used to pull back towards the machine spindle, but in most machines, they can also do a little pushing out away from the spindle as well. It's important to note some machines have variable, or different capabilities, in one direction or the other. This means the force may be stronger pulling back on the drawbar than it is pushing out on the drawbar. It is important to determine this in advance so the proper workholding design can be implemented.

So how does drawbar movement help make a workholding process more intelligent? EMUGE-FRANKEN USA offers a tool-less mechanical clamping design where the machine side has a locking bayonet connection and a pull stud. The machine drawbar pulls the workholding device into the spindle face, while centering the device into the taper of the machine spindle . The bonus in this design is the absence of bolts, so a quick-change mechanical system can use the existing machine drawbar. With only a few controller commands the machine will reach a specified value for the required clamping force to properly seat the workholding device onto the machine spindle. Using existing machine tool technology is smart, efficient and accurate, as well as saves time.

Now let's use the drawbar in the opposite direction, which is away from the spindle. This action can help facilitate unclamping of a work piece by using the drawbar's axial stroke to push on mechanical rods, which interact with the device's clamping elements to help facilitate their unclamping. This action helps ensure proper workpiece release. Similar to the pullback of the drawbar, the pushing element of a drawbar can generally be set to a max force, or even a set distance from spindle face 0. For security, a mechanical stop is used in the workholding device, so over stroke is limited in both directions.

EMUGE-FRANKEN workholding designs include using the machine drawbar pullback for actuation of one clamping element in the design, and also the axial pullback stroke to release compression pressure on a spring package, which allows the package to expand and clamp a secondary location on the workpiece. So, one axial pullback stroke can accommodate two different clamping areas with the required clamping force for that area's geometry. This is especially important when clamping locations carry different diameters, and/ or, tolerances. To summarize, one clamping stroke can activate two separate clamping locations and meet the requirements for two different zones with two different applied clamping forces, all while utilizing the existing machine tool.

Pneumatic or hydraulic workholding solutions can also utilize other technology from the machine tool. If the machine has air through the spindle, the air can be used in the workholding device — this is called airflow control.

EMUGE-FRANKEN airflow adapted clamping solutions channel this airflow through the device and exit where the workpiece meets the end-stop. With no workpiece in place the air flows freely, but when a workpiece is placed into position against the end stop, the airflow is now restricted, which is something the machine can recognize, and be programmed to begin the clamping and subsequent machining processes.

For a hydraulic design, however, there can be pressure feedback similar to how the airflow control functions. If the workholding device has an onboard piston and hydraulic reservoir, when pressure is applied to this internal piston, it moves axially and compresses a spring package. Or it may create an opposite direction axial stroke, which activates the clamping element in the design. At some point in the cycle, the workpiece will be clamped, and a mechanical stop achieved. In this case the back pressure to the machine increases, which is something the machine recognizes, and prompts the next steps in the programmed process, knowing the machine has reached full clamping pressure.

It is advantageous to efficiently utilize available machine tool technology and intelligence to optimally interact and work with precision workholding devices.

www.emuge.com

MPIF Examines State of the Powder Metal Industry

Dean Howard, PMT, President, MPIF

This is an excerpt from Dean Howard's yearly State of the PM Industry article from MPIF.

Thanks to material development and additive manufacturing opportunities, it's important for the gear and power transmission industries to monitor the trends, technologies and future forecasts in the powder metal market.

The Impact of the Pandemic

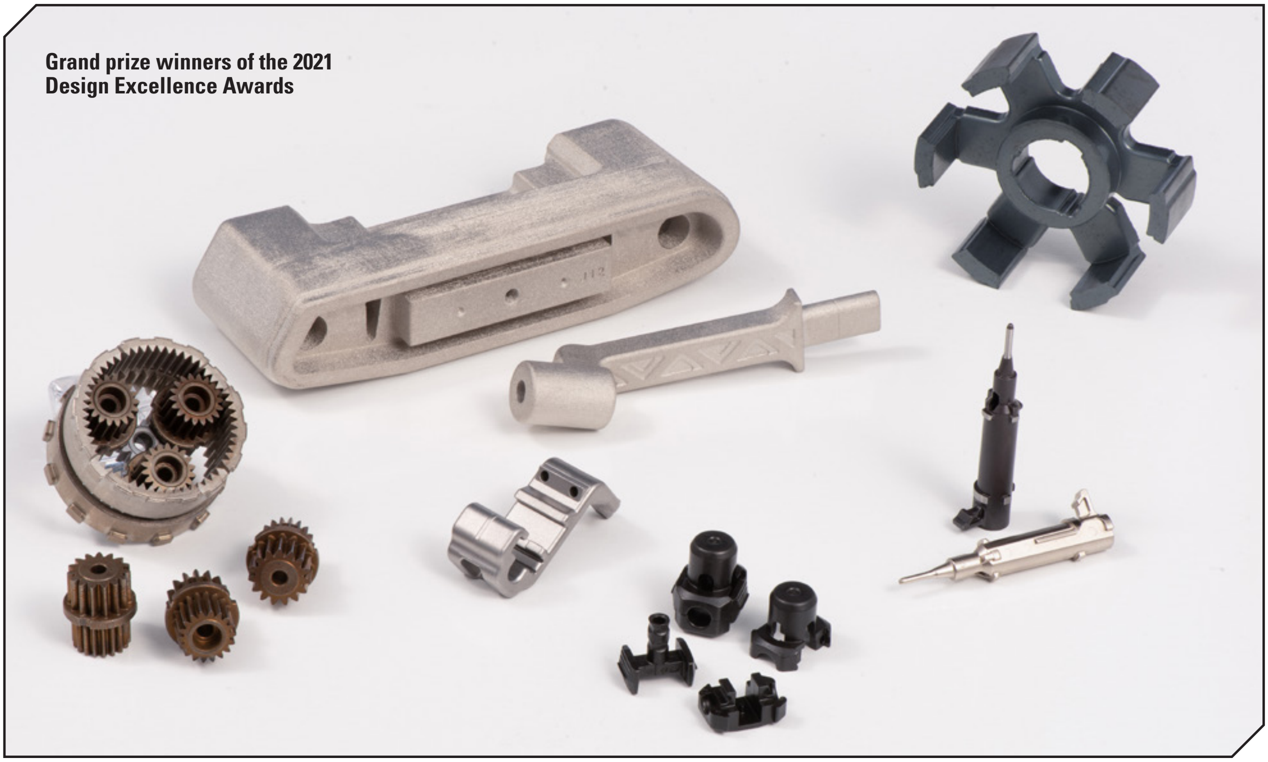
During the pandemic, manufacturing in North America was disrupted, hitting the PM industry especially hard, as the automotive industry, the primary consumer of PM parts, came to a standstill. Shelter-in-place mandates resulted in more people cooking at home and provided time to renovate kitchens, garages, and laundry rooms. This was great for PM suppliers to small and large appliance manufacturers, until inventories of finished goods were exhausted, as assembly lines were shut-down due to the mandates.

Healthcare providers were constantly in the news, receiving the praise that they deserved for going above and beyond, treating those that required medical assistance because of this horrible virus. However, many elective surgeries, those that required metal injection molding (MIM) components, were postponed, stalling deliveries, and increasing inventories. The North American oil rig count, an important barometer for the drilling industry, dropped more than 50% in 2020, compared with 2019. When drilling rigs are active, supplying many industries that rely on petroleum-based products, they consume tungsten carbide inserts for drill heads, made from metal powders, but again, demand was not required.

This is just a small example of how the PM industry was impacted by the pandemic. The trickledown effect resulted in a flurry of cost-cutting solutions, including wage and benefits cuts, furloughs, permanent lay-offs, retirements, and temporary plant closures for facilities deemed as non-essential. Some government programs, such as the Paycheck Protection Program, helped many small to medium enterprises stay afloat, while other programs intended to help the displaced workforce became a hinderance, as some displaced workers received more money for staying home and did not return when they were called back to work.

However, the PM industry is a resilient consolidation of many forces, which found its inner strength to rally and became stronger as a result of these turbulent times. I am unaware of a single North American PM company that permanently closed its operations as a direct result of the pandemic. Many companies' representatives report that their organizations are working mandatory overtime due to shortages of skilled workers and engineers, while setting new production levels because of pandemic induced solutions. We are all survivors, and the PM industry is still alive and well, landing back on its feet, well on its way to recovery. Let's take a deeper dive.

Grand prize winners of the 2021 Design Excellence Awards



New Material Development

Several PM parts makers report that the future for PM will be to supply value-added, near-net shape parts that have cost-effective lean-alloy materials with high material utilization rates. To help accomplish this, powder producers are improving and developing new materials that exhibit higher green strength, excellent machinability, increased compressibility, and have their sights on increasing the development and use of soft magnetic composites (SMC).

SMC materials have an integral role in the future of electric vehicles, as well as home appliances and other electric devices. Advances in magnetic modeling are allowing engineers to create more efficient designs with the 3-dimensional manufacturing capabilities of SMC materials, that are not constrained by 2-dimensional construction limitations of laminated steel. SMC materials operate at very high frequencies without hysteresis and eddy current losses, another advantage over their laminated steel counterparts.

Technology Trends

The Internet of Things, or Industry 4.0, has made its presence known in the PM industry. Augmented intelligence continues to assist and optimize the manufacturing processes through sensors that learn the process and adjust based on data trends. COVID-19 workforce reductions affected many companies' ability to efficiently operate equipment, increasing the demand for automation. From pick-and-place robots at the compacting presses and furnaces to 100% vision system inspections, automation continues to increase.

Compaction presses continue to evolve with sophisticated motion controls, resulting in precise movement of tools with faster cycle times. Fully integrated electric compaction presses are increasing the productivity for tungsten carbide and ceramic high precision cutting tool inserts.

Furnace manufacturers also see the future of SMCs. New approaches to lubricant removal and the ability to cure parts in one continuous cycle will reduce manufacturing costs and increase throughput, while improving handling and quality.

Single transmission bush gear.

Metal Injection Molding and Additive Manufacturing

While general manufacturing was down in 2020, metal injection molding (MIM) and metal additive manufacturing (AM) performed much better. Domestic and globally produced MIM and AM fine powders (less than 20 micrometers) consumed in North America increased an estimated 3-5% to 3,741-3,809 mt (4,125-4,200 st). Low-alloy and stainless-steel made up the bulk of the powders consumed.

Improving powder quality, most recently driven by AM, including a narrower particle size distribution range, greater sphericity, fewer satellites, and less internal porosity, will improve throughput, mechanical properties, and overall process consistency. Typically, these powders are manufactured by gas atomization, but capacity has been added recently for plasma atomization and research continues to develop water-atomized low-alloy materials for MIM and AM. Industry sources don't see radical changes on the horizon for injection molding machines, other than applying Internet of Things utilities and augmented intelligence to reduce labor while increasing productivity. AM build machines continue to evolve. Office-friendly small units to production scale are being released monthly. Multi-laser units continue to increase speed, build size, consistency, and robust properties for performance parts. Bi-directional single-pass binder-jet units are resulting in speeds up to 100 times faster than other metal AM platforms.

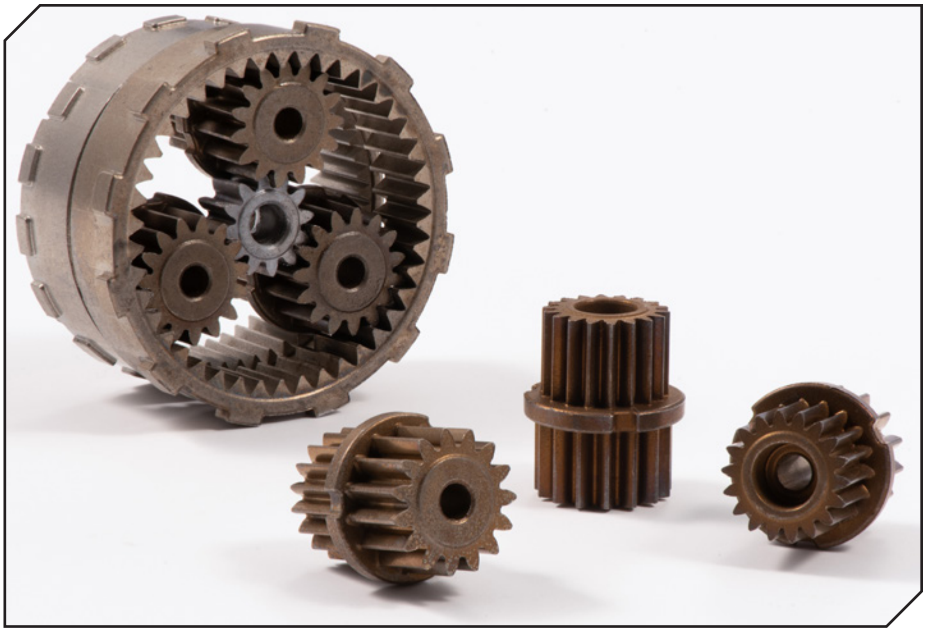
There continues to be a need for additional thermal treatment equipment for MIM and AM. MIM and AM binder-jet processes require de-binding prior to sintering, and most direct laser sintering process require stress relieving after printing. Research activities continue to provide new insight into identifying ideal temperature and atmosphere conditions for more efficient energy utilization and process optimization.

It is safe to say that the partition between MIM and AM processes is disappearing. At least a dozen MIM companies have added in-house AM capabilities or are collaborating with others, bringing parts to market quicker, using the same powders, without the need for tooling. When quantity levels justify, the parts can be moved to MIM.

The Future of PM

The MPIF Technical Board continues to keep a keen eye on lean alloys, advanced PM steels, SMC, and lightweight materials. The Technical Board is also studying processing variables and their influences on variation in material properties and dimensional stability in PM parts. The latter review concerns how materials react to heat treatment and compacting with the goal of achieving closer tolerances and reducing the need for extensive machining. Additionally, during 2021, the Technical Board will assess and update the PM Industry Roadmap, most recently revised in 2017, to ensure that our industry has identified the technology challenges to remain the preferred metal-forming solution.

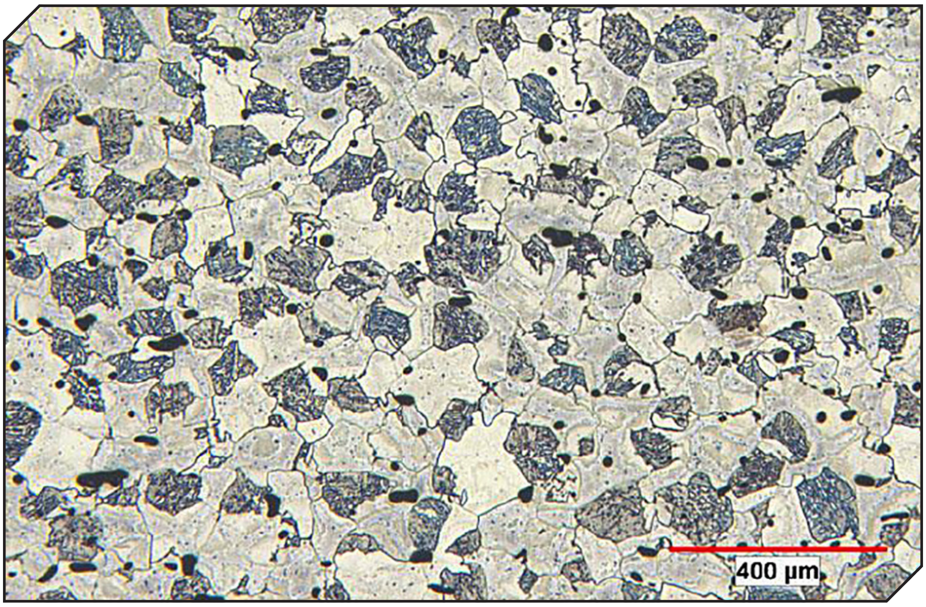
The Center for Powder Metallurgy Technology (CPMT) continues to work on numerous projects. Ongoing investigations include corrosion prevention, impact testing of gear teeth, joining PM components, variation reduction in the PM process and fatigue testing. The variation reduction investigation is a collaboration with the MPIF Technical Board, and the fatigue study is in coordination with the MPIF Standards Committee, resulting in new data for the MPIF Standard 35-SP.



Phoenix stepped planetary gear

MPIF, CPMT, and the National Science Foundation (NSF) have been champions of advancing the PM technology through educational outreach. Over the past 4 years, over 200 engineering students have been awarded conference grants through the efforts of these organizations. The grants provide the opportunity for the PM industry to showcase the technology to some of the brightest young minds that will someday, hopefully, select PM as their metal-working solution. MPIF, the European Powder Metallurgy Association (EPMA), and the Asian Powder Metallurgy Association (APMA) have continued collaborating to advance the technology through the Global Powder Metallurgy Materials Property Database. Launched back in 2004, the updated database is easier to navigate, download data, and best of all, it puts materials property data into the hands of the parts designers for free. The writing is on the wall. Whether we like it or not, the automotive industry will change due to ambitious efforts to curb the production of ICE propelled vehicles by 2035, and the trickledown effect will affect the entire PM industry. I believe the industry will be able to adapt and overcome, but we will need the mindset and resources to adjust to the changing environment.

There are unlimited opportunities for metal powders. Some of the most interesting research relates to sustainable solutions for our planet. For a digital copy of the PM Industry report, contact Dora Schember at 609-452-7700 or *dschember@mpif.org.*



The cross-section of the FSLA material shows the dual-phase microstructure after heat treatment. By the heat treatment, the proportion of the different phases and the grain size can be adjusted to achieve unique physical properties (photo courtesy of GKN Powder Metallurgy).

Dean Howard, PMT, President, MPIF.

PM Design Award Winners

The winners in the 2021 Powder Metallurgy (PM) Design Excellence Awards competition, sponsored by the Metal Powder Industries Federation (MPIF), demonstrate outstanding examples of PM's diversity. From electric vehicles to golf putters, these components use PM's flexibility to push forward new concepts and process controls to demonstrate the inexhaustible well of capabilities PM can marshal in the service of component design. Designers continue to choose PM for complex and critical applications such as automotive, medical devices, consumer products, hardware, and more. Six Grand Prizes and sixteen Awards of Distinction have been given in this year's competition.

Grand Prize Awards

A Grand Prize in the Automotive—Chassis Category for Conventional PM components was awarded to Phoenix Sintered Metals LLC, and customer Dana Incorporated, for a stepped planetary gear used in a ridged rear axle gear box for battery electric light commercial vehicles. It was essential to be able to deliver tight dimensional control for this complex shaped part. The five-level pinion is made using FL-4405-100HT. No other metal forming technology could provide the part geometry at a commercially competitive price.

In the Aerospace/Military/Firearms Category for MIM components, a Grand Prize has been awarded to ARC Group Worldwide for an enclosed striker used in the firing mechanism of a commercial handgun. The part is made in a 2-cavity mold, and strategic tool design and staging was implemented. Postsintering, HIP and heat treatment are performed to increase mechanical properties. The position of the tip to the primary body of the component is critical for part functionality. The parts are finished with an Enickel coating.

A Grand Prize has been awarded to Parmatech Corporation in the Hand Tools/Recreation Category for Metal AM components for a 316L stainless steel putter head made for Cobra Puma Golf and used in the King Supersport-35 golf putter. The use of AM technology allowed designers to place or remove material strategically to optimize mass distribution, stiffness, and the development of the unique lattice structure eliminated the need for supports during the sintering process. The flexibility also allowed production of both right- and left-hand versions of the putter head and hosel without the need for tooling changes.

A Grand Prize has been awarded to ARC Group Worldwide in the Hand Tools/Recreation Category for MIM components, for a quick disconnect assembly used for a variety of small handheld devices like binoculars, cameras, and firearms. Utilizing MIM allowed for a near-net-shape molded assembly and enabled the incorporation of smooth transitions and rounded edges as well as the elimination of any machining marks on the visible portions of the parts.

In the Hardware/Appliances Category for Conventional PM components, a Grand Prize has been awarded to Metalpo Ind e Com Ltda and their customer Groupe SEB — Arno Clock Krups Panex Penedo Rochedo, for a soft-magnetic composite (SMC) superior and inferior stator for a monophase induction motor for a ceiling fan. The component was specifically designed for the PM process to take advantage of the 3D magnetic flux, resulting in less copper wiring, a 76% reduction in the mass of the motor, and 35% less energy consumption and quieter operation.

In the Medical/Dental Category for MIM components, a Grand Prize has been awarded to OptiMIM for a compression frame used in Nextremity Solutions Lapidus System for holding and aligning the targeting drill guide during tarsometatarsal fusion. The parts are produced using MIM-420 stainless steel in a single cavity open and shut mold with two slides. The first forms the rectangular opening and the second the two holes at a 60° angle on the opposite end of the frame. The parts are sized in a die with two slides so that forces can be applied in perpendicular directions to the parts.

Awards of Distinction

In the Automotive—Transmission Category for MIM components, an Award of Distinction has been given to ARC Group Worldwide for a worm gear used in a transmission locking mechanism. MIM processing was selected because of the complexity of the helical gear teeth and the adjacent shaft geometry. Custom staging furniture is used for sintering the parts which require no secondary operations to be functional in the mating assembly.

In the Automotive—Transmission Category for MIM components, an Award of Distinction has also been given to Indo-MIM Pvt. Ltd. for an oil spray piston cooler. The MIM-4605 parts are used in the engine of heavy vehicles and were previously made by machining. Holes are formed by two different slide pins at different angles in the tool, and the side core has to travel through the center pin with a delay mechanism.

In the Aerospace/Military/Firearms Category for Metal AM components, an Award of Distinction has been given to 3DEO Inc. for a 17-4 PH stainless steel casing extractor for Glock brand pistols. A hybrid AM approach is used to make the parts that offers the robustness and accuracy of CNC machining and the scalability of MIM while overcoming the drawbacks of each process. The part has a complex geometry with several small, critical features.

In the Aerospace/Military/Firearms Category for MIM components, an Award of Distinction has been given to Indo-MIM Pvt. Ltd. for a frame chassis, part of a pistol assembly. The parts are made using MIM-17-4 PH in the H900 condition. Prior to MIM the parts were machined from bar stock by the customer. The MIM parts meet

80% of the required part features with the remainder being machined by the customer, reducing the machining cycle by 70%.

In the Aerospace/Military/Firearms Category for MIM components, an Award of Distinction has also been given to Advanced Powder Products Inc. and their customer Savage Arms for a bolt handle for a hunting rifle. The part assists with loading the next round of ammunition and in removing the shell after it has been fired. The complex curvature and intricate design presented challenges with molding and sintering. MIM processing was able to convert a two-piece design machined from bar stock to a single piece MIM part.

In the Lawn & Garden/Off-Highway Conventional PM components Category, an Award of Distinction has been given to Sintergy Inc. and their customer Knott Brake Company for a drum brake shoe for off highway units. The parts have localized infiltration to improve the region subject to wear. The PM parts replaced a three-piece weldment and passed extensive durability and performance testing.

In the Lawn & Garden/Off-Highway Conventional PM components Category, an Award of Distinction has also been given to Singhal Sintered Pvt. Ltd. for bush speed gears for tractor transmissions. The previously forged parts have an inner diameter spline with a step. Maintaining the tight spline tolerance during the heat-treatment process was challenging. Finishing operations include OD grinding and face grinding.

In the Hand Tools/Recreation Category for Metal AM components, an Award of Distinction has been given to 3DEO Inc. and their customer Blackland Razors for an open comb base plate used in a double-edge safety razor. A hybrid AM approach is used to make the parts that offer extremely tight dimensional tolerances that set the blade gap for this shaving razor.

In the Hand Tools/Recreation Category for Conventional PM components, an Award of Distinction has been given to Nichols Portland LLC for a positive displacement gerotor assembly for customized performance-racing fuel pumps. Racing applications require higher delivery pressures with fuel formulations that provide very low levels of lubricity. A novel material was developed to meet these needs in which a wear resistant hard phase is dispersed within a matrix.

In the Industrial Motors/Controls & Hydraulics Category for Conventional PM components, an Award of Distinction has been given to Capstan for a coupling handle used to prevent accidental disconnects. Previously a casting, conversion to PM permitted elimination of the casting gate, incorporation of a locational pin-button hole, and lettering. The coupling handles are used to provide improved pressure and temperature control capabilities in fluid power controls for a wide variety of applications.

An Award of Distinction has been given to Indo-MIM Pvt. Ltd. in the Industrial Motors/Controls & Hydraulics Category for MIM components for a casing and ground used in industrial gas sensors. Both parts require high magnetic permeability and low coercive field strength. The ground has many holes and threads, and the casing is a complex part with thin walls, sectional differences, and three threaded holes on the outer walls.

In the Hardware/Appliances Category for MIM components, an Award of Distinction has been awarded to Indo-MIM Pvt. Ltd. for a knob shaft, clutch, knob shield, core plug, core body, and control sleeve actuator used in door locks. The previously machined stainless-steel parts have intricate profiles, thin walls, multiple holes, blind threads, aesthetic requirements, and sectional differences adding to the complexity of the part.

In the Hardware/Appliances Category for MIM components, an Award of Distinction has also been awarded to ARC Group Worldwide for a key blade used in an electronic security system. Sintering requires custom staging to minimize distortion of the delicate geometries critical to part functionality. The parts require two sizing steps to ensure twelve critical dimensions meet the customer specifications. Fitment to the mating part and the aesthetic appearance of the primary visual surface was essential.

In the Medical/Dental Category for MIM components, an Award of Distinction has been given to ARC Group Worldwide for a pusher used in the ratcheting assembly for the consistent placement of high viscosity adhesives in incisions, used as an alternative to sutures or staples in surgical procedures. Strategic tool design, venting, and a 3-plate pin gate allow complete material fill of the complex part geometry, keeping distortion to a minimum and allowing tight profile and dimensional requirements to be maintained.

An Award of Distinction has also been awarded in the Medical/Dental Category for MIM components to Alpha Precision Group — Metal Injection Molding and their customer Elite Biomedical Solutions for an LVP door latch for an IV pump. The component has a tight tolerance on the hole position for the assembled roller. In use, the roller is latched on to a mating component that the company also makes to complete the latch/hook mechanism. The parts are made in-house from start to finish and the machining and multi-stage assembly are considered value added to the customer.

In the Electronics/Electrical Components category for MIM components an Award of Distinction has been awarded to Indo-MIM Pvt. Ltd. for a ceramic sensor used in an electronic device. The awards were presented here during the 2021 International Conference on Powder Metallurgy & Particulate Materials (PowderMet2021) and co-located conference Additive Manufacturing with Powder Metallurgy (AMPM2021) and Tungsten2021.

www.mpif.org

The Undercut Phenomenon

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

QUESTION

"It appears that undercut can be eliminated in some cases but in most cases, the elimination of undercut, for example by increasing the root fillet radii of a pinion, results in performance problems in the operation with its mate. My question is, when can I eliminate undercut and why is it not possible in most cases?"

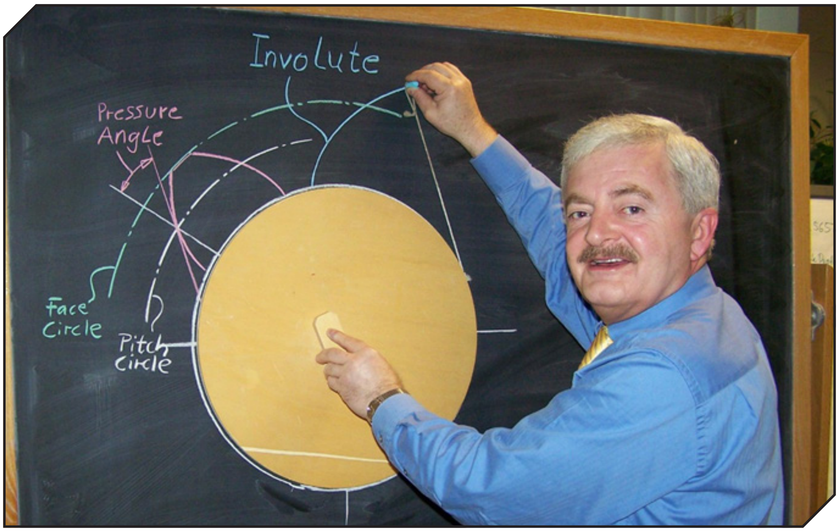


Figure 2 Involute development.

Expert response provided by Dr. Hermann J. Stadtfeld

Introduction

The first questions are, where does the undercut come from and which physical or kinematical effects lead to undercut? Then the following questions are, can it be avoided and how, or can it be avoided only in certain cases?

A comparison between a tooth profile without undercut and a similar profile with undercut is shown in Figure 1. The profile at the left side of Figure 1 shows a healthy profile with a root fillet radius which blends perfectly tangential with the involute profile. In contrast, the right-side graphic in Figure 1 shows a severe undercut resulting in a ridge on both sides of the tooth which weakens the root and reduces the amount of profile depth, where the mating tooth can mesh.

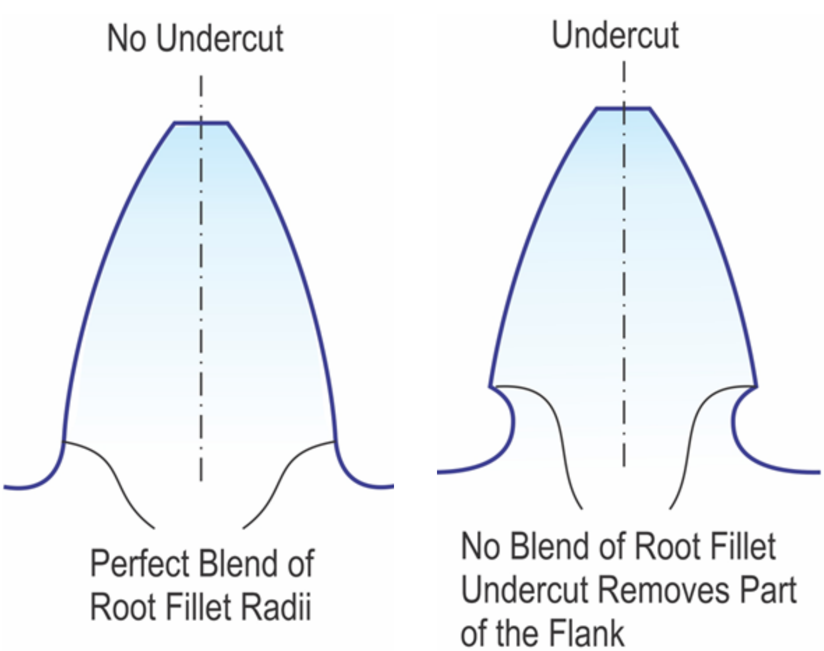


Figure 1 No undercut and undercut comparison.

Rule of Involute Generation

The term "undercut" comes from "undercutting," which is a hollowing out of an area because the cutting take place below a certain depth, where no Involute exists. In Figure 2 the author of this article demonstrates a classroom development of an involute by unrolling a cord from a disk. The disk holds here the place of the base circle and several geometric laws can be demonstrated with an involute development. It appears logical that the chalk which is used to draw the involute cannot draw anything below the base circle. In other words, no part of the involute exists below the base circle (or inside of the disk). This is because of the definition of the involute function and the resulting restrictions in the mechanics of drawing an involute.

The drawing in Figure 2 also shows that the unrolling of the cord can be continued into infinity. If a particular gear design has a pressure angle of

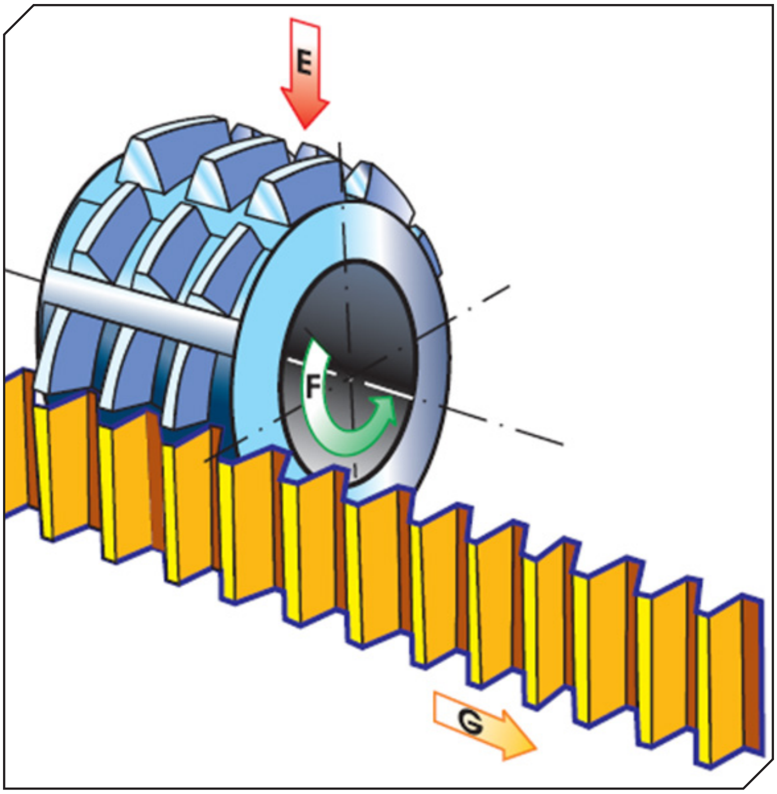


Figure 3 Hob cutter representing the trapezoidal generating profile.

20° for example, then the point where the tangent to the involute includes an angle of 20° to the line which connects this point with the center of the base circle is the pitch point. A larger pressure angle is realized merely by unrolling the cord further. The nominal pressure angle of a gear per definition is recorded at the pitch circle. However, the effective pressure angle below the pitch circle decreases as the distance to the base circle becomes smaller. Finally, at the base circle, the effective pressure angle is zero degree. The critical area is therefore at the beginning of the involute at the base circle. If the pressure angle is chosen very small, for example 15°, then the risk occurs that the dedendum (the distance from the pitch point to the root) reaches the base circle or even extends below the base circle.

The Mechanisms of Undercutting

Provided the gear is manufactured with a hob cutter, which has straight cutting edges and a rounding at the tip corners, then the hob cutter in Figure 3 represents the teeth of a trapezoidal generating profile and only the section of the cutting edge which stays above or at the base circle can form an involute profile (Ref. 1).

The angle of the trapezoid side walls is equal to the pressure angle. This means, if the pitch diameter is given by the product of the module and the number of teeth, then the base circle is automatically defined by the rules of the involute function:

Pitch Diameter cos (Pressure Angle) = Base Circle Diameter

In case of a depth factor larger than 1.00 and a large root clearance value, it is possible that the tip of the cutting edge protrudes below the base circle and will not generate any involute profile. To the contrary, the finish profile below the base circle is formed by the tip edge of the blade profile. The mathematical function it creates is a trochoid.

How the Trochoid Removes Part of the Involute

While the involute generation creates the flank surface points from the top of the tooth to the root, the trochoid generation works the opposite way. Figure 4 shows this generation in four steps. The green generating rack profile (equal to one cutting edge of the hob cutter) forms the upper involute section in position 1. A line which begins at the generated flank point and is perpendicular to the green line generating line, ends tangentially at the base circle. As the generating process progresses, the cutting-edge profile takes the position 2. The length of the green line towards the left side of the drawing is given by the center distance between the hob cutter and the gear blank. Already in position 2 it can be observed that the left end of the cutting edge penetrates below the base circle. From this point on, the blade tip begins to form a trochoidal root function, while in the same position the cutting edge towards the right side still forms the involute.

Cutting positions 3 and 4 show how the blade tip cuts deeper below the base

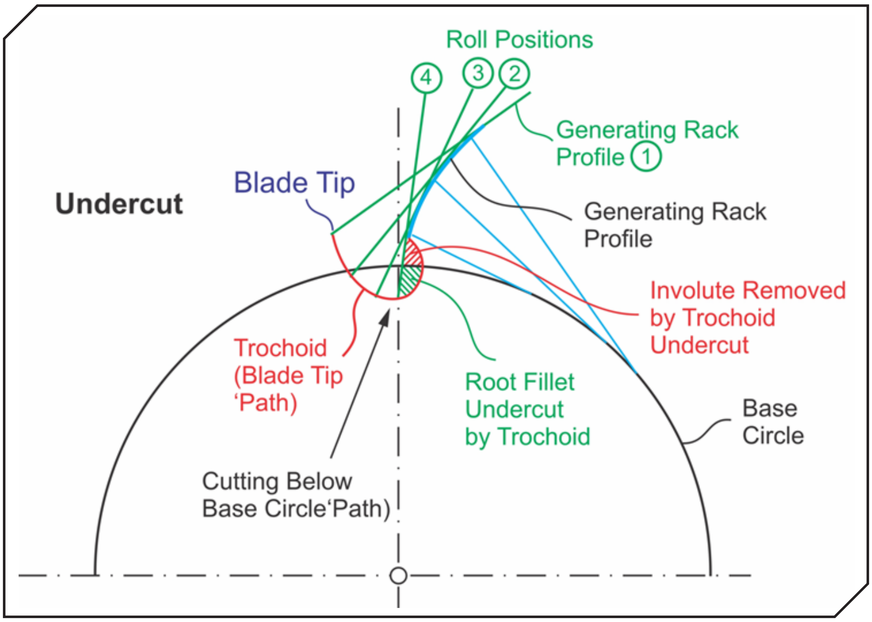


Figure 4 Generation of involute and trochoid.

circle and begins after position 4 to create undercut. Due to the length of the dedendum section of the blade, the undercut does not end below the base circle, but removes a considerable part of the already generated involute towards the root of the tooth.

Why is the Created Undercut Required for a Correct Meshing?

During the meshing process with the mating member, the top corner as shown in Figure 5 requires the room the undercut provides in order to roll without any interference through the entire mesh. Although the opposite flank of the red tooth in Figure 5 (left flank) is already in contact with the flank of the preceding tooth of the undercut pinion, the room the undercut provides in the circled area is required to avoid a collision.

The reason why the kinematic interaction between the two members is always as shown in Figure 5 is the fact that both members are generated with the same virtual generating rack. The generating rack is "only" virtual, but the hob cutter in Figure 3 represents the generating rack from the back in order to generate the pinion teeth, and another hob cutter (not shown in Figure 3) is positioned at the front of the generating rack to generate the mating gear. In other words, the virtual generating rack becomes a physical reality which provides the kinematic coupling which is necessary for an undisturbed meshing and the correct motion transmission between pinion and gear.

The graphic in Figure 6 shows a two-dimensional top-view onto the green generating rack with the blue pinion tooth being generated with undercut, and the red gear tooth (without undercut). The graphic shows that the edge corner of the red tooth comes very close to the generating rack corner which creates the undercut on the blue tooth. If two mating gears are generated according to the graphic in Figure 6, then there will be a small amount of clearance between the undercut root and the top edge corner of the blue mate (Ref. 2).

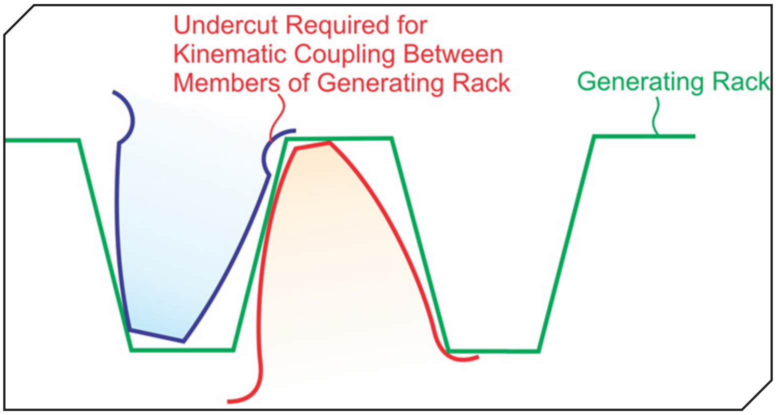


Figure 6 Kinematic link of two meshing teeth with the generating rack.

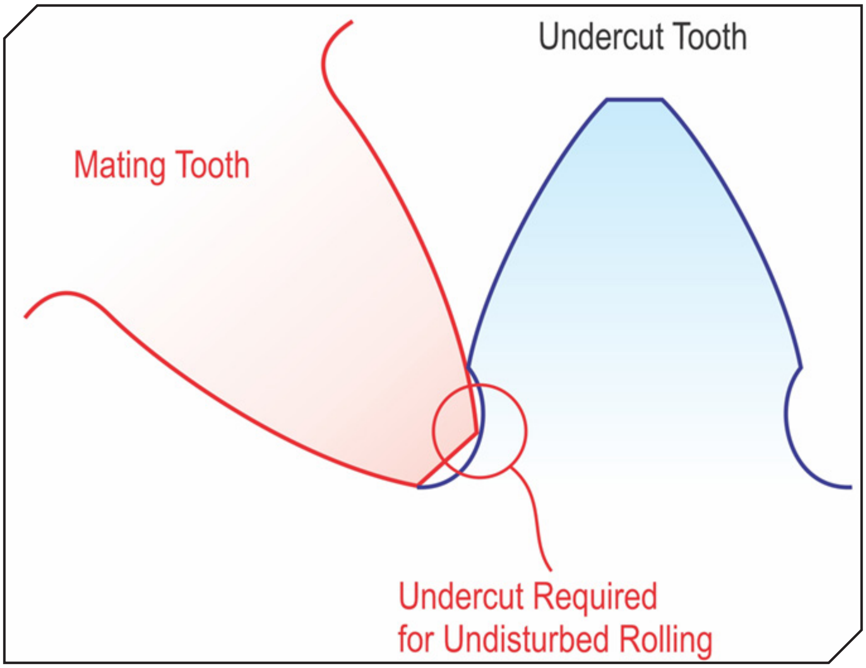


Figure 5 Interaction of undercut tooth with the mating tooth.

Possibilities to Eliminate Undercut

Gear engineers like to find ways to avoid an undercut condition. If the attempt is made to eliminate the undercut for example with a larger edge radius of the hob cutter blades, then an interference is created as shown in the top section of Figure 7. If the top edges of the mating tooth receive an adequate topland chamfer (bottom section), then the interference is eliminated. This is a procedure which is applied in cases where the undercut is not acceptable; for example, because of the reduced root bending strength.

The more common way to avoid undercut is applied at the beginning of a gearset design. Pinions with a low number of teeth show undercut due to the high angular rotation amount while being generated in a cutting machine. Therefore, most pinions below 17 teeth require a positive profile shift. The profile shift increases the center distance between the work gear and the manufacturing tool. Subsequently, the center distance between pinion and gear is also changed. If a center distance change is not desirable, then a so-called V0 profile shift is recommended. The V0 shift uses the same amount of positive profile shift applied to the pinion, with a negative sign for the gear. If the gear has a much higher number of teeth, then it will not be prone to undercut and will maintain a healthy profile and root fillet. The center distance in case of V0 gearing is identical to that without profile shift.

The effect of a positive profile shift is shown in Figure 8. The gear to the right is in mesh with its generating rack in a non-profile shifted configuration. It can be seen in the graphic that the root fillets show a beginning undercut. The positive profile shift at the left side gear increases the effective pressure angle of the involute because a part of the involute with a larger radius is used for the flank. Positive profile shifted gears do not have a smaller base circle, however, the root moves away from the base circle to a larger radius.

The profile shift factors of pinions and gears are often defined to optimize the sliding conditions within the flank surface, or they are used to balance the tooth thickness in the root between pinion and gear. This is a definite restriction if undercut is an issue. Small amounts of undercut do not present a problem in most cases. Small amounts of undercut can be seen as a way to realize a certain gear design and avoid interferences or rolling disturbances.

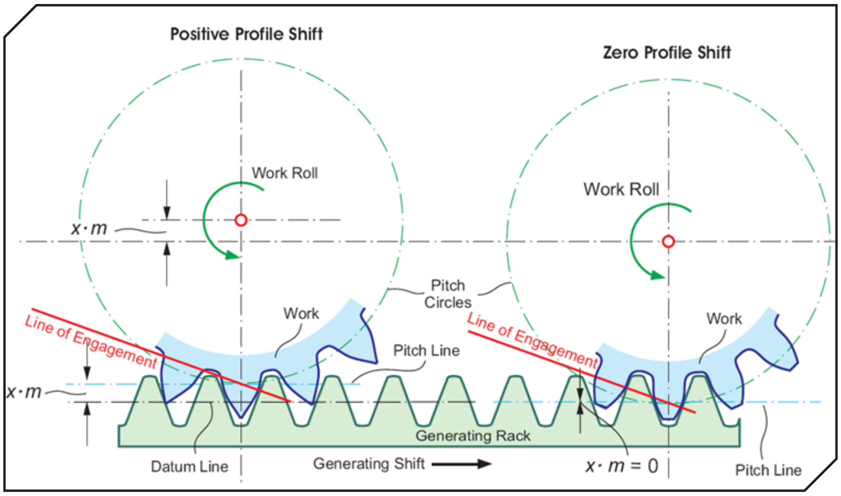


Figure 8 Elimination of undercut with profile shift.

Summary

Gear engineers like to avoid undercut, which is possible to some extent in the early design stages by choosing the right amount of profile shift. However, it is not always possible to eliminate undercut completely. In particular, if the number of pinion teeth is below 13, the profile shift factor is often not sufficient. If undercut is detected, this shows that the additional room in the root fillet transition to the flank is required for an undisturbed meshing process. This undercut means that the base circle is above the root diameter of the pinion. The top region of the meshing gear has a perfect involute which, however, cannot find an involute surface in the pinion root for a correct meshing. The undercut solves this problem partially by avoiding a metal-to-metal interference. Such an interference induces vibration and noise and creates small scratches and surface damage which can lead to crack propagation with the result of a tooth breakage.

If this undercut is eliminated merely by increasing the tool edge radius, an interference will occur. There is a possibility to eliminate the undercut by increasing the tool edge radius in combination with a correct dimensioned topland chamfer of the mating member. Because there is no software to aid in determining the required value of the tool edge radius increase and for the required topland chamfer dimension, this process requires experience as well as some trial-and-error loops.

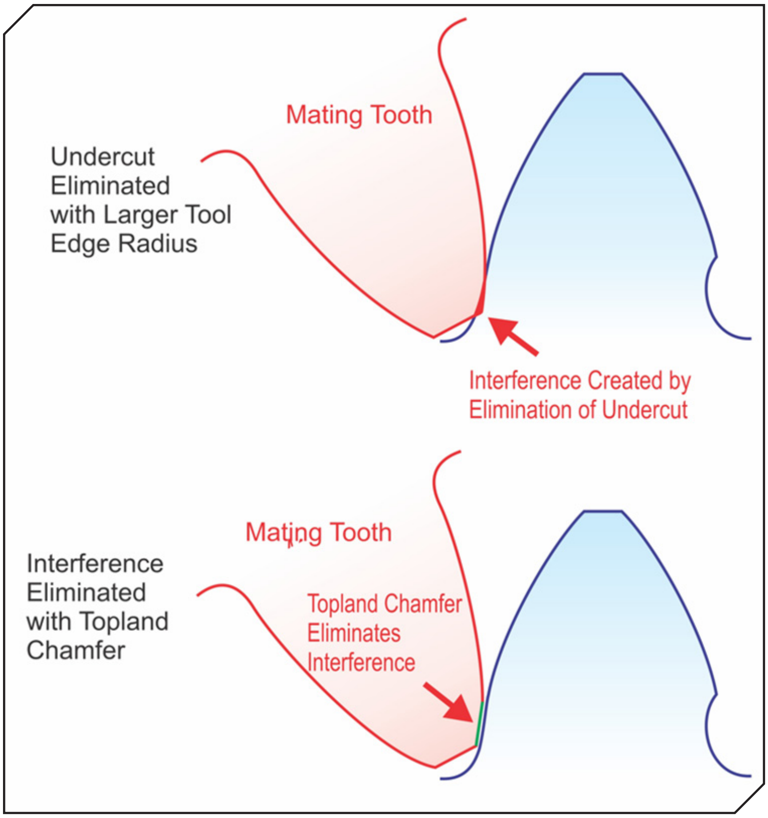


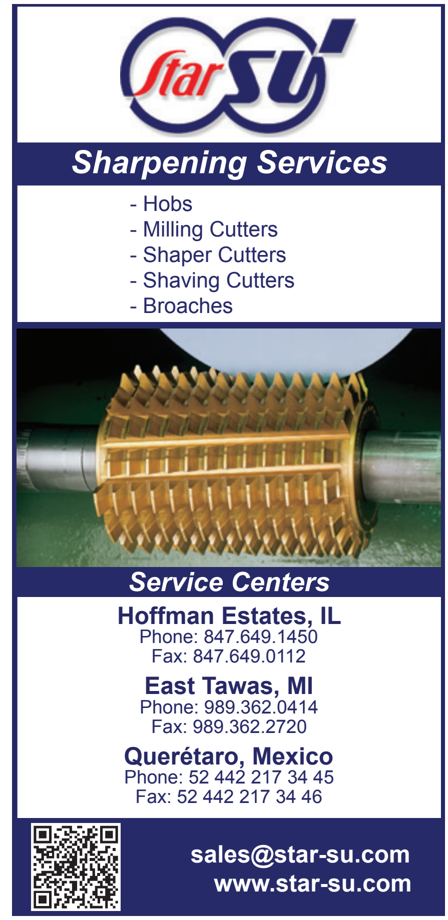
Figure 7 Elimination of Undercut (top) and elimination of interference (bottom).

References

1. Stadtfeld, H.J., "*Gleason Bevel Gear Technology, The Science of Gear Engineering and Modern Manufacturing Methods for Angular Transmissions*," Company Publication, The Gleason Works Rochester, New York, March 2014, Pages 17 to 19.
2. Stadtfeld, H.J., "*Practical Gear Engineering, Answers to Common Gear Manufacturing Questions*," Company Publication, The Gleason Works Rochester, New York, March 2019, Pages 107 to 108.

Dr. Hermann J. Stadtfeld is the Vice President of Bevel Gear Technology and R&D at the Gleason Corporation and Professor of the Technical University of Ilmenau, Germany.


Gears for the toughest machines on earth.
Together, we are the force that moves the world.
We offer a wide variety of manufacturing capabilities covering almost the entire powertrain and driveline applications.
We make available one of the widest production capability for custom gears for heavy duty vehicles of the entire industry to enable our O.E.M. Customers to focus more on their projects.
IATF 16949 and ISO 14001 Cerified
CATTINI NORTH AMERICA
www.cattinina.com
Pedetemptim sed incessanter®


Star SU
Sharpening Services
- Hobs
- Milling Cutters
- Shaper Cutters
- Shaving Cutters
- Broaches
Service Centers
Hoffman Estates, IL
Phone: 847.649.1450
Fax: 847.649.0112
East Tawas, MI
Phone: 989.362.0414
Fax: 989.362.2720
Querétaro, Mexico
Phone: 52 442 217 34 45
Fax: 52 442 217 34 46
sales@star-su.com
www.star-su.com


Dillon Chuck Jaws
CHUCK JAWS
HARD JAWS
JAW NUTS
FULLGRIP JAWS
CUSTOM JAWS
VISE JAWS
JAW BORING RING
JAW FORCE GAGE
CHUCK GREASE
COLLECT PADS & COLLECT JAWS
Dillon Manufacturing, Inc.
2115 Progress Drive,
Springfield, Ohio 45505
ISO 9001:2015 - Sold through distributors
P 800.428.1133
F 800.634.6480
dillonmfg.com
sales4@dillonmfg.com


Gear Research Institute
ALWAYS IN GEAR!
Gear Research and Testing Specialists
Aaron Isaacson
(p) 814-865-5832
(e) aci101@arl.psu.edu
gearresearch.org
An ASME, AGMA Institute at Penn State
Sign up for our free newsletter or visit our employment opportunities page today!
PennState
Applied Research Laboratory

Characteristic Value-Based Process Design of Gear Hobbing Processes with Radial Infeed

Thomas Bergs, Christoph Löpenhaus and Nico Troß

Introduction

In industrial practice, axial gear hobbing is generally used as common process variant of the gear hobbing process. If an interference is present near the gear teeth, the process is limited in terms of applicability as the required infeed path is no longer available. For components with interference close the gear, alternative soft machining processes, e.g., gear skiving or shaping, are often used. One way of countering the limitation due to the limited working space is to adjust the infeed direction of the tool during the infeed phase. Since only pure roughing and no profiling of the gap takes place during the infeed, a change in the feed amount and feed direction has no influence on the shape and dimensional accuracy of the gear flank. To avoid a collision with the interference, it is therefore possible to carry out the infeed not axi ally, but radially or diagonally at any infeed angle φ to the workpiece axis (Fig. 1).

In contrast to axial hobbing, there are no knowledge-based methods for designing the process for radial or diagonal infeed strategies, but only rule of thumb or empirical values. Scientific studies on the efficiency of the hobbing process under consideration of the infeed strategy are only available to a limited extent. In the research project "Design of gear hobbing processes with variable infeed," on which this report is based, an analysis of the technological interdependencies for different infeed angles is currently conducted. On the basis of the results, it will be possible to produce parameters and models for the design of the hobbing process for any infeed strategy in future.

State of the Art

The design of axial hobbing processes is generally based on various parameters, such as the maximum feed mark depth δ_x or the maximum tip chip thickness $h_{cu,max}$. Since no profiling of the final gap takes place during the infeed, a design of the infeed according to the height of the feed marks is not relevant. For the maximum tip chip thickness, a mathematical correlation according to Equation 1 was derived by Hoffmeister (Ref. 1).

$$h_{cu,max} = 4.9 \cdot m_n \cdot z_2^{(9.25 \cdot 10^{-3} \cdot \beta_2 - 0.542)} \cdot e^{-0.015 \cdot \beta_2} \cdot e^{-0.015 \cdot x} \cdot \left(\frac{r_{a0}}{m_n}\right)^{-8.25 \cdot 10^{-3} \cdot \beta_2 - 0.225} \cdot i^{-0.877} \cdot \left(\frac{f_a}{m_n}\right)^{0.511} \cdot \left(\frac{T}{m_n}\right)^{0.319} \quad (1)$$

$h_{cu,max}$	[mm]	Maximum tip chip thickness
z_2	[-]	Number of workpiece teeth
x	[-]	Profile shift coefficient
i	[-]	Effective number of gashes
T	[mm]	Cutting depth
m_n	[mm]	Module
β_2	[rad]	Helix angle
r_{a0}	[mm]	Tip radius of the hob
f_a	[mm]	Axial feed

However, this equation was developed for the full-cut in axial gear hobbing and is not permissible for a design of the infeed under consideration of any infeed angle. For the design of the radial infeed, a design according to Equation 2 is recommended in the literature (Ref. 4). According to this method, the feed ratio f_r to f_a is chosen accordingly to the ratio of the respective infeed path E to the cutting depth T. This way, a process

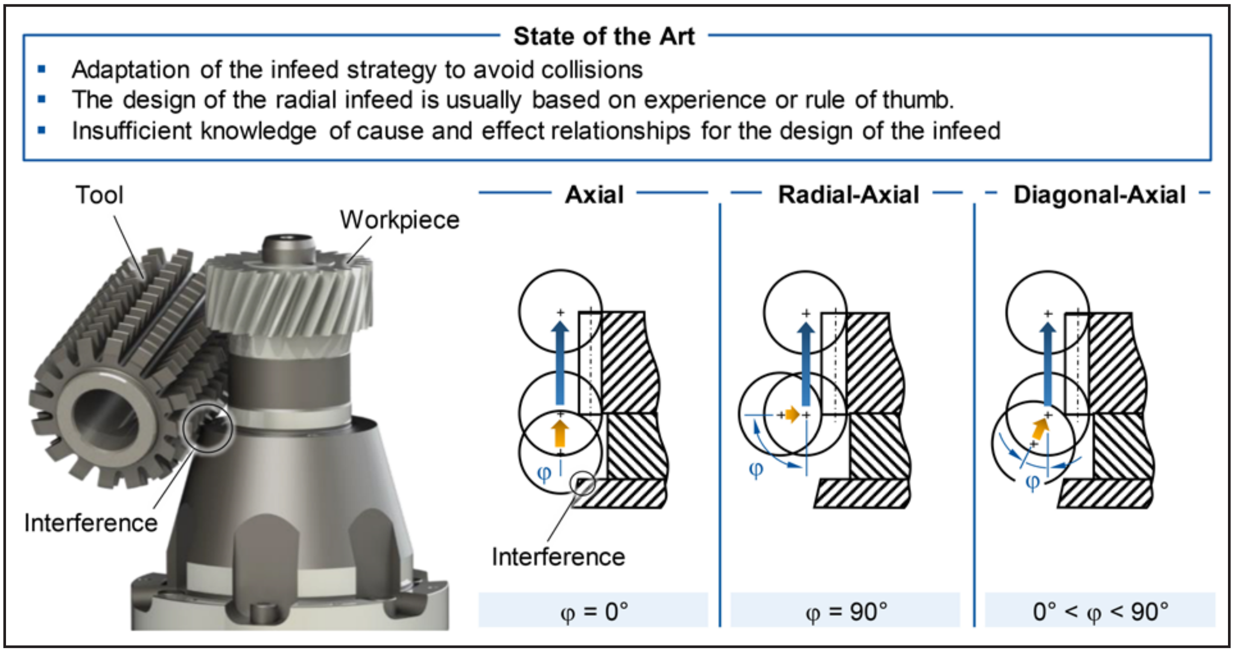


Figure 1 Motivation and challenge.

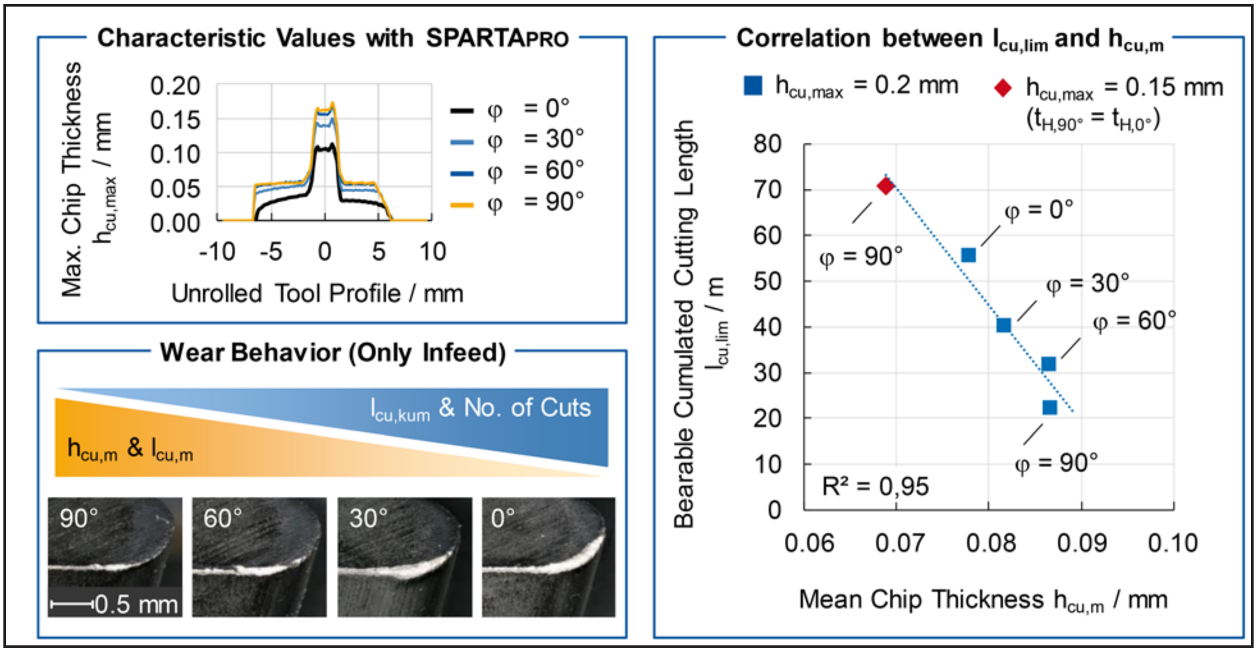


Figure 2 Influence of the infeed angle on tool wear (Ref. 5, Ref. 6).

design with a constant process time is realized. However, with this design method the technological interdependencies during machining are not taken into account and no conclusions can be drawn regarding the tool load.

$$f_r = f_a \cdot \frac{T}{E} \qquad (2)$$

f_r	[mm]	Radial feed
T	[mm]	Cutting depth
f_a	[mm]	Axial feed
E	[mm]	Axial infeed path

One possibility of determining the characteristic chip values and designing the hobbing process is given by the manufacturing simulation software *SPARTApro*. The workpiece is abstracted by a defined number of parallel planes, which are penetrated by the tool profile under simulation of the machine kinematics. The intersection results in the penetration area which corresponds to the undeformed chip geometry of the respective generating position in the process. The determined chip characteristics allow an assessment of the loads acting on the hob during the cutting process (Ref. 2).

With the help of *SPARTApro*, Weber analyzed the cutting conditions during gear hobbing for different infeed angles for the first time. For a design according to a constant main time t_H, chip characteristics for different infeed angles were determined individually by means of the geometric penetration calculation. In fly-cutting trials the number of machined workpieces N, from hereafter expressed as tool life N, was determined for this design with increasing infeed angle. By interpolating the previously determined chip thicknesses, a design with constant maximum chip thickness $h_{cu,max}$ was realized in a subsequent test series. With this method, a reduction of the main time t_H with increasing infeed angle φ was achieved, but there was a significant decrease in the tool life N. Furthermore, the investigations showed a linear relationship between the mean chip thickness $h_{cu,m}$ and the tool life N. Based on this correlation, the process could be designed according to the tool life and a good approximation of the tool life for the radial infeed to the tool life of the axial infeed was be achieved. However, the design methods described require a laborious iteration of the characteristic values, which makes a practicable design of the infeed more difficult. (Ref. 7).

Troβ extended the manufacturing simulation software *SPARTApro* by a calculation method, which enables an automated penetration calculation for any infeed angle φ. This method was used to analyze the influence of the infeed angle φ on the chip parameters and the associated tool load (Fig. 2, top left). For the investigated gear case, a regression analysis was conducted on the basis of the results and a mathematical relationship was derived to describe the maximum chip thickness $h_{cu,max}$ as a function of the infeed angle φ and the path feed f_b. This equation allowed a characteristic value-based design of the infeed on the basis of the maximum chip thickness $h_{cu,max}$. (Ref. 5).

Based on the theoretical considerations, fly-cutting trials were carried out to investigate the influence of the infeed angle φ on tool wear. In the tests, only the infeed was machined in order to determine the influence of the infeed angle φ on tool wear detached from the workpiece width. In a design based on the maximum chip thickness hcu,max, a decrease in the tool life N was observed with increasing infeed angle φ. In the case of infeed angles with a large axial component, the tool is worn due to crater and flank wear as a result of the high number of load cycles and cumulative cutting arc length (Fig. 2, bottom left). With an increasing infeed angle φ the mean chip thickness $h_{cu,m}$ and the mean chip length $l_{cu,m}$ increase, which results in an increase of the tool load and a faster wear of the tool on the flank. In an additional test, the radial infeed was designed so that the machining time was identical to that of the axial infeed. This showed a slight increase of the tool life N and thus, potential for saving tool costs (Ref 6. TROß19b).

In contrast to the investigations carried out by Weber, a linear relationship between the mean chip thickness $h_{cu,m}$ and the tool life N could only be determined to a limited extent. The regression line has a coefficient of determination of $R^2 = 0.79$ if all determined data points, including the additional test, are taken into account. If, on the other hand, the bearable cumulated cutting length $l_{cu,lim}$ is plotted over the mean chip thickness, the linear correlation becomes more concise and the coefficient of determination is $R^2 = 0.95$ (Fig. 2, right). The mean chip thickness $h_{cu,m}$ and the bearable cumulated cutting length $l_{cu,lim}$ have a high potential for designing the infeed according to the tool life (Ref. 7).

The previous investigations on the influence of the infeed angle on tool wear only consider machining in the infeed phase and not the subsequent axial machining with final profiling of the workpiece. Furthermore, the knowledge gained from the fly-cutting trial in the hobbing process must be validated in order to make a design recommendation.

Objective and Approach

The objectives and approach of the research project IGF 18517 are shown in Figure 3. As can be seen from the state of the art, the required calculation method for the automated determination of the chip characteristics, taking into account any infeed angle, has already been developed. The method allows the characteristic value-based design of the hobbing process under consideration of any infeed angle. In theoretical investigations, the influence of the infeed angle on the chip characteristics and on the associated tool load was analyzed with the help of the extended calculation method. In subsequent fly-cutting trials, the influence of the infeed angle on tool wear shall be empirically determined on the basis of theoretical considerations. For this purpose, an isolated analysis of the cutting conditions during the infeed phase has already been carried out.

The present report focuses on the combined consideration of the infeed and the subsequent axial machining with additional variation of the workpiece width in order to evaluate the influence of the infeed with increasing or decreasing full cut area. The findings from the fly-cutting trials and the theoretical considerations will then be validated in gear hobbing tests. For this purpose, the process will be designed on the basis of characteristic values using the calculation method developed within the research project. The knowledge gained will be combined in a design method, which enables a knowledge-based design of the infeed during gear hobbing.

Fly-Cutting Trials

In order to evaluate the combined influence of the infeed and the subsequent axial machining, analogy tests were carried out in fly-cutting trials. In addition to the variation of the infeed angle, the workpiece width and the machining direction (climb and conventional cutting) were also varied in order to determine any differences in wear behavior.

Experimental Setup and Tool Life Prognosis.

The combination of tool and workpiece used for the investigations was chosen in analogy to the investigations for the isolated consideration of the infeed in (Ref. 6) (Fig. 4). The workpiece material corresponds to case-hardened steel typical for gears with the abbreviation 20MnCr5 and has a fine-grained, uniform, ferritic-pearlitic structure. The Brinell hardness of the workpiece was measured with 187 HB on the workpiece surface and converted to a tensile strength of $R_m \approx 630$ MPa according to DIN EN ISO 18265 (Ref. 3). The analogy test imitates a 3-start, right-hand hob with a tip diameter of $d_{a0} = 110$ mm and a number of gashes of $n_{i0} = 20$. The tool was manufactured from powder metallurgical high-speed steel (PM-HSS) and coated with a commercially available (Al,Cr)N. The layer thickness was $s = 2.5\,\mu m$ on the rake face and flank. The initial micro-geometric condition of the fly-cutter is documented in the upper section of Figure 4. The roughness of the rake face and flank as well as the cutting edge radius, the K-factor and the chipping are displayed.

The trials were carried out in dry cutting condition on a Gleason-Pfauter P400 gear hobbing machine. A maximum width of flank wear $VBmax = 120\,\mu m$ and a maximum depth of crater $KTmax = 100\,\mu m$ were defined as wear criteria. The

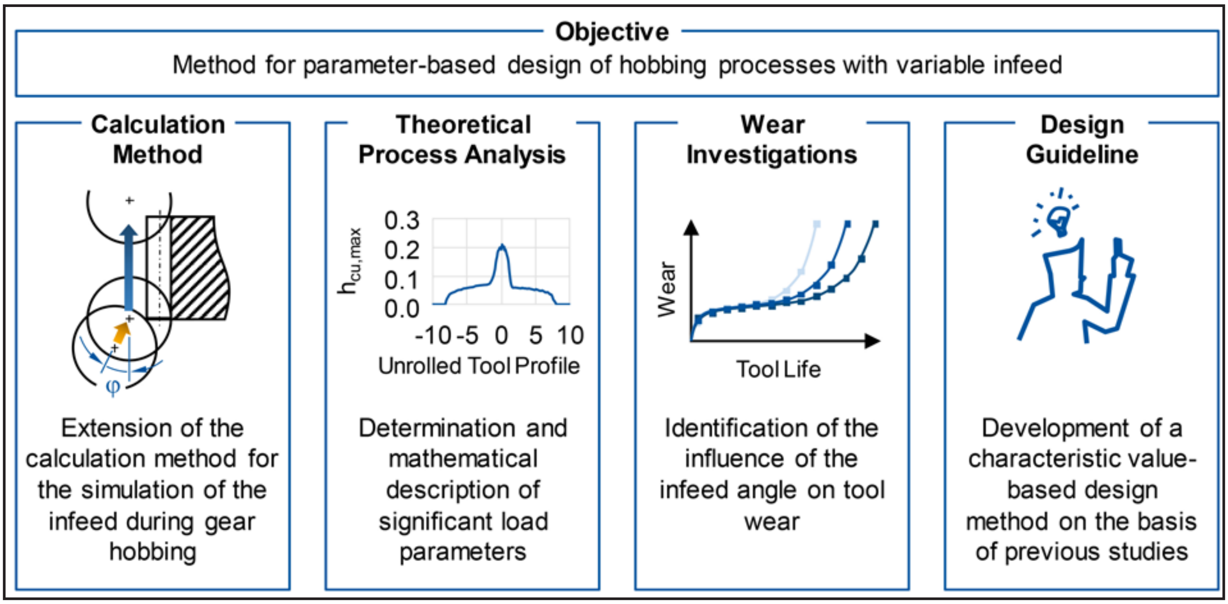


Figure 3 Objective and approach of the research project IGF 18517.

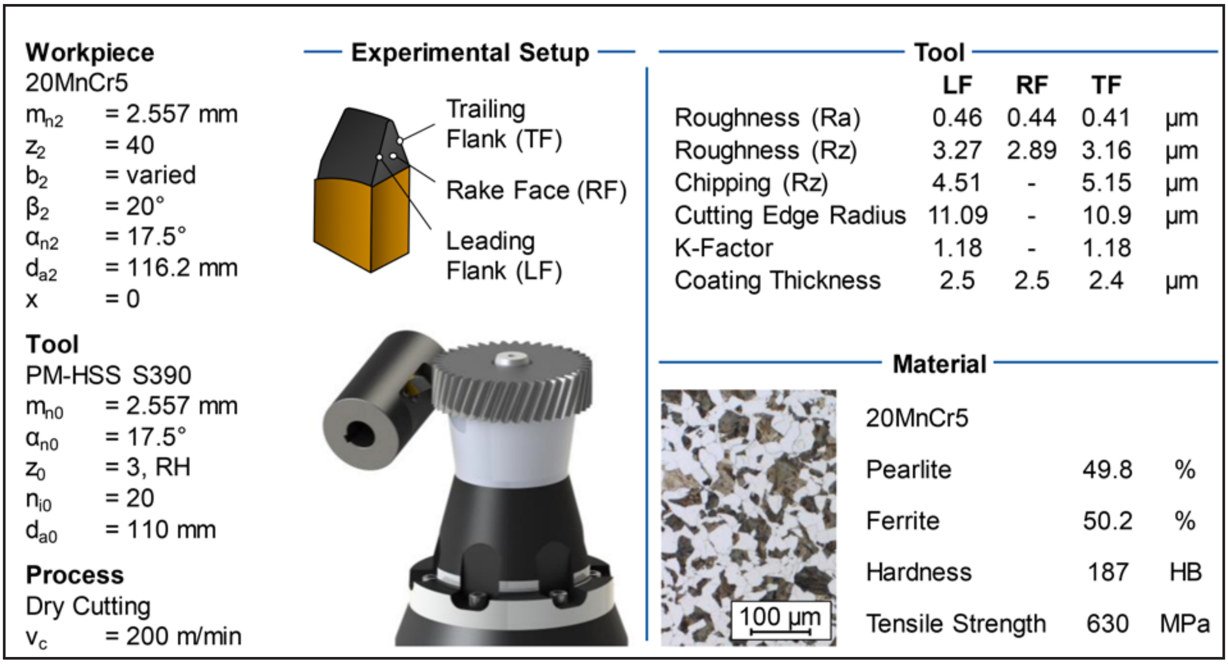


Figure 4 Experimental setup, tool and workpiece characterization.

width of flank wear VB was documented on the trailing (TF) and leading (LF) flank and on the tip clearance surface. The depth of crater was measured on the rake face (RF). For the test, a cutting speed of $v_c = 200$ m/min and a maximum tip chip thickness according to Hoffmeister of $h_{cu,max,Hoff} = 0.2$ mm were selected. In order to achieve the defined maximum chip thickness $h_{cu,max,Hoff} = 0.2$ mm, the required axial feed f_a in full-cut is $f_a = 1.95$ mm. For the climb cut trials, the workpiece width ($b_2 = 10$ mm, $b_2 = 30$ mm and $b_2 = 50$ mm) and the infeed angle ($\varphi = 0°$ and $\varphi = 90°$) were varied (Fig. 5). For workpieces with $b_2 = 30$ mm, the infeed was also investigated at $\varphi = 45°$.

The path feed f_b in the infeed phase was designed with consideration of the infeed angle φ in such a way, that maximum chip thickness $h_{cu,max}$ is the same in the infeed and in the subsequent axial machining. The extended calculation method from *SPARTApro* was used to determine the corresponding path feeds. In this case, the feed rates are $f_{b,0} = 1.95$ mm for the axial infeed, $f_{b,90} = 0.75$ mm for the radial infeed and $f_{b,45} = 0.9$ mm for the infeed at an angle of $\varphi = 45°$. Corresponding to the investigations in climb cut, trials were conducted on workpieces with $b_2 = 30$ mm in conventional cutting with otherwise identical process parameters.

In addition to the experimental design, the main time of the different variations is shown in Figure 5. The machining time of the variants with $\varphi = 90°$ and $\varphi = 45°$ for the respective workpiece width refers to the variant with $\varphi = 0°$. With a design according to the maximum chip thickness, the required machining time in the infeed and thus, also the total machining

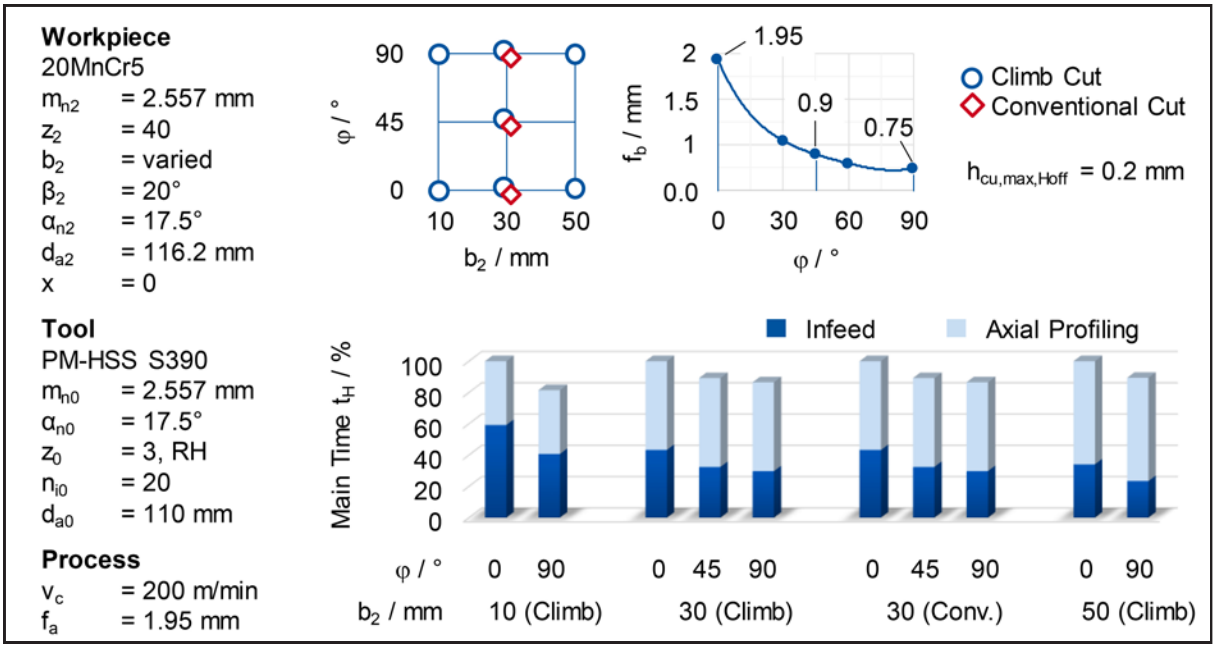


Figure 5 Design of experiments and resulting main times.

time decreases continuously with increasing infeed angle. The machining time for radial-axial process control corresponds to between 80% and 90% of the machining time for axial process strategy at the test points under consideration. This indicates a potential for increasing the process productivity.

Based on the investigations of the isolated influence of the infeed and the determined linear correlation between the bearable cumulated cutting length $l_{cu,lim}$ and the mean chip thickness $h_{cu,m}$, a tool life prognosis was performed for the following experiments. Depending on the workpiece width b_2, the geometric parameters $h_{cu,m}$ and $l_{cu,kum}$ were determined using *SPARTApro* (Fig. 6). Depending on the mean chip thickness $h_{cu,m}$, the bearable cumulated cutting length $l_{cu,lim}$ can either be taken graphically from the diagram in Figure 2 or, if the regression parameters a and b are known, calculated according to Equation 3. By inserting the determined parameters in Equation 4, the tool life N and, based on this, the machined length L, hereafter expressed as tool life L, can be determined according to Equation 5.

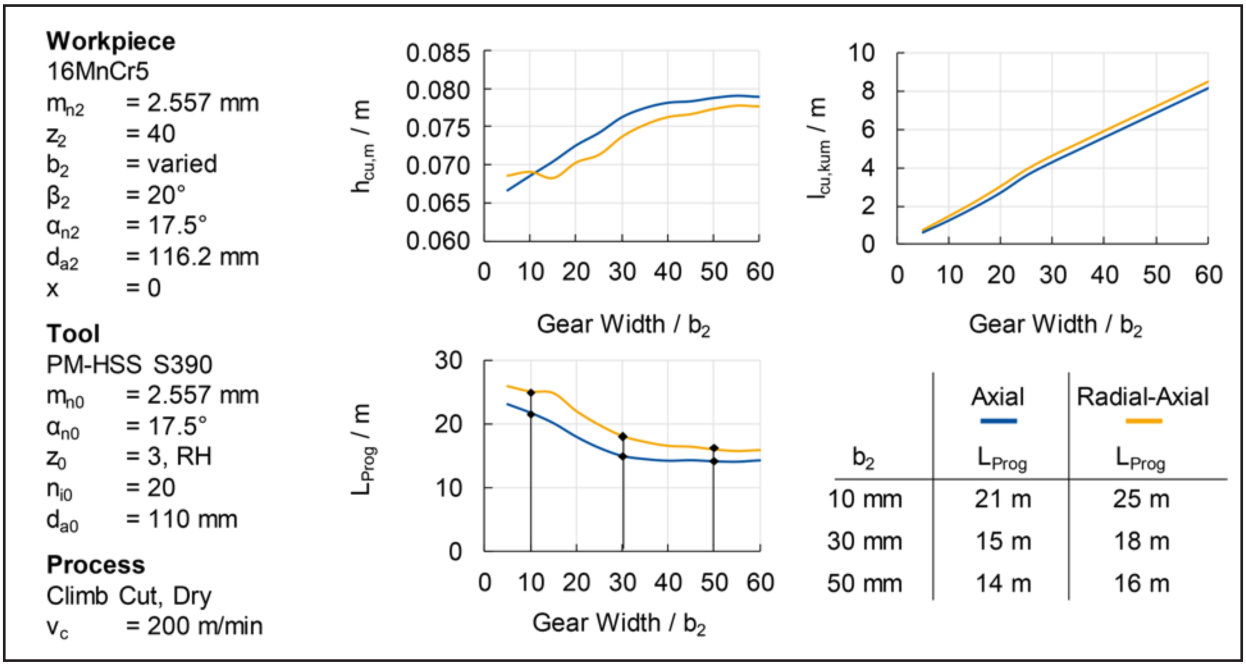


Figure 6 Tool life prognosis.

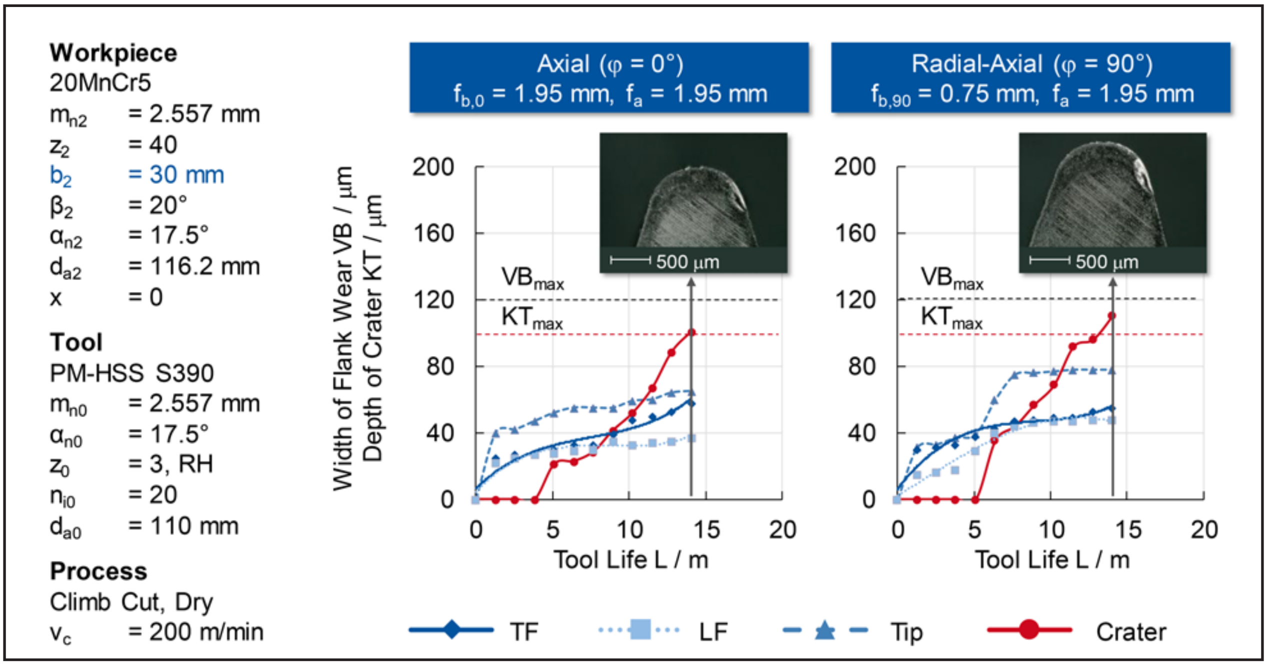


Figure 7 Wear behavior for axial and radial-axial process control (b_2 = 30 mm) for a design of the infeed according to the maximum chip thickness $h_{cu,max}$ = 0.2 mm.

$$l_{cu,lim} = a \cdot h_{cu,m} + b \quad (3)$$

$$N = \frac{l_{cu,lim}}{l_{cu,kum} \cdot z_2} \quad (4)$$

$$L = N \cdot \frac{b_2 \cdot z_2}{\cos(\beta)} \quad (5)$$

$l_{cu,lim}$	[mm]	Bearable cumulated cutting length
$h_{cu,m}$	[mm]	Mean chip thickness
$l_{cu,kum}$	[mm]	Cumulative cutting arc length
L	[m]	Tool Life (machined length)
β	[°]	Workpiece helix angle
a, b	[mm]	Empirical regression parameters
N	[-]	Tool Life (machined workpieces)
z_2	[-]	Number of teeth
b_2	[mm]	Workpiece width

For the trials with axial and radial-axial process control in climb cut, the predicted tool life L_{Prog} is plotted over the workpiece width. With a workpiece width of $b_2 = 10$ mm, the largest tool life is expected with $L_{Prog} = 21$ m for the axial and $L_{Prog} = 25$ m for the radial-axial variant. With increasing workpiece width, the predicted tool life decreases degressively to $L_{Prog} = 15$ m or $L_{Prog} = 18$ m for $b_2 = 30$ mm and $L_{Prog} = 14$ m or $L_{Prog} = 16$ m for $b_2 = 50$ mm. For all cases, the predicted tool life of the radial-axial variant is higher than of the axial variant due to a lower mean chip thickness $h_{cu,m}$.

Discussion of the Fly-Cutting Trials

The wear curves of the climb cutting trials with $b_2 = 30$ mm are shown for $\varphi = 0°$ and $\varphi = 90°$ in Figure 7. With a design of the infeed according to the maximum chip thickness $h_{cu,max}$, reaching the permissible depth of crater $KT_{max} = 0.1$ mm led to the end of the test in both cases. The documented wear curves at the leading and trailing flank as well as at the tool tip show a qualitatively and quantitatively similar curve in comparison of the radial to the axial variants. An exception to this is the course of the width of flank wear at the tip clearance surface. In the tool life range from L = 5 m to L = 7.7 m, the width of flank wear at the tip of the radial variant was doubled from VB = 40 mm to VB = 80 mm, which was due to a stochastic breakout of the cutting edge. As the tests were continued, a linear wear development without further, sudden damage occurred. In contrast to the investigations on the isolated influence of the infeed area, no significant influence of the infeed strategy on the tool wear could be determined. This can be explained by the fact, that with increasing workpiece width the proportion of the full cut area increases continuously and the influence of the infeed decreases accordingly.

The phenomenon, that the influence of the infeed decreases with increasing workpiece width and that the difference between the wear characteristics of an axial and a radial-axial process control decreases is also supported by the test results for the gear with $b_2 = 50$ mm. The wear development of the tools for the climb cutting trials with $b_2 = 50$ mm for $\varphi = 0°$ and $\varphi = 90°$ are displayed in Figure 8. Qualitatively, the wear behavior of the variants hardly differ from each other. Quantitatively, there is a difference between the curves due to a deviating initial wear on the tip clearance surface and on the flanks.

The difference in the wear behavior should be more significant when machining narrower workpieces. So far, this could not be verified, since in the investigations on the workpieces with $b_2 = 10$ mm the tools reached an end of life due to unsystematic breakouts at the tip cutting edge. These tests must be repeated in the future in order to verify or falsify the hypothesis.

The tool lives determined in the wear investigations for the combined influence of infeed and axial machining until reaching the tool life criterion are displayed in Figure 9. Machining the workpieces with a width of $b_2 = 10$ mm resulted in a tool failure due to breakouts at the tool tip after a comparatively low tool life of 7.4 m < L < 8.8 m in both axial and radial-axial process control. When machining the workpieces with $b_2 = 30$ mm,

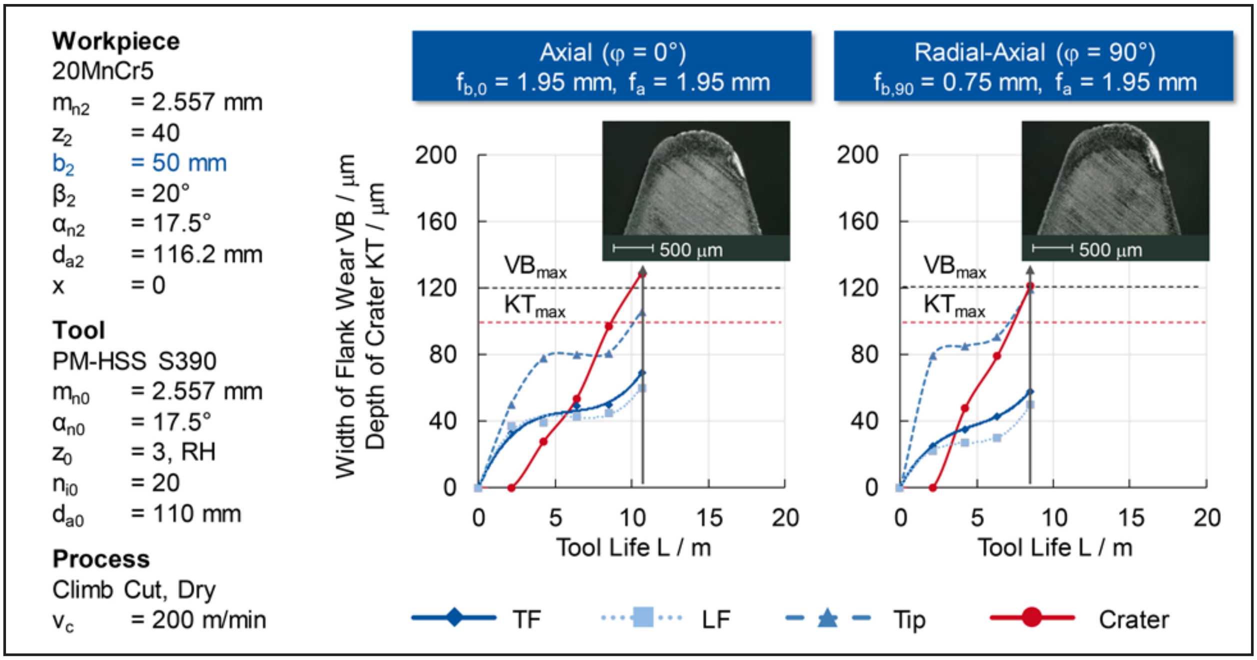


Figure 8 Wear behavior for axial and radial-axial process control (b_2 = 50 mm) for a design of the infeed according to the maximum chip thickness $h_{cu,max}$ = 0.2 mm.

a radial-axial strategy achieved an identical tool life with L = 14.4 m as the axial process control while simultaneously increasing productivity. Compared to the predicted tool life L_{prog} = 15 m or L_{prog} = 18 m, a lower tool life was achieved in the experiment. Furthermore, no difference in tool life could be determined between the radial and radial-axial variants. A design with φ = 45° infeed angle resulted in a lower tool life with L = 11.8 m in direct comparison. The tool life could be further increased by machining in conventional cut. While for the variant with axial infeed the tool life was L = 17 m, the largest tool life of all variants with L = 19.6 m could be achieved with radial-axial process control. However, a diagonal-axial machining strategy resulted in an abortion of the experiment as a result of premature tool failure due to cutting edge breakouts. With an increase in the workpiece width from b_2 = 30 mm to b_2 = 50 mm, a decrease in the tool life was recorded. This result is also in accordance with the previously carried out tool life prognosis. In contrast to the prognosis, the tool lives determined in the test are lower than those prognosticated and the tool life of the axial variants was higher than the tool life of the radial-axial variants.

To verify the linear correlation of the bearable cumulated cutting length $l_{cu,lim}$ with the mean chip thickness $h_{cu,m}$, the individual tool lives L of the variants were converted into the bearable cumulated cutting length $l_{cu,lim}$ according to Equation 4 and Equation 5 and plotted over the corresponding mean chip thickness $h_{cu,m}$. In this case, too, the bearable cumulated cutting length $l_{cu,lim}$ correlates with the mean chip thickness h (Fig. 10). The tools which failed due to breakouts were excluded from the evaluation.

In comparison to the investigations on the isolated influence of the infeed angle, the regression line shows a different slope

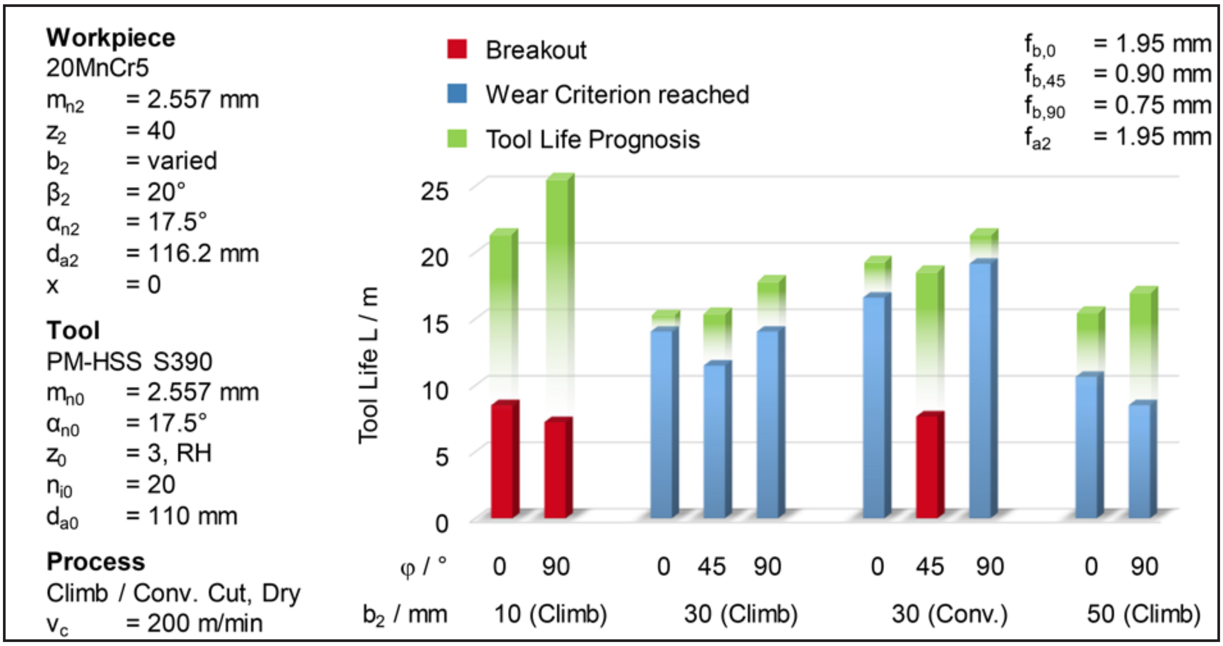


Figure 9 Comparison of the tool life of the investigated variants.

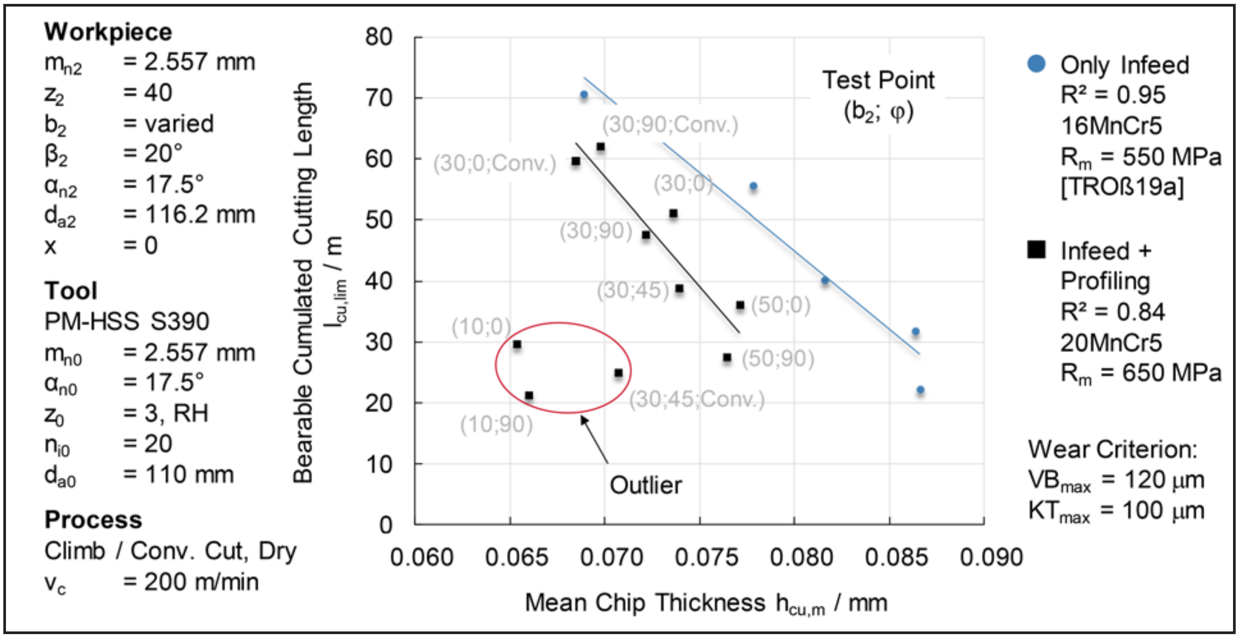


Figure 10 Correlation of the total arc length with the mean chip thickness.

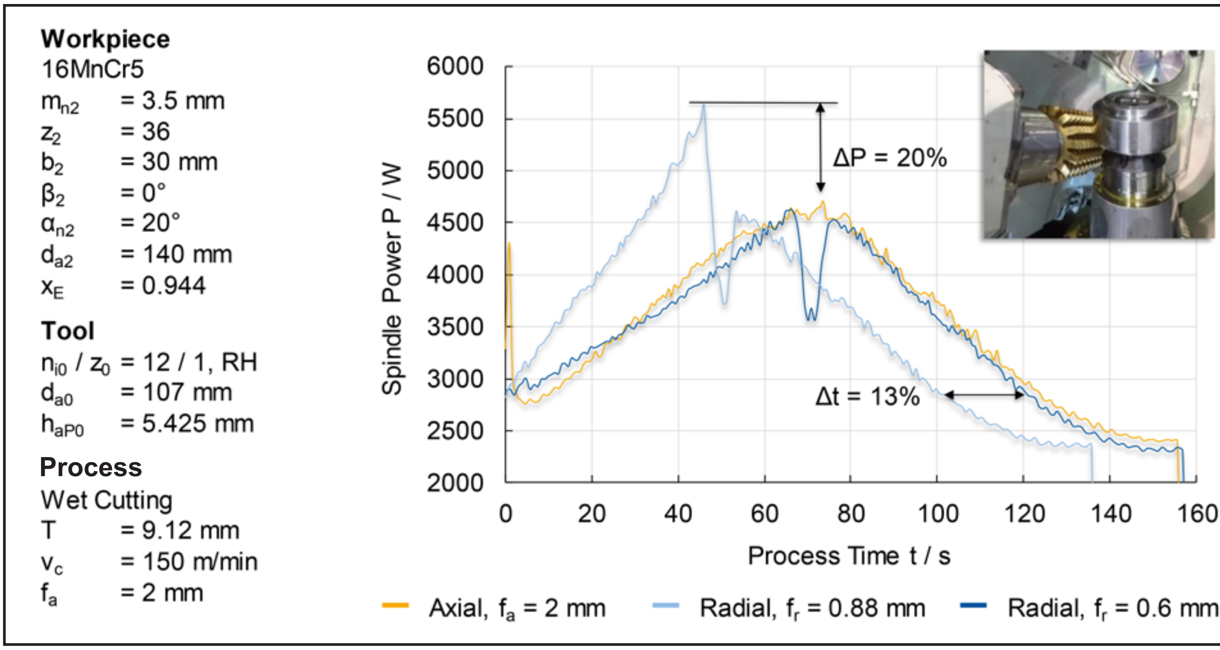


Figure 11 Comparison of the spindle power curves of the process strategies investigated.

and ordinate segment. This explains the lower tool lives in the experiment compared to the prognosis. The lower bearable cumulated cutting length $l_{cu,lim}$ determined in the investigations can be explained by the higher strength of the workpiece material 20MnCr5 with a tensile strength of $R_m \approx 630$ MPa. In the previous tests, a case hardening steel 16MnCr5 with a tensile strength of $R_m \approx 550$ MPa was machined.

Based on the characteristic values, the tool lives determined in the fly-cutting trial can be analyzed more precisely. An increase of the workpiece width leads to an approximation of the chip thickness and the chip length to the respective maximum value, which is present in the full-cut (see also Fig. 6). This means that the load on wider workpieces is higher than on workpieces which have no or hardly any full cut area. This explains the shorter tool life of the wide workpieces ($b_2 = 50$ mm) compared to the narrow workpieces ($b_2 = 30$ mm).

By adjusting the infeed angle or the machining direction, the penetration geometry changes during machining with otherwise identical parameters. This results in a change of the chip geometries, the resulting tool load and thus, the tool life. The results show that the process variables examined here, i.e. infeed angle, machining direction and workpiece width, influence the tool life only indirectly. A variation of the machining strategy and the workpiece width results in a change of the geometric penetration ratios and thus, of the tool load. Which process strategy led to the formation of these conditions is of secondary importance.

Knowledge of the linear relationship between the bearable cumulated cutting length $l_{cu,lim}$ and the mean chip thickness $h_{cu,m}$ can be used to design the hobbing process on the basis of tool life. The bearable cumulated cutting length $l_{cu,lim}$ can either be determined graphically from the diagram or calculated according to Equation 3. The coefficients a and b are to be determined empirically in wear investigations, e.g. in the fly-cutting trial. The mean chip thickness $h_{cu,m}$ can be derived numerically using the *SPARTApro* manufacturing simulation software. Equation 4 and Equation 5 can be used to transfer the bearable cumulated cutting length $l_{cu,lim}$ to the number of machined workpieces N or the tool life L. For this purpose, the cumulative chip length per gap must be known, which can be determined simulatively with *SPARTApro*.

Hobbing Trials

In order to validate the knowledge gained in the fly-cutting trials and to identify a suitable design method, tests were carried out in the hobbing process based on the previous investigations. For this purpose, trials were performed at the research facility and in an industrial environment.

Hobbing Trials at the Research Facility

The path feed f_b for the fly-cutting trials was designed based on the maximum chip thickness $h_{cu,max}$. In order to confirm or reject the suitability of this design method for the actual hobbing process, various process strategies and their effect on the spindle power P were tested at the research facility.

Climb cut axial gear hobbing at a cutting velocity of $v_c = 150$ m/min and an axial feed of $f_a = 2$ mm was used as a reference process. Radial-axial gear hobbing in climb cut was used as a further process strategy. The cutting velocity v_c and feed rate f_a during axial machining were selected in analogy to the reference process. The path feed f_b for the infeed was initially designed so that a maximum chip thickness $h_{cu,max}$ comparable to that of the subsequent axial machining is available when the tool is immersed. In this case, the radial feed rate is $f_r = 0.88$ mm.

During the infeed phase of the axial reference process, the power signal continuously increased until the maximum value $P_{max} = 4{,}500$ W was reached (Fig. 11). Due to the small workpiece width in relation to the tip diameter of the tool, there is hardly any full-cut for the tool/workpiece combination under consideration. Thus, the infeed phase went directly into the emersion phase, which is expressed by a continuous decrease of the effective power signal due to decreasing chip sizes.

For the radial-axial process, a continuous increase in spindle power was also be observed at the beginning. Compared to the reference process, the signal increased faster and reached a by ΔP = 19.5% higher peak value. In the transition from radial plunging to axial machining, the power dropped briefly and then proceeded analogously to the reference process. With regard to the spindle power, the difference between the two process strategies in a design based on the maximum chip thickness was only present in the infeed phase. With regard to the machining time, the use of the radial-axial process strategy resulted in a productivity gain of Δt = 13%.

In order to avoid the power difference between the infeed and the full-cut and to perform the radial-axial process under comparable conditions to the reference process, the radial feed was further reduced from $f_r = 0.88$ mm to $f_r = 0.60$ mm. The reduced radial feed results from adapting the machining time to the reference process. With the same process time, the same volume per time is machined, whereby the performance curves converge. A design based on the machining time allowed a comparable spindle power progression and thus, a robust, radial-axial process control was achieved. Due to the significantly higher spindle power in the infeed phase, a design of the infeed solely according to the maximum chip thickness $h_{cu,max}$ can only be evaluated as conditionally suitable.

Hobbing Trials in Industrial Environments

Since the batch size of the test gear production at the research facility is not sufficient to make a meaningful assessment of the tool life, a series production was accompanied in the industrial environment. Figure 12 shows the production of a double sun gear at ZF Friedrichshafen AG in Saarbrücken, Germany. Sun gear 2 is currently produced with a two-cut strategy due to an interference resulting from the front face of sun gear 1. By

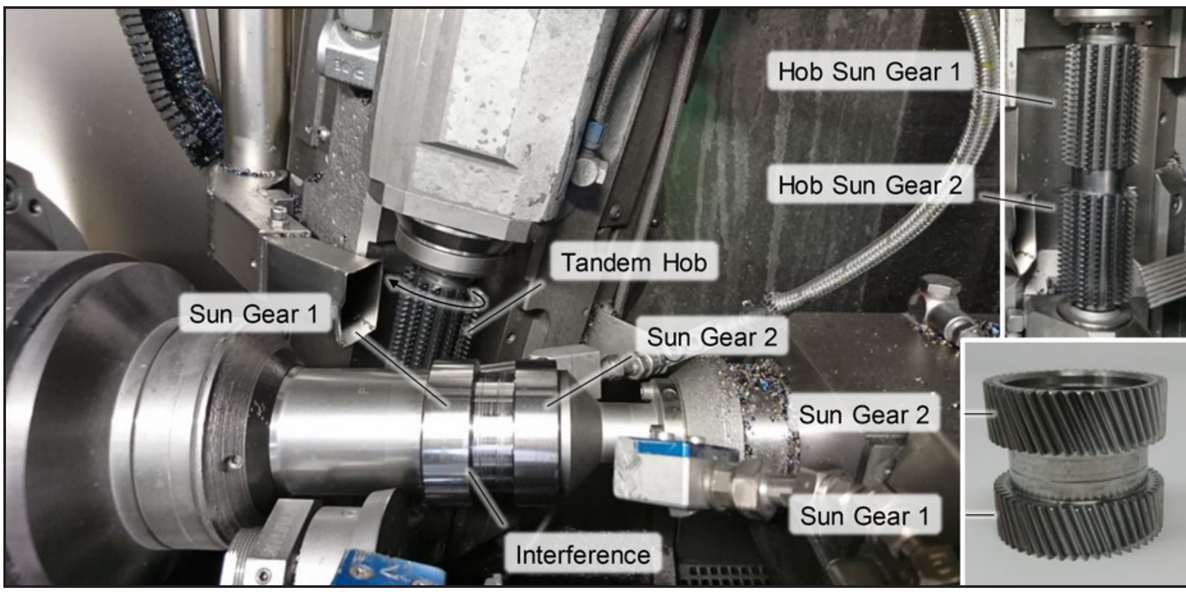


Figure 12 Manufacturing of a double sun gear at ZF in Saarbrücken, Germany.

Reference Process (2-Cut-Strategy)

	1 (Climb)	2 (Conv.)
v_c	400 m/min	500 m/min
f_a	1.7 mm	2.3 mm
t_H	8.73 s	3.26 s
$\mathbf{t_{H,tot}}$	**11.99 s**	
$h_{cu,max}$	0.156 mm	0.1 mm
$\mathbf{h_{cu,m}}$	**0.048 mm**	
$\mathbf{l_{cu,kum}}$	**1964.2 mm**	

Radial-Axial (1-Cut-Strategy)

	Radial	Axial (Climb)
v_c	400 m/min	400 m/min
f_r or f_a	0.5 mm	1.7 mm
t_H	3.14 s	5.51 s
$\mathbf{t_{H,total}}$	**8.65 s**	
$h_{cu,max}$	0.129 mm	0.16 mm
$\mathbf{h_{cu,m}}$	**0.049 mm**	
$\mathbf{l_{cu,kum}}$	**1717 mm**	

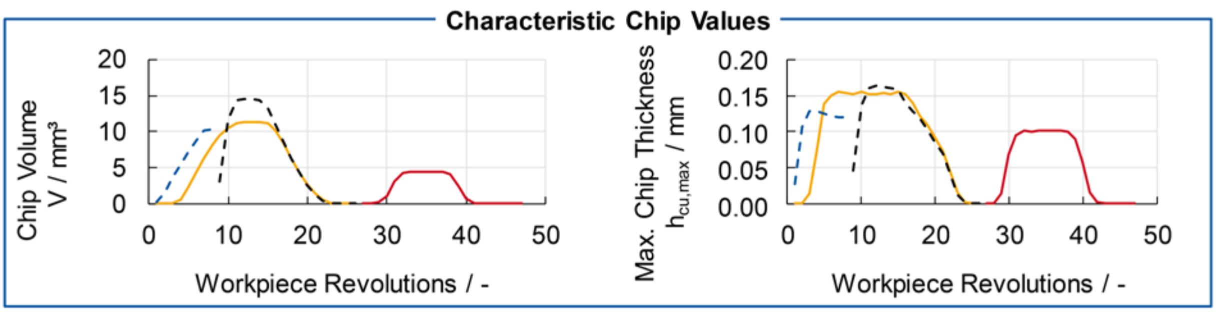


Figure 13 Design of a radial-axial machining strategy for the production of the sun gear 2.

reducing the number of cuts and thus, increasing productivity, the methods developed in this project were used to design a radial-axial process strategy for manufacturing sun gear 2. The gear was then produced in series with the developed strategy until a defined tool life was reached.

The process parameters of the developed radial-axial process strategy as well as those of the reference design are shown in Figure 13. The use of radial-axial hobbing for the process parameters shown is expected to increase productivity by around $\Delta t \approx 3$ s. A comparison of the characteristics $l_{cu,kum}$ and $h_{cu,m}$ indicates a slightly higher load ($\Delta h_{cu,m} = 0.001$ mm) with a simultaneously shorter cutting length compared to the reference process. If these parameters are considered solely based on the linear correlation between $l_{cu,lim}$ and $h_{cu,m}$ determined in the fly-cutting trial, no deterioration of the tool life is expected. Furthermore, for the second cut, the cutting speed was reduced to $v_c = 400$ m/min, which can also indicate a lower tool life due to lower temperature development during machining. The maximum chip thicknesses are smaller or equal to the maximum chip thickness for the first cut of the reference process for both the radial infeed and the subsequent axial machining. Therefore, no tool life losses are expected. The curves of the chip volume and the maximum chip thickness are shown in the lower part of the figure. Due to the shorter machining time, the course of the machined volume has a higher maximum value than for the reference process. For this reason, a slight increase in the spindle power signal is expected.

The objective of the radial-axial process strategy is to achieve a tool life that is in a similar range as the average tool life of the reference process as well as to meet all quality criteria. A comparison of the profile and helix deviation of the reference process and the radial-axial process strategy is shown in Figure 14. Despite a change of the infeed strategy, it was possible to achieve a comparable gear quality to the reference process. Due to the lower axial feed in the radial-axial variant, feed marks were also reduced. Compared to the reference process, the right flanks show a lower helix crowning. This could result from the higher forces due to the higher chip volume during axial machining.

The tool life, expressed as number of machined workpieces N, documented for the reference process is plotted for the period from November 2018 to March 2019 in the form of a frequency distribution (Fig. 15). The normal distribution was used as the distribution function. At the time of the evaluation, the mean value of the tool life achieved in the reference process was $N_\mu = 2{,}570$ workpieces and the standard deviation $N_\sigma = 750$ workpieces.

The tool life achieved with the radial-axial process strategy is illustrated in the bell curve. After reaching a tool life of $N = 3{,}000$ workpieces, the hob was removed and analyzed with a reflected-light microscope at the research facility. The achieved tool life lies within the interval $N_\mu + N_\sigma$ and is higher than the average tool life of $N_\mu = 2{,}570$ workpieces. The degree of wear on the tool is shown representatively in Figure 15 on the right. The left flank with $VB_{max} = 40$ mm has a larger maximum width of flank wear than the right flank with $VB_{max} = 20$ mm. Crater wear was not observed on the rake faces of the tool and is not to be expected as carbide cutting material was used. Despite the high number of machined workpieces, only a comparatively low degree of wear was observed. Thus, a potential for increasing the tool life by means of a radial-axial process strategy could be identified.

Conclusion and Design Recommendation

A radial-axial process strategy offers an effective alternative to conventional axial hobbing to avoid collisions with interference. Since no profiling of the final gap geometry takes place during the infeed, the infeed strategy has no influence on the gear quality. This could also be verified by trials in industrial environment. A significant advantage of a diagonal infeed strategy over a radial or axial infeed strategy could not be identified in the investigations and is therefore not recommended. Figure 16 compares a conventional axial machining strategy to two design approaches for a radial-axial strategy, on the one

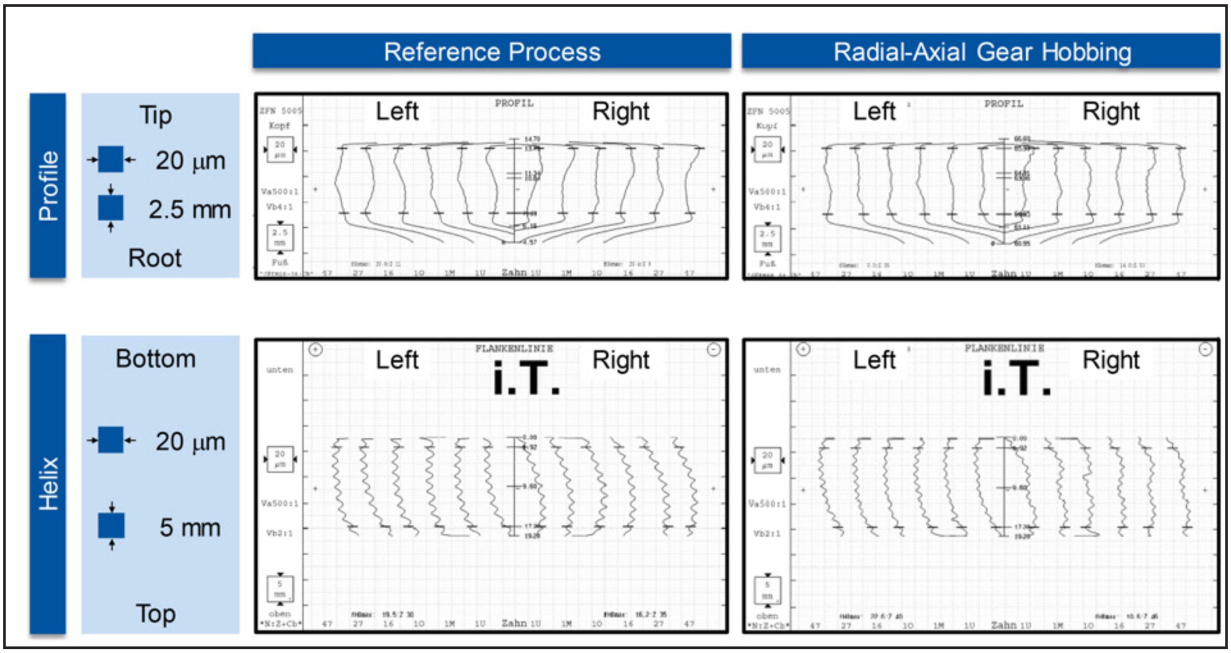


Figure 14 Comparison of gear quality.

hand according to the maximum chip thickness $h_{cu,max}$ and on the other hand according to a constant main time t_H.

Due to a design of the radial-axial hobbing process based on characteristic values, a robust process control can be realized and a potential for increasing tool life and productivity is given. In this project, different procedures for an appropriate design were shown. A design based on a constant machining time was identified as a practicable and quick to implement method, which enables a robust process control. The manufacturing simulation *SPARTApro* was extended by the consideration of the infeed angle in the context of this research project for characteristic value-based design. This allows the determination of common chip parameters, which can be used as further parameters for process design. For the empirical investigations, a design based on the maximum chip thickness resulted in an increase of productivity on the one hand and a decrease on tool life on the other. Taking the correlation of the bearable cumulated cutting length $l_{cu,lim}$ and the mean chip thickness $h_{cu,m}$ into account for process design, an increase of process efficiency was achieved for the industrial series test.

Summary and Outlook

Based on the theoretical considerations and fly-cutting trials on the isolated influence of the infeed angle, the combined influence of infeed and subsequent axial machining was further investigated in wear investigations. In addition to the infeed angle, the workpiece width and the machining direction (climb and conventional cut) were varied as well. The investigations indicated that the influence of the infeed decreases with increasing workpiece width and that the difference between the wear

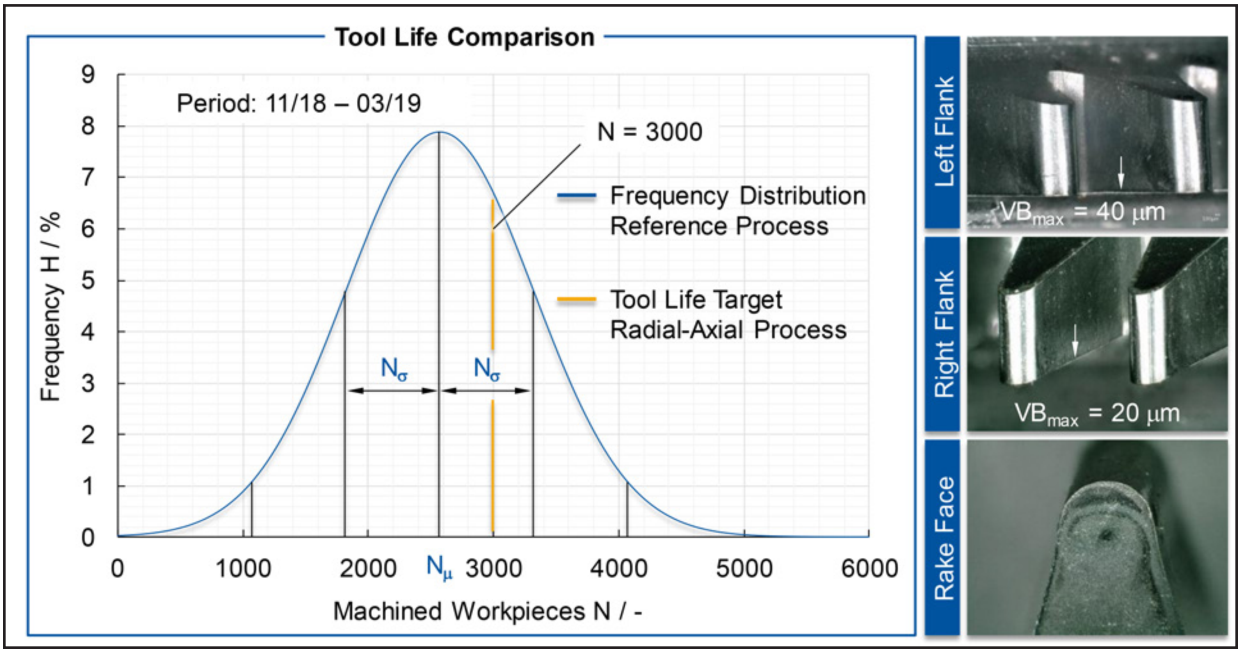


Figure 15 Assessment of the achieved tool life by radial-axial hobbing.

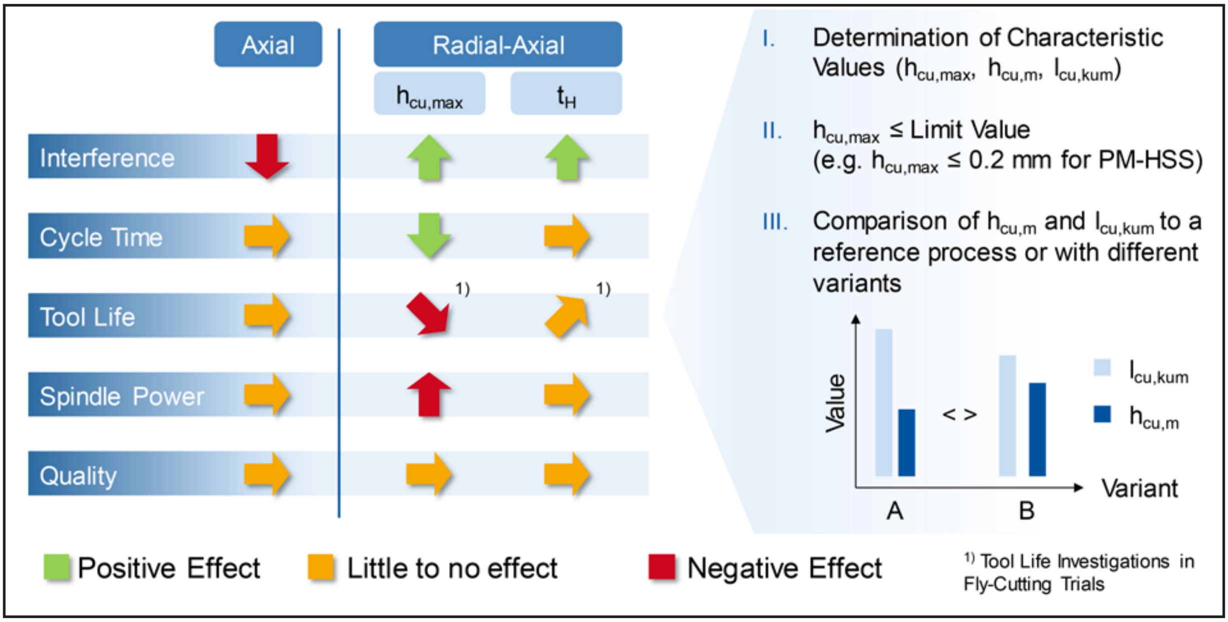


Figure 16 Comparison of a radial-axial to an axial process strategy.

characteristics of an axial and a radial-axial process control decreases. This can be explained by the fact that with increasing workpiece width, the proportion of the full-cut increases continuously and the influence of the infeed decreases accordingly. Further wear trials are necessary to verify this phenomenon.

In order to validate the findings gained by the fly-cutting trials, the research institute produced test gears by conventional axial gear hobbing and, with otherwise identical process parameters, by radial-axial gear hobbing. The latter strategy was designed in such a way that the maximum chip thickness in the infeed is comparable to that of the subsequent axial machining. A design of the radial-axial hobbing process according to the maximum chip thickness achieved a shorter process time on the one hand, but on the other hand resulted in higher spindle power for the infeed phase. The radial feed rate was further reduced in order to avoid the high power difference between the infeed phase and the full cut phase as well as to carry out the radial-axial process under comparable conditions as the reference process. The reduced radial feed resulted from an adaptation of the machining time to the reference process. This method enabled a comparable spindle power curve and thus, a robust radial-axial process control.

For the industrial series test, an increase of process efficiency could be achieved by means of radial-axial hobbing through a characteristic value-based design. The results confirm that there is no deterioration in gear quality due to an adjustment of the infeed strategy and an increase in productivity can be achieved with a comparable tool life. The main parameters for the design were the bearable cumulated cutting length $l_{cu,lim}$ and the mean chip thickness $h_{cu,m}$. Despite the high number of machined workpieces, only a small width of flank wear was measured on the hob. In further investigations, the tool is to be reinstalled and used up to the point where regrinding is necessary in order to determine the maximum tool life. For a statistical verification of the result, additional tools based on the radial-axial strategy for series produc tion are to be used.

Acknowledgement

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages

The IGF project 18517 "Design of gear hobbing processes with a variable infeed" of the research association VDW-Forschungsinstitut e.V. is funded by the Federal Ministry of Economics and Energy through the AiF within the framework of the Program for the Promotion of Industrial Community Research (IGF) on the basis of a resolution of the German Bundestag.

The authors gratefully acknowledge financial support by the WZL Gear Re search Circle.

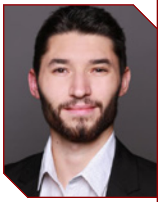
Seit 1956 Since 1956 WZL Getriebekreis Gear Research Circle

References

1. Hoffmeister, B.: Über den Verschleiß am Wälzfräser.
2. Diss. RWTH Aachen University, 1970.
3. Klocke, F., C. Brecher. Zahnrad- und Getriebetechnik. Auslegung - Herstellung - Untersuchung - Simulation. München: Carl Hanser, 2017.
4. Norm DIN EN 18265 (February 2004) Metallische Werkstoffe, Umwertung von Härtewerten.
5. Pfauter, H.: Pfauter-Wälzfräsen, Berlin, Springer, 1976.
6. Troß, N.; Löpenhaus, C.; Bergs, T.: Influence of the Infeed Strategy on the Cutting Conditions in Gear Hobbing, 7th International Conference on Gear and Drivetrain Production, Würzburg, 19.-20. März 2019. Frankfurt a.M.: Eigenverlag, 2019, pp. 275–280.
7. Troß, N., C. Löpenhaus and F. Klocke. Analysis of the Cutting Conditions for Radial-Axial Infeed Strategies in Gear Hobbing, Procedia CIRP, Vol. 79, 2019, pp. 68–73.
8. Weber, G.-T. Auswahl und Auslegung von Fräsprozessen für Großverzahnungen, Diss. RWTH Aachen University, 2017.

For the main part of his academic qualification, **Prof. Dr.-Ing. Thomas Bergs** studied design engineering at the Rheinisch-Westfälische Technical University, Aachen. He graduated in 1995 having written his diploma thesis at the Engineering Research Center for Net Shape Manufacturing in Columbus, Ohio. In 2001 he went on to earn a doctorate in engineering at the RWTH Aachen University for which he was awarded the Borchers Plaque. He also graduated as an Executive Master of Business Administration in 2011. Thomas Bergs was a research associate in the Process Technology Section at the Fraunhofer Institute for Production Technology IPT in Aachen from 1995 to 2000. In the year 2000, he was appointed Manager of the Laser Engineering Group and of the Business Unit »Aachener Werkzeug- und Formenbau«(Aachen Tool and Die Making). Since 2001 he has also held the position of Managing Director under Professor Fritz Klocke as institute head. Thomas Bergs has additionally founded the company Aixtooling in 2005, where he became Managing Director untiel 2018. Core area of the expertise at Aixtooling was tool making for precision glass molding as well as advanced glass optics manufacturing.
In 2018 Thomas Bergs was appointed as Professor at the Chair of Manufacturing Technology at the Laboratory for Machine Tools and Production Engineering WZL of the RWTH Aachen University and as Director of the Process Technology Division at the Fraunhofer Institute for Production Technology IPT. As the successor to Professor Fritz Klocke, he is also a member of the Board of Directors of both production engineering institutes. Main focus of his ongoing research activities comply the digital transformation of manufacturing technologies—so called networked adaptive production.

Dr. -Ing. Dipl. -Wirt. -Ing. Christoph Löpenhaus is since 2021 working with Flender GmbH as head of production for the part manufacturing plants in Bocholt and Voerde, Germany. Flender is a worldwide leading provider of drive systems especially for wind turbine and industry applications. From 2019-2021 he was Business Development Manager Geared Bearings at Cerobear GmbH, a leading manufacturer of hybrid bearings especially in the aerospace, space, and industry segment. From 2014–2019 he held the position as Chief Engineer of the Department of Gear Technology of WZL, RWTH Aachen with research focus on gear manufacturing, design, and testing. He previously worked with WZL as Team Leader and Research Assistant. His educational background is in the field of Industrial Engineering with a diploma in 2009 and a Ph.D. in mechanical engineering in the field of gear technology in 2015. For his scientific achievements he was awarded the Springorum Commemorative Coin in 2010 and the Borchers Badge in 2016.



Nico Troß M.Eng. received his bachelor's degree in mechanical engineering from the University of Applied Sciences in Saarbrücken in 2013, and his master's degree in mechanical engineering from the University of Applied Sciences in Aachen in 2016. In 2017, he became a research assistant in the department of gear technology of the Laboratory for Machine Tools and Production Engineering WZL in Aachen. Since 2019, he has been team leader of the research group gear soft machining. His research area is gear manufacturing with a special focus on gear hobbing and process chain optimization.

Psychoacoustic Optimization of Gear Noise - Chaotic Scattering of Micro Geometry and Pitch on Cylindrical Gears

Marcel Kasten M.Sc., Dr.-Ing. Jens Brimmers M.Sc.
and Prof. Dr.-Ing. Christian Brecher

Introduction and Motivation

Increasing sensitization for the topic noise, reduced masking noises and increased customer demands lead to an increasing importance of transmission noise. Especially due to the tonal characteristic of gear whining, gear noises move quickly and negatively into the customer's focus (Ref. 1). One of the most important criteria in the qualitative evaluation of gear transmissions in automotive engineering is the noise behavior (Ref. 2). The control of vibrations and the optimization of noise behavior inside of the vehicle is therefore an important development aim of automobile and transmission manufacturers (Ref. 3). A large part of the vibrations and noises inside of the a vehicle are generated in the drive train. Especially in motor vehicles, the reduction of masking noise sources through downsizing as well as electrification and hybridization of the drive train increases the importance of a low-noise transmission (Ref. 4).

However, increasing the quality of the gears and decreasing the gear excitation does not prevent the gear noise from being perceived as annoying. For an improvement of the perceived noise quality, a reduction of the noise level alone is not always the best solution. The characteristics of the noise and thus the human perception are decisive (Ref. 5).

In the design of transmissions, the high demands on running and noise behavior are fulfilled by specific topography designs. A compromise must be found between low gear excitation, sufficient load carrying capacity and high efficiency. The selection of the target topography for an optimized operational behavior over a wide torque range is the challenge in gear design (Ref. 6). Up to now, the quasi-static transmission error of a gear set is used as an evaluation variable for the resulting noise behavior.

The dominant noise characteristic of gears is howling and whining at high frequencies. This is caused by rolling the gear pair under load. Figure 1 shows the source-path-receiver concept in the automotive technology, based on Carl (Ref. 5). The source-path-receiver concept systematically describes the origin and transfer of the gear whining up to the hearing-related evaluation of the noise. Here, the noise behavior of a transmission can be represented by the machine acoustic transfer chain consisting of noise excitation (source, tooth mesh), noise transfer (path, structure-borne noise) and noise radiation (receiver, airborne noise).

The starting point of the noise generation chain is the quasi-static gear excitation. The gear excitation is quantifiable as the transmission error (TE) of a gear set and leads in interaction with the operating point-dependent dynamics of the drive train to a dynamic load fluctuation in the gear mesh. The resulting vibrations in the tooth contact are transmitted as structure-borne noise to the shaft bearing system and subsequently to the housing surface. Depending on the structural dynamic

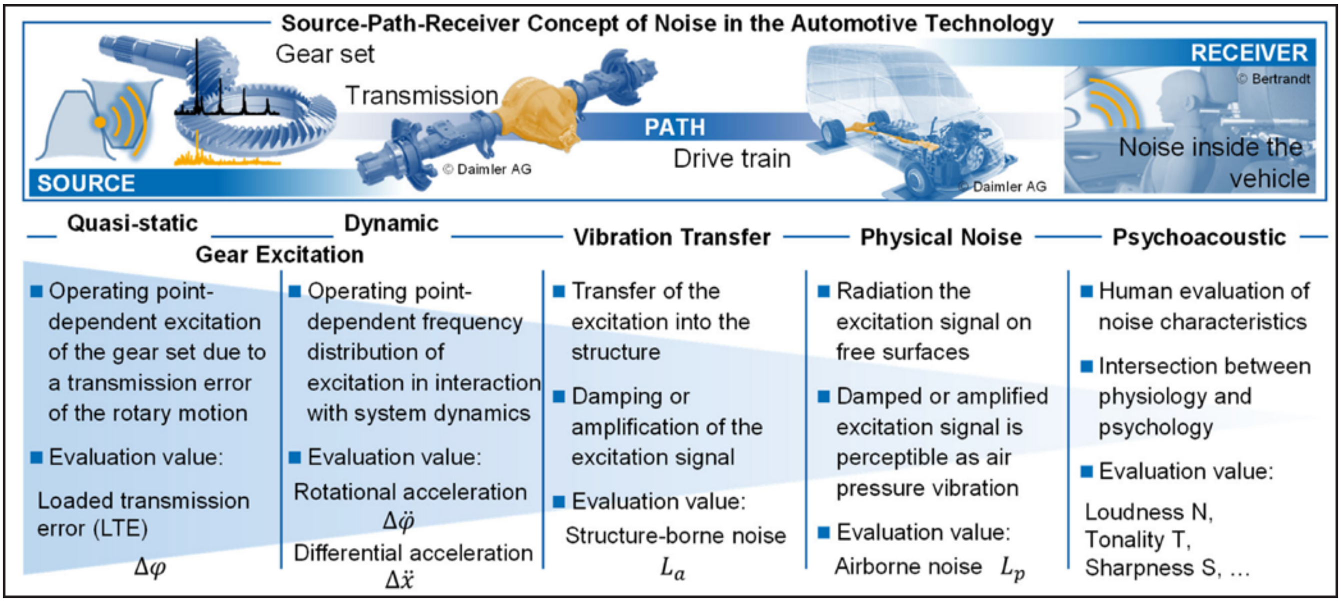


Figure 1 Source-path-receiver concept of noise in the automotive technology based on Carl (Ref. 5).

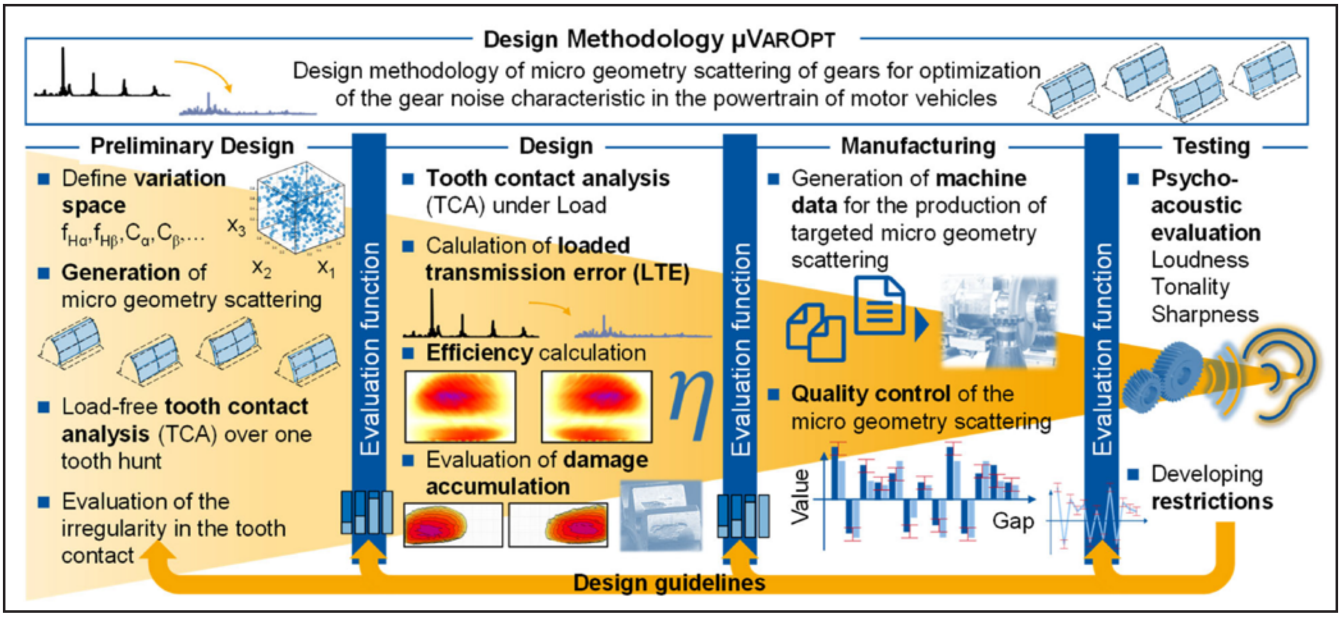


Figure 2 **Design methodology μVarOpt.**

properties of the transmission, the structure-borne noise is converted into airborne noise in the form of noise pressure fluctuations on the surfaces. Psychoacoustic evaluation methods are used to assess the effect of physical noise on the human hearing. The principle illustrates the connection between the gear excitation and the perception-specific noise characteristics of a transmission. (Ref. 5).

Objective and Approach

In the gear design process, increasingly extensive simulation options are being used to counter the rising requirements placed on modern gears. In addition to sufficient load capacity, good noise and running behavior with high power density is required for gear units. A target design for the application is generated on the basis of the framework conditions of the specifications.

With the minor disturbance of the meshing conditions by micro geometry scattering, the regularity of the transmission error signals in the time domain is disturbed and the background noise is increased. This is a new approach for the design of the target geometry of gears. This approach has already been used successfully for bevel gears (Refs. 7–9).

In this context, it could already be shown that a targeted micro geometry scattering on a beam style rear axle in a light commercial vehicle resulted in an improvement of the noise inside the vehicle (Refs. 9–10). The investigations described in the present paper were conducted as a part of a project sponsored by German Research Foundation (DFG) [Project Number BR 2905/82-1], which is carried out with the cooperation partners Daimler AG and Klingelnberg GmbH. The objective of the research project is the development of a method for the perception-oriented design of gears by the application of a targeted micro geometry scattering. The research hypothesis is that a specific design of a micro geometry scattering on gears leads to an improvement of the noise characteristics without loss of efficiency or load capacity.

The micro geometry scatters designed with the μVarOpt methodology were machined in a discontinuous profile grinding process. It was observed that the grinding of the micro geometry scatter results in a stochastic course of the pitch error. The research question in this report is the influence of a stochastic course of the pitch error compared to a micro geometry scattering on the excitation and noise behavior of cylindrical gears. For this purpose, the quasi-static excitation behavior of cylindrical gears with and without a stochastic course of the pitch error, as well as cylindrical gears with and without micro geometry scattering, is first investigated in the test field. Then, a simulation model is built to represent the quasi-static excitation behavior with stochastic course of the pitch error and the micro geometry. The simulation model is built using the FE-based tooth contact analysis ZaKo3D developed at Laboratory of Machine Tools and Production Engineering (WZL). The simulation results are validated using real transmission error measurements with the WZL cylindrical gear measuring cell.

The validated simulation model is used to analyze more in-depth investigations into the influence of a stochastic course of the pitch error on the quasi-static excitation behavior. In addition to the quasi-static behavior, the dynamic excitation behavior of the different gear set variants is also investigated. Here, the rotational acceleration close to the gear mesh is recorded and evaluated. In addition, noise behavior is analyzed by airborne noise measurements with psychoacoustic metrics (loudness and tonality).This is realized with a separate test rig setup for dynamic investigations.

Methodology μVarOpt for the Design of Micro Geometry Scattering on Gears

The design methodology μVarOpt for the determination of a targeted micro geometry scattering is about the limit setting of reliability at given high validity or in other words the design of a controlled chaos. The multistage perception-oriented design method μVarOpt of micro geometry scattering is shown in Figure 2. In the first step of the first design stage (preliminary design), gear sets with individual micro geometries are generated on the basis of a variation space. A basic design of macro

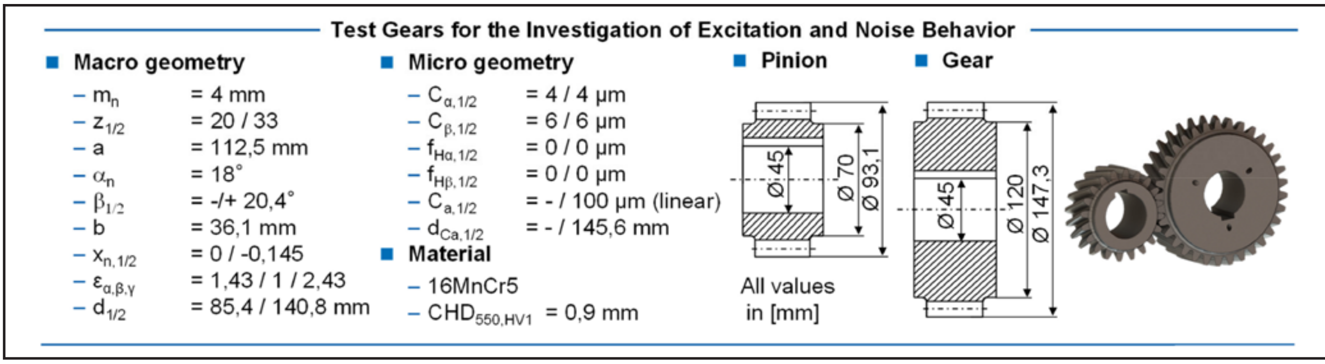


Figure 3 Test gears.

and micro geometry, which is to be varied, must be defined. In addition, it must be specified whether micro geometry scattering is to be generated at the pinion and/or mating gear, together with the respective number of individual micro geometries. Also, the type of distribution of the micro geometry scattering can be chosen between random and normally distributed. After the generation of a variant with micro geometry scattering, the FE-based tooth contact analysis ZaKo3D is automatically activated and the load-free transmission error over a tooth hunt is calculated. The evaluation of the simulation results is stored in a result matrix. At the end of the first stage of the variant calculation, all variants are evaluated with an evaluation function and the best variants in the load-free case are selected. The amplitudes of the first four gear mesh orders of the load-free transmission error are evaluated. In addition, the stochastic component in the transmission error course is evaluated by a modified autocorrelation function and is used to describe the irregularity of the tooth contacts (Ref. 7).

In the second stage, a tooth contact analysis under load is performed for the selected variants. The tooth contact analysis ZaKo3D is used to calculate the excitation behavior under load. In order to represent the signal-noisy effects of a micro geometry scattering under load, a tooth hunt is also simulated. In addition, the tooth contact analysis FE Stirnradkette Stirak can be controlled to calculate the efficiency, as well as the evaluation of damage accumulation due to irregular tooth meshing. At the end of the second stage, all variants calculated with a tooth contact analysis under load are graded with an evaluation function and the best gear set variant is determined.

In the third step, machine data for the grinding process is automatically generated to produce a targeted micro geometry scattering. After manufacturing, the quality control of the designed scattering of the micro geometry is carried out and evaluated.

In the fourth and final step, the manufactured gear sets are examined with regard to their operational behavior. The focus here is on the psychoacoustic evaluation of the noise behavior. With all the information obtained, restrictions can then be worked out and design guidelines can be made, for example, for the parameterization of the evaluation functions.

In the research work of Kasten et al., restrictions for the design of micro geometry scattering on ground bevel gears were developed. In addition, it could be shown that an optimization of the excitation behavior can already be achieved by applying a topography scattering with two to four different micro geometries, which are randomly distributed over all teeth of the component. The complexity of manufacturing and quality control of gears with mixed topographies (micro geometry scattering) is reduced by this insight. By comparing different types of scattering, the random application of micro geometry parameters and the random distribution of the different micro geometries from tooth to tooth were identified as the successful approach. The identification of the main influencing variables of the micro geometry parameters showed that the scattering of the angle modifications (profile and flank angle modifications) have a significant influence on the psychoacoustical optimized excitation behavior. By separately applying micro geometry scattering to the pinion and the gear, it could be demonstrated that the complete optimization potential of micro geometry scattering on gears can be achieved by generating mixed topographies on pinion and gear (Ref. 7)

Test Method

In this chapter, the test gears for the excitation and noise investigations are presented first. This is followed by a description of the two test rig setups for the quasi-static and dynamic investigation of the excitation behavior.

Test Gears

The test gears for the investigation of the excitation behavior is a helical gear set with normal modulus of $m_n = 4$ mm, a gear ratio of $z_{1/2} = 20/33$ and a helix angle $\beta_{1/2} = \pm 20.4°$ (Ref. 11). Both the macro geometry and micro geometry data are shown in Figure 3. The gears is made of 16MnCr5 steel alloy. The heat treatment selected is case hardening followed by cleaning blasting. With a center distance of $a = 112.5$ mm, the gear set can be applied to the test rigs described below.

Test Rig Setups

Test Rig Setup for the Investigation of the Quasi-static Excitation Behavior

For the investigation of the quasi-static excitation behavior of cylindrical gears, the WZL Cylindrical gear measuring cell was used for single flank test under operating conditions, see Figure 4 (left part). The measuring cell has an open design with oil injection. An oil cover serves as splash protection. Bearings are provided by bearing blocks at the input and output. The gears are supported by flanges. In order to provide misalignments caused by bending, an additional bearing is mounted on the shaft side facing away from the bearing block. The oil injection temperature is monitored and controlled to $T_{Oil} = 60°C$.

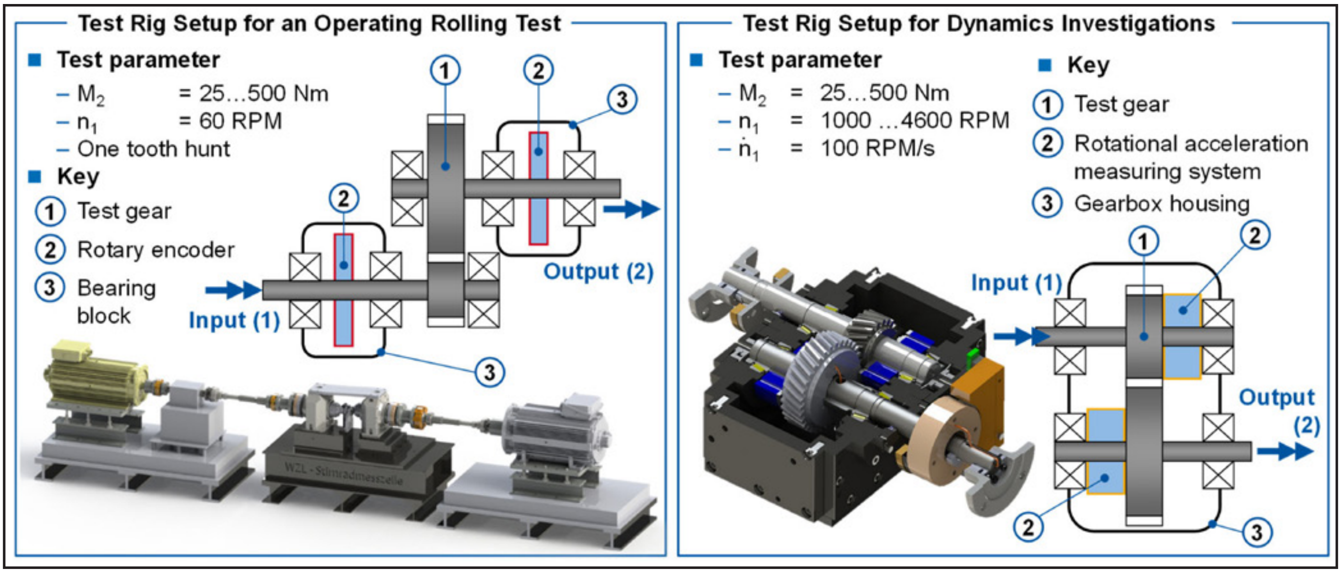


Figure 4 Test rig setups for quasi-static and dynamic investigation of excitation and noise behavior.

During the single flank test under operating conditions, at a low input speed of $n_1 = 60$ RPM and a maximum output torque of $M_2 = 500$ Nm, the transmission error of the gear set (Ref. 1) is detected by incremental rotary encoders (Ref. 2).

Test Rig Setup for the Investigation of the Dynamic Excitation Behavior and the Noise Behavior

The test rig setup for the dynamics investigations is carried out on the WZL's universal transmission test rig, which consists of an electric input machine and two electric output machines. The motors and the test object are each located on separate clamping fields, which are supported by air springs. This decoupling of the individual clamping fields from the building avoids excitations of the test object which are not generated by the drive train itself. An acoustic measuring chamber, which encloses the clamping field of the test object, allows the measurement of the airborne noise without the influence of external noise sources, such as the noise sources of the pump for the circulating oil lubrication and the noise of the electrical machines. For the investigation of the dynamic excitation behavior and the noise behavior, the WZL dynamic measuring cell (single-stage cylindrical gear set) developed by Carl was used (Ref. 5). The basic design of the measuring cell as well as the measuring technique used are shown in Figure 4 on the right side. The WZL dynamic measuring cell enables the investigation of the differential acceleration by means of rotational acceleration measuring systems (Ref. 2), which are mounted close to the gearing for a metrological recording of the dynamic gear excitation. By means of the speed ramp-ups at constant torque, the dynamic behavior of the different gear set variants was investigated. To ensure reproducibility, the gearbox temperature $T_{Gearbox}$ and the oil injection temperature T_{Oil} were measured. The oil injection temperature was $T_{Oil} = 60°C$.

Influence of Chaotic Scattering of the Pitch and Micro Geometry on the Quasi-static Excitation Behavior

In this chapter, the influence of a chaotic scattering of the micro geometry and the pitch on the quasi-static excitation behavior of cylindrical gears is investigated. For this purpose, the manufactured gear set variants are first characterized with respect to micro geometry and single pitch deviation. Then, an FE-based simulation model for reproducing the effects of micro geometry scattering and a stochastic pitch error course is validated with experimental results. The validated simulation model is used to build a deeper understanding of the influence of a chaotic scattering of the micro geometry and the pitch on the quasistatic excitation behavior.

Table 1 Overview of the gear set variants

Feature		Pinion / Gear	Pinion / Gear	Pinion / Gear	Pinion / Gear
Pitch	f_{pmax} [µm] (IT)	2.7 (IT3) / 1.0 (IT1)	3.3 (IT3) / 2.1 (IT2)	7.7 (IT6) / 3.1 (IT3)	10.3 (IT7) / 2.3 (IT2)
	F_p [µm] (IT)	11.8 (IT4) / 4.1 (IT1)	16.0 (IT5) / 13.1 (IT4)	17.6 (IT5) / 12.0 (IT4)	18.4 (IT5) / 10.8 (IT3)
	Course	Sinusoidal	Stochastic	Stochastic	Stochastic
Micro geometry	$f_{H\beta.max}$ [µm] (IT)	–3.6 (IT4) / 2.8 (IT3)	–3.4 (IT4) / 3.7 (IT4)	5.3 (IT5) / 4.9 (IT4)	–12.5 (IT7) / –2.5 (IT3)
	$f_{H\alpha.max}$ [µm] (IT)	4.4 (IT4) / –2.9 (IT3)	4.2 (IT4) / –2.1 (IT3)	–2.9 (IT4) / –2.6 (IT3)	–4.7 (IT5) / 6.5 (IT5)
	Course	Sinusoidal	Sinusoidal	Sinusoidal	Stochastic

Overview of the Variants

A total of four gear set variants were manufactured to investigate the influence of chaotic scattering of the micro geometry and pitch on the excitation behavior. The maximum deviation with respect to micro geometry and pitch as well as the characteristics of the course are shown in Table 1. Only the right tooth flanks of the gearing are considered, since these flank sides are strained in the transmission.

A gear set variant with no targeted micro geometry scattering serves as reference REF. The course of the values of the profile line angle deviation $f_{H\alpha}$

and the flank line angle deviation $f_{H\beta}$ are sinusoidal. Likewise, the pitch error course is also sinusoidal. The µVarOpt variant was designed with a focus on optimizing the noise characteristics for the design torque $M_2 = 400$ Nm. The µVarOpt design methodology was used to design a targeted micro geometry scattering within the IT7 quality limit according to DIN ISO 1328-1 for the profile line angle deviation $f_{H\alpha}$ and the flank line angle deviation $f_{H\beta}$ (Ref.12). Likewise, the profile crowning C_α was scattered by a maximum of ±4 µm and the width crowning C_β by ±6 µm. The grinding of the µVarOpt variant also leads to an irregular course of the pitch due to manufacturing and design reasons in addition to the scattering of the micro geometry. The irregularity in the course of the individual pitch deviations f_p results from the wear of the grinding wheel, dressing errors, errors when re-centering the grinding wheel, the quasi-stochastic sequence of the gap selection and the different profile and flank angle modifications of the design. In addition, two gearset variants were manufactured with a stochastic pitch error course. In the fp_Random variant, the wear of the grinding wheel and a quasi-stochastic choice of the order in grinding the gaps were used to achieve a stochastic course of the single pitch error f_p. The objective of the fp_µVarOpt variant was to achieve as similar a course and characteristic of the single pitch deviations f_p as possible as with the µVarOpt variant. For this purpose, the same grinding program was used for profile grinding of the fp_µVarOpt variant as for the µVarOpt variant, with the adjustment that the targeted scatter of the micro geometry was set to zero.

Characterization of the Micro Geometry and Pitch

The profile and flank lines of all tooth gaps as well as the individual pitch deviations f_p are measured for each gear set variant on a precision measuring center P16 from Klingelnberg. Figure 5 shows the measured tooth flank deviations of the pinion for each gear set variant. As a reference, the limits of tolerance class IT5 according to DIN ISO 1328-1 are drawn in (Ref. 12).

The systematic and sinusoidal scattering of the micro geometry in the form of a small wobble and eccentricity can be seen for the REF, fp_Random and fp_µVarOpt variants. The micro geometry of the µVarOpt variant shows the intended chaotic course. The single pitch deviations f_p of the variants µVarOpt and fp_µVarOpt are comparable in their course and characteristics, so that with these two gear set variants the influence of a chaotic pitch error can be investigated with and without micro geometry scattering. The maximum single pitch deviation of µVarOpt is $f_{pmax} = 10.33$ µm (IT7) and for the variant fp_µVarOpt $f_{pmax} = 7.7$ µm (IT6). The REF variant shows a sinusoidal course of the pitch error, with the maximum single pitch deviation at $f_{pmax} = 2.7$ µm (IT3). The course is caused by the wear of the grinding wheel. The pitch error of the fp_Random variant is in the same order of magnitude $f_{pmax} = 3.3$ µm (IT3). However, since the teeth in the fp_Random variant were ground in a random sequence, the course of the pitch has a stochastic component and is not purely periodic. Analogous to the manufacturing deviations with regard to the micro geometry and pitch on the pinion, qualitatively similar deviations can be observed on the gear.

Validation of the Simulation Model

The quasi-static excitation behavior of the gear set variants already presented was investigated in the following. For this purpose, the loaded transmission error (LTE) (ptp: peak-to-peak) of the gear set variants is investigated on the test rig with the WZL cylindrical gear measuring cell and, in addition, a simulation model is set up to represent the LTE with a scattering of the micro geometries and the pitch in cylindrical gears.

Figure 6 shows the experimental results for the loaded transmission error (LTE) of the gear set variants on the left side. Shown are in each case the course of the first and second gear mesh order 1.fz & 2.fz of the LTE over the load with respect to $M_2 = 500$ Nm. The LTE is measured at a constant drive speed of $n_1 = 60$ RPM. For this purpose, a tooth hunt is performed and each gear set variant is measured three times. The test results in

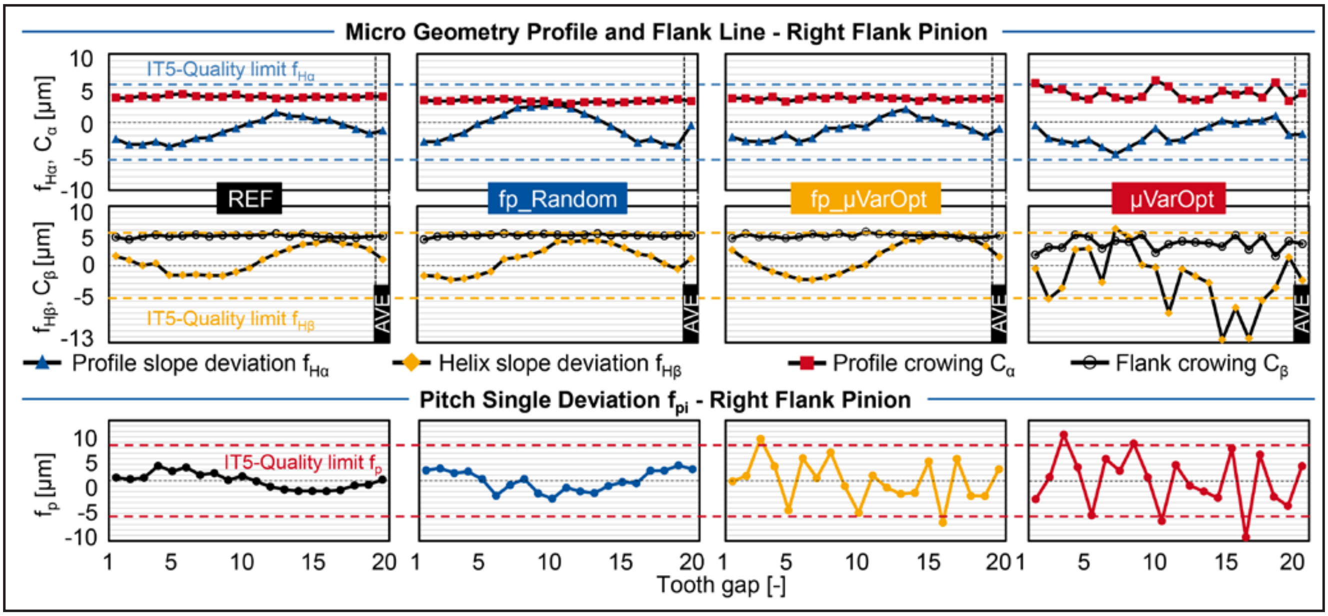


Figure 5 **Course of deviations pitch and micro geometry on the pinion for all gaps.**

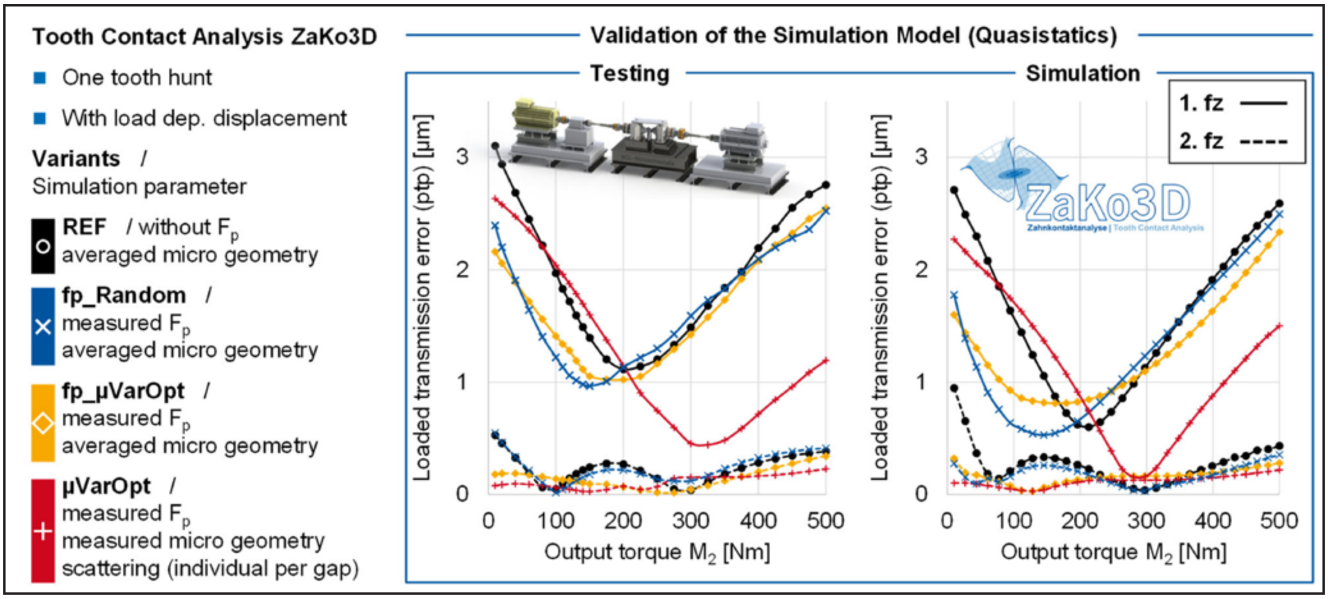


Figure 6 Validation of the simulation model for modeling the quasi-static excitation behavior.

Figure 6 show the mean value from the three measurements.

The gear set variant REF with a low wobble and a sinusoidal pitch error curve shows a high excitation of the first gear mesh order 1.fz of $\Delta\varphi_{LTE,1.fz} = 3.1\,\mu m$ in the LTE at a low torque of $M_2 = 10\,Nm$. With increasing torque, the amplitude of the first gear mesh order 1.fz of the LTE decreases to a minimum of $\Delta\varphi_{LTE,1.fz} = 1.1\,\mu m$ at $M_2 = 200\,Nm$. A further increase of the torque leads to an increase of the amplitude of the first gear mesh order 1.fz up to $\Delta\varphi_{LTE,1.fz} = 2.7\,\mu m$ at $M_2 = 500\,Nm$.

All other gear set variants with chaotic deviations over the circumference of pinion and gear basically show a similar course as REF. A high excitation of the amplitude of the first gear mesh order 1.fz over a prominent minimum of the excitation up to again increasing amplitudes.

However, the amplitudes as well as the prominent minimum are differently distinct. Thus, the variant fp_Random shows a low amplitude of the first gear mesh order 1.fz of the LTE $\Delta\varphi_{LTE,1.fz}$ in the torque range $M_2 = 10–200\,Nm$. In addition, the prominent minimum is shifted to a low torque of $M_2 = 150\,Nm$. From a torque of at $M_2 = 200\,Nm$, REF thus also fp_Random show similar amplitudes. For the second gear mesh order 2.fz of the LTE $\Delta\varphi_{LTE,2.fz}$, the two variants REF and fp_Random are comparable in their excitation. It can be observed that a comparatively low stochastic pitch error course of the variant fp_Random shows advantages of a lower excitation especially in the load range up to the minimum of the amplitude of the first gear mesh order 1.fz.

Compared to the variant fp_µVarOpt with a more pronounced stochastic course of the single pitch deviation f_p, this stronger irregularity in the pitch error also leads to a reduction of the amplitude of the LTE of the second gear mesh order $\Delta\varphi_{LTE,2.fz}$. Moreover, the prominent minimum is characterized over a wider torque range of $M_2 = 150–225\,Nm$. At higher torques from $M_2 = 225\,Nm$, the variant fp_µVarOpt shows slightly lower amplitudes of the first gear mesh order 1.fz of the LTE $\Delta\varphi_{LTE,1.fz}$. The increase of the stochasticity in its expression and amplitude in the course of the single pitch deviation f_p is combined with a further decrease of the amplitude of the first two gear mesh orders of the LTE. If the fourth gear set variant µVarOpt, with a very comparable stochastic course of the single pitch deviations f_p as fp_µVarOpt and an additional targeted micro geometry scattering within IT7, is included in the comparison, differences of the two stochastic deviations become clear. In the µVarOpt variant, the excitation minimum is shifted to $M_2 = 300–325\,Nm$. This shift can be attributed to the scatter of the twist S_α and the scatter of the profile crowning C_α. The superposition of a chaotic scattering of the micro geometry and the pitch error leads to significantly lower amplitudes of the first gear mesh order 1.fz of the LTE $\Delta\varphi_{LTE,1.fz}$ for torques from $M_2 = 225\,Nm$. The amplitude of the second gear mesh order 2.fz of the LTE $\Delta\varphi_{LTE,2.fz}$ continues to be lower than with the REF variant over a wide torque range.

For the simulation of the quasi-static excitation behavior with chaotic scattering of micro geometry and pitch, a model was built in the FE-based tooth contact analysis ZaKo3D. For this purpose, the macro geometries of pinion and gear were tool-based generated using the geometry generation *GearGen*. To calculate the LTE of the REF variant, the measured and averaged micro geometry after manufacturing was taken into account. The course of the pitch error was not considered in the model for REF. For the two variants with stochastic course of the single pitch deviation f_p fp_Random and fp_µVarOpt, the pitch error was considered in the model in the form of the measured sum pitch error F_p. The measured and averaged micro geometry was specified as for the REF variant. For the µVarOpt variant, the individual and measured micro geometry from tooth to tooth was also specified in the model in addition to the measured sum pitch error F_p. In addition, a load-induced displacement of the gear set was assumed. The characteristic of a change in the center distance a as well as the inclination and skew under load was determined with the help of the measured course of the amplitude of the first gear mesh order 1.fz of the LTE $\Delta\varphi_{LTE,1.fz}$ of REF. One pitch per torque was calculated for the REF variant, and one tooth hunt of 660 pitches per torque is necessary to calculate the effects of stochastic deviations over the circumference of the pinion and gear on the excitation behavior.

The results of the simulated quasi-static excitation behavior of the four variants are shown in the right part of Figure 6. The simulation model can rebuilt the characteristic features of the four gear set variants already described very validly in terms of quantity and quality under the assumption of the selected load-induced displacement. The increasing complexity of the gear geometry can be countered with an increased individual consideration of micro geometry and pitch. Basically, the amplitudes of the first gear mesh order 1.fz of the LTE $\Delta\varphi_{LTE,1.fz}$ are slightly lower in the simulation model compared to the experimental results. The differences between the individual variants can be modelled realistically by the simulation model. The tooth contact analysis is thus well suited for further simulative investigations as well as the design of targeted micro geometry scattering.

Influence of a Chaotic Pitch Error Course

The validated simulation model will be used in the following to build up a deeper understanding of the influence of a chaotic pitch error course on the quasi-static excitation behavior. After presenting the experimental results, the question is raised at which amplitude or IT quality class of the pitch error an optimum for improving the noise characteristics exists. For this purpose, ten variants each were generated within an IT quality class of IT1–IT8 with a stochastic pitch error. Care was taken to ensure that both the individual pitch deviations f_p and the resulting summed pitch deviation F_p were within the respective IT quality class. The REF (IT0) variant is used as a reference for which no pitch error was specified in the simulation model.

During the simulation, one tooth hunt with 660 pitches was performed and the output torque of $M_2 = 10–500$ Nm was examined. No load-related displacement was specified. The results of the simulation study on the influence of different IT quality classes of a stochastic pitch error on the LTE are shown in Figure 7. In each of the four diagrams, the curves of the averaged LTE ($M_2 = 10–500$ Nm) from the first to the fourth gear mesh order 1.fz–4.fz are shown. In addition, the scatter bands of the averaged excitation are shown with the course of the maximum and minimum amplitudes. It can be seen that in the considered torque range a stochastic scattering of the pitch in the quality class IT6 causes the strongest decrease of the amplitude of the first gear mesh order 1.fz of the averaged LTE $\Delta\varphi_{LTE,1.fz}$. The amplitude of the first gear mesh order 1.fz can be reduced by 20.2% on average. For the amplitude of the second gear mesh order 2.fz, a minimum can be detected at the maximum deviation within the IT7 class. The amplitudes of the third and fourth gear mesh order 3.fz–4.fz decrease continuously with the increased stochasticity of the pitch. Likewise, it can be observed that with an increase in the stochasticity of the pitch from IT6, the amplitude of the first gear mesh order 1.fz increases again and can even exceed the excitations without pitch error at IT8. In addition, the risk of premature teeth meshing increases with increasing pitch error. IT7 and IT8 are to be judged as critical. Therefore, for the considered torque range $M_2 = 10–500$ Nm, an optimum of stochasticity can be found in the pitch error curve at IT6. This corresponds to the pitch error curve of the variant fp_µVarOpt investigated in the test field.

Superposition of Chaotic Scattering of Micro Geometry and Pitch

Following, the influence of a micro geometry scattering with a layered pitch error is investigated. Four gear set variants were generated for this purpose. The REF variant has no scattering of the micro geometry and the pitch. For the variant fp_µVar, a stochastic pitch error curve within the IT5 limit for the single pitch deviation f_p and the sum pitch deviation F_p was applied in the simulation model. The micro geometry corresponds constantly to the REF variant for all teeth. For the variant MGS_µVar, a stochastic scattering of the profile line angle deviations $f_{H\alpha}$ and the flank line angle deviation $f_{H\beta}$ within the IT5 limit was specified as micro geometry scattering (MGS). No pitch error was considered for the variant MGS_µVar. The variant fp_MGS_µVar has the identical scatter of the pitch as fp_µVar and the identical dispersion of the micro geometry as MGS_µVar. The stochastic deviations for the variants fp_µVar, MGS_µVar and fp_MGS_µVar

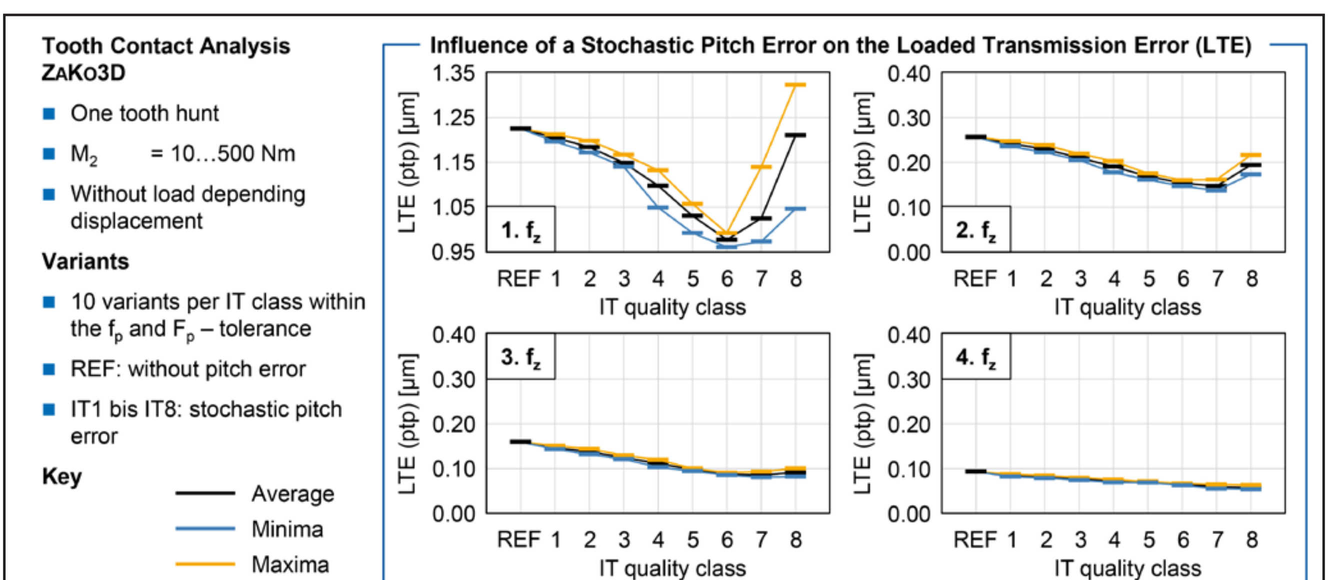


Figure 7 influence of a stochastic pitch error curve on the loaded transmission error (LTE).

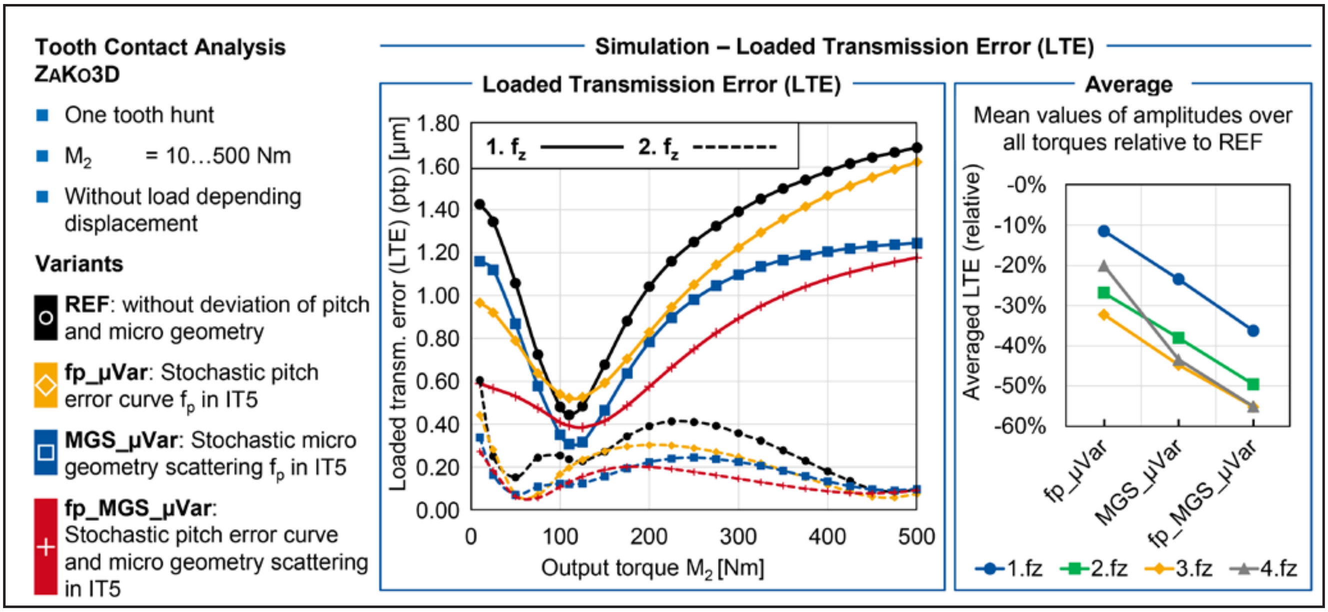


Figure 8 **Superposition of the influences of a stochastic pitch error curve and a micro geometry scattering on the loaded transmission error.**

were generated on the pinion as well as on the gear.

In the simulation of the loaded transmission error (LTE), one tooth hunt was calculated for the variants with stochastic deviations over the circumference. For the reference variant, only one pitch was calculated. No load-induced displacements were assumed.

Figure 8 shows the amplitude curves of the first two gear mesh orders 1.fz and 2.fz of the LTE over the validated load range up to $M_2 = 500$ Nm. It can be seen that the effects of amplitude reduction for the first gear mesh order 1.fz is larger for a stochastic pitch error up to the torque of $M_2 = 60$ Nm compared to a stochastic micro geometry scattering. The stochastic micro geometry scattering in the form of the variant MGS_µVar shows a larger decrease of the first gear mesh order 1.fz at higher torques from $M_2 > 60$ Nm. The superposition of stochastic pitch error course and stochastic micro geometry scattering (fp_MGS_µVar) shows the best results for the reduction of the first and second gear mesh order 1.fz–2.fz.

The effects on the higher harmonics up to the fourth gear mesh order are shown in the right part of Fig. 8 when calculating the mean values of the amplitudes over all torques relative to the results of REF. It can be seen well that both the first and the higher harmonics up to the fourth gear mesh order can be reduced more and more as the proportion of stochastic deviations increases over the circumference. Thereby, a stochastic pitch error course has a smaller influence on the reduction of the amplitudes of the first four gear mesh orders 1.fz–4.fz compared to the stochastic micro geometry scattering. The averaged relative comparison to the REF variant also shows that a superposition of stochastic scattering of the micro geometry and the pitch has the greatest effect on the reduction of the excitation amplitudes of the gear mesh orders. In contrast to the results from the test rig or the validated simulation results, the variant MGS_µVar as well as fp_MGS_µVar do not show any shift of the prominent excitation minimum of the first gear mesh order 1.fz. In the variants, only the profile line angle deviations $f_{H\alpha}$ and the flank line angle deviations $f_{H\beta}$ were scattered, so that a reduction of the amplitudes of the first gear mesh orders 1.fz of the LTE is possible in a very large torque range. If one does without an additional scattering of the crowning and the twist, no shift of the excitation minimum is to be expected.

Investigation of the Dynamic Excitation Behavior

In this chapter, the dynamic excitation behavior of the gear set variants is investigated experimentally. For this purpose, the WZL dynamics measurement cell was set up and operated on the WZL universal transmission test rig.

To investigate the dynamic excitation behavior, the signals of the differential acceleration were evaluated. Figure 9 shows the measurement results of the differential acceleration for the first four gear mesh orders 1.fz–4.fz above the output torque M_2. The gear set variants examined at 12 measuring points in a range of $M_2 = 20–470$ Nm. For each measuring point, the signals were measured over a speed ramp-up of $n_1 = 1000–4600$ RPM and then the arithmetic mean (single number value) was calculated. The ordinate of the diagrams is scaled in dB.

The course of the reference REF for the first gear mesh order 1.fz starts at its maximum value, then falls to a prominent minimum at $M_2 = 150$ Nm and then rises again with increasing torque. The curve matches the simulated and tested curves from quasi-statics in Figure 6. Only the prominent minimum is at $M_2 = 200$ Nm in the quasi-static curves. This is caused by the different displacement behavior under load of the measuring cells used. The measurement results of fp_Random follow the course of REF, but due to the stochastic pitch error course in the marginal areas of the investigated torque range, slight advantages arise with respect to the excitation of the first gear mesh order 1.fz. The µVarOpt variant shows, similarly to quasi-statics, a more significant shift of the minimum $M_2 = 250$ Nm. The results show stronger excitation in the torque range $M_2 = 80–180$ Nm. For lower torques $M_2 = 10–80$ Nm or higher torques $M_2 = 180–500$ Nm, there is less excitation. At the higher harmonics, the reference REF always has the highest excitation in the examined load range up to $M_2 = 470$ Nm.

The frequency spectra for the measuring point with

$M_2 = 400$ Nm are shown in Figure 10. The frequency spectra are scaled in dB, the drive speed n_1 is plotted on the abscissa and the frequency on the ordinate. The gear mesh orders can be identified as rising straight lines in the spectrum. It can be clearly seen that in the comparison of the gear sets from left to right (increase in the degree of chaotic scattering of the micro geometry and pitch), the level of the gear mesh orders decreases and more orders are excited in between.

In the case of the REF variant, the individual amplitudes of the gear mesh orders in the frequency spectrum can be clearly seen in Figure 10, as well as the sidebands caused by the sinusoidal deviations of the gear geometry.

The variant fp_Random also clearly shows the amplitudes of the gear mesh orders in the frequency spectrum. The sidebands occur in a narrower band. Due to the slight stochastic course of the pitch error f_p, the excitation of the first gear mesh order is lowered by 8.3% at a torque of $M_2 = 400$ Nm (see order spectrum in the lower part of Fig. 10). A greater effect is seen in the reduction of the higher harmonic gear mesh orders, where the amplitudes could be reduced by 45.9% and more. The stronger chaotic scattering of the pitch error fp with variant fp_µVarOpt intensified the observed effects. Thus, the amplitude of the first gear mesh order was reduced by 33.1% and the higher harmonics by 64% and more. The best excitation behavior results shows the µVarOpt variant, only the first gear mesh order becomes prominent and the amplitude could be reduced by 59.4% compared to REF. The higher harmonics are lost in the background noise, since the amplitudes of the higher harmonics are lowered by 81.8% and more.

Investigation of the Noise Behavior

Analogous to the investigation of the dynamic excitation behavior, the noise behavior was measured in the form of airborne noise from the drive train and evaluated as a frequency and order spectrum. A ½" free-field microphone was set up at a distance of 1 m from the measuring cell. The test rig is located in a Q2 certified acoustic measurement room according to DIN EN ISO 3744 (Ref. 13). By using an acoustic measuring room, noises

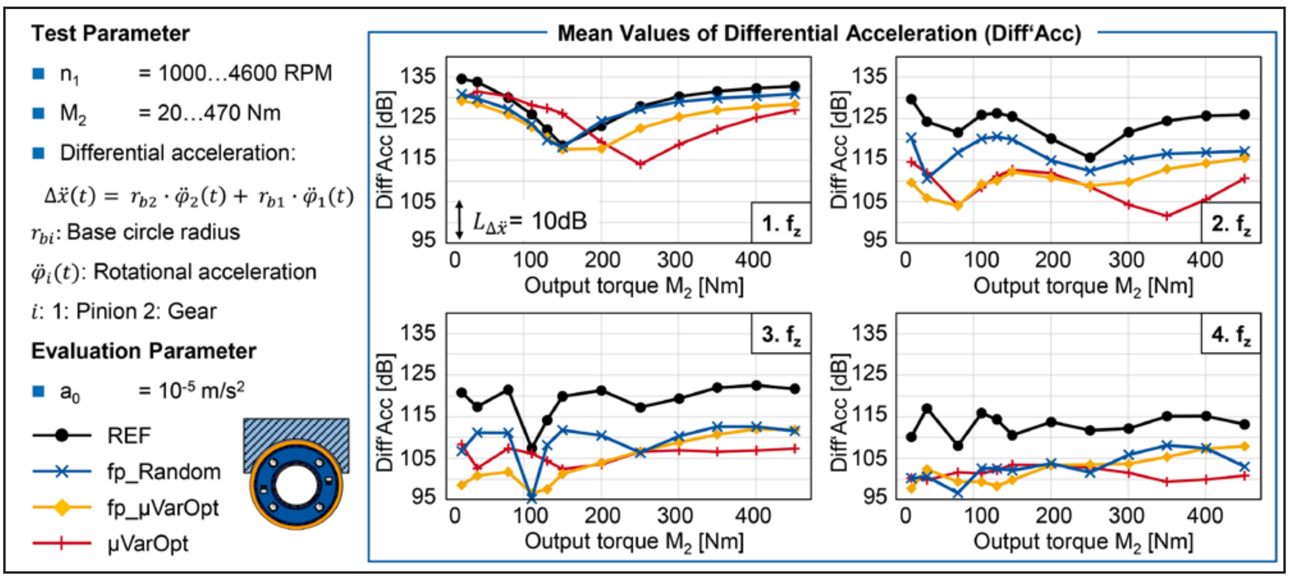


Figure 9 Dynamic excitation behavior under load.

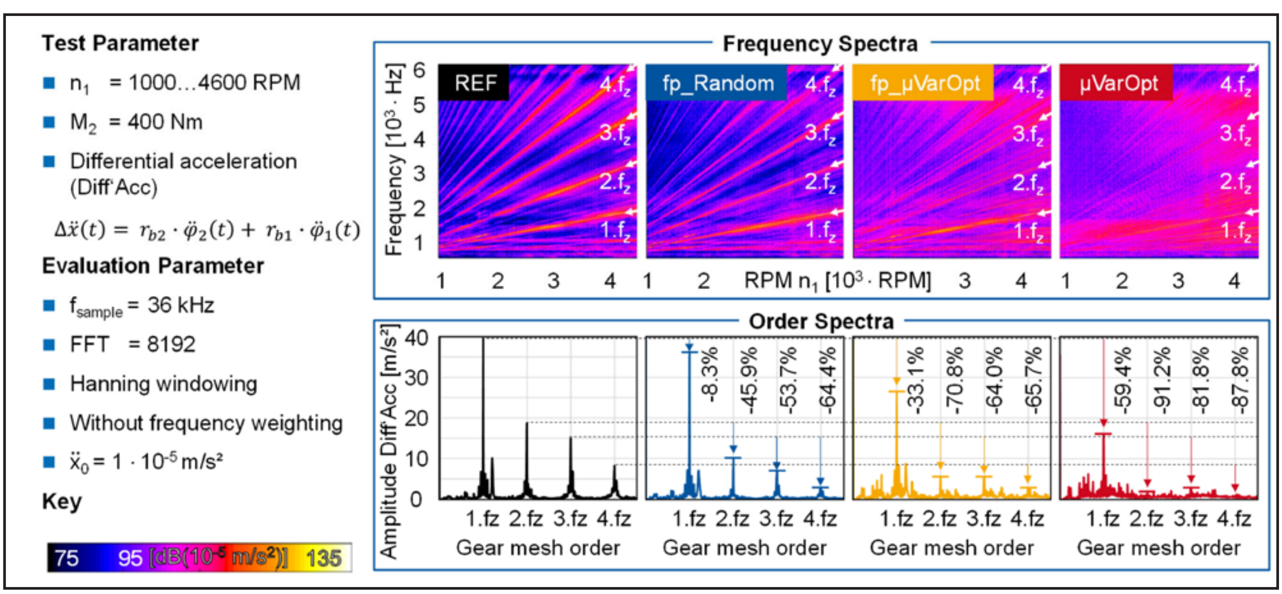


Figure 10 Dynamic excitation behavior at $M_2 = 400$ Nm.

from the environment around the test object (drive and driven machines, pneumatic control of the clamping fields, external oil unit, etc.) are not measured. The upper part of Figure 11 shows the measured airborne noise at $M_2 = 400$ Nm as a frequency spectrum. Similar to the evaluation of the differential acceleration, the airborne noise shows that with an increasing chaotic deviation of the gear geometry from tooth to tooth, the dominant peaks in the form of the amplitude of the gear mesh orders are lowered. At the same time, the background noise increases. For a better evaluation of the change in airborne noise emission, the lower part of Fig. 11 shows the respective order spectra and the percentage change relative to the REF in the amplitudes of the first four gear mesh orders.

The observed characteristics during dynamic excitation are also reflected in the noise behavior. With increasing chaotic gear geometry in the form of the pitch error and the micro geometry, less and less strongly dominant peaks appear in the frequency or order spectrum.

Psychoacoustics

In addition to the physical excitation, a psychoacoustic evaluation was carried out on the basis of the airborne noise measurement with the metrics tonality according to the Sottek hearing model (Ref. 14) and loudness according to DIN 45631/A1 (Ref. 15).

Psychoacoustic Metrics for the Evaluation of Human Noise Perception

The loudness describes the frequency-dependent sensitivity of human noise perception and has the unit sone, see Figure 12. DIN 45631/A1 describes a standardized procedure for determining loudness based on a loudness comparison between sinusoidal tones and noises (Ref. 15). Thus as shown in the audible frequency range according to Zwicker is divided into 24 frequency groups (0 bark to 24 bark) and the respective sound level is weighted according to the human hearing sensitivity. The method is suitable for comparing the loudness of noises with different spectral resolution (Ref. 16).

An essential feature for the characterization of gear noise is the tonality. Noise is perceived as annoying if they are composed of individual, strongly pronounced tones or narrow band frequencies. The Sottek hearing model is used to determine tonality. Previous algorithms for calculating tonality did not take into account or did not take sufficient account of short-term changes in tonality due to the low time resolution. In addition, tonalities below the hearing threshold are considered, although they are irrelevant for the human hearing. The new method according to Sottek includes the human hearing limit and the dependence of noise perception on psychoacoustic loudness. The method determines the loudness of tonal and non-tonal noise components using a permanently performed autocorrelation function. By means of a high temporal resolution, short-term and strongly fluctuating tonalities can be examined. The algorithm also allows the strength and frequency of the tonality

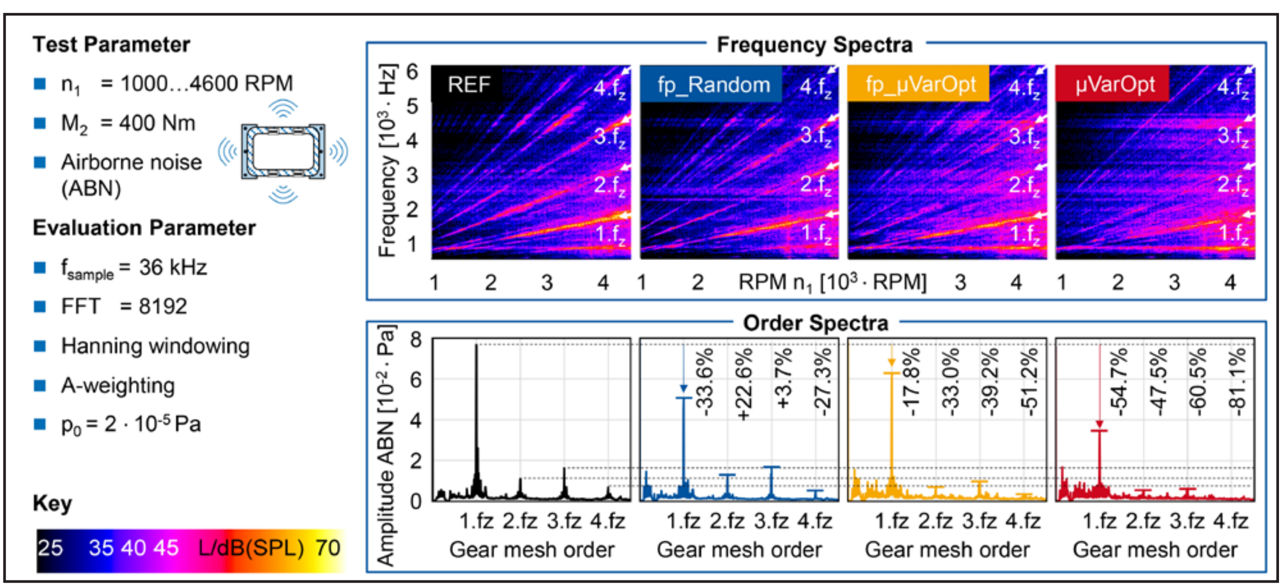


Figure 11 Physical noise behavior at $M_2 = 400$ Nm.

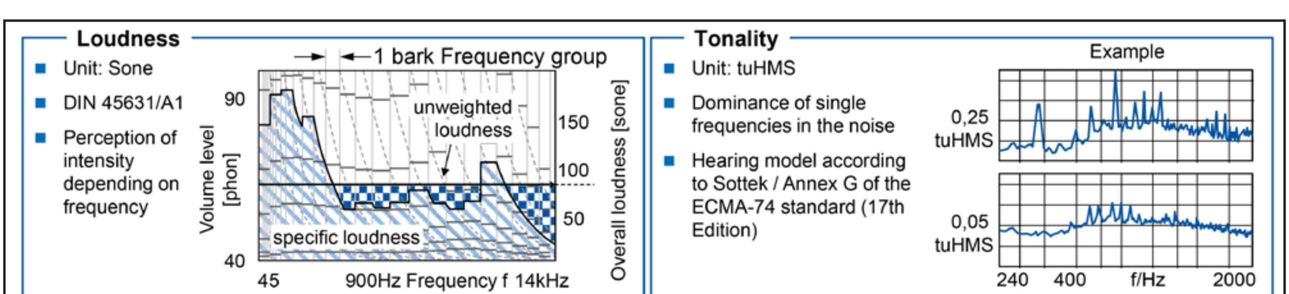


Figure 12 Psychoacoustic metrics: loudness and tonality.

to be determined relative to the time and rotational speed. The tonal value according to the Sottek hearing model is described in the unit tuHMS (Ref. 14).

For this purpose, Annex G of the international standard ECMA-74 (17th Edition) describes a perception-based method developed by HEAD acoustics for the automatic detection and classification of tonal components and their characteristics in noise emissions (Ref. 16). The criterion for prominence of tonalities for the psychoacoustic tonality calculation method according to Sottek is independent of frequency 0.4 tuHMS (Ref. 14). Tonality is hardly perceptible below the value of 0.4 tuHMS (Ref. 16).

Both psychoacoustic metrics loudness and tonality have a linear scale of intensity (Refs. 15, 17). In addition, the metrics were developed and validated in extensive listening tests (Refs. 14–16).

Psychoacoustic Evaluation of the Noise Behavior

For the psychoacoustic evaluation of the variants, the tonality and loudness of the airborne noise signal is evaluated as a single value in each case, see Figure 13, upper part. This allows the load-dependent behavior to be analyzed. In addition, the arithmetic mean was calculated for all load levels.

The lower part of Figure 13 shows the behavior of tonality and loudness as a function of speed for the design torque $M_2 = 400$ Nm. For tonality, the arithmetic mean was always evaluated. For loudness, the 5-% percentile N_5 of the loudness spectrum was calculated. The 5-% percentile as a single number value gives a better impression of the subjective perception of loudness as in the case of transient noises, because human perception focuses on the loudest noise components (Refs. 19, 20).

The evaluation of the tonality shows that already with a stochastic pitch error course the tonality can be reduced by 5.2% with the variant fp_Random and by 7.8% with variant fp_µVarOpt on average. A combination of stochastic pitch error course and a specific design of a micro geometry scattering, as with variant µVarOpt, has significantly reduced the tonality by 36.1% on average. In the design torque $M_2 = 400$ Nm, the tonality could be more than halved by 55.8%. In the course of the tonality over the speed it can be seen that the variant µVarOpt is partly below the limit value of 0.4 tuHMS. Analogous to the evaluation of the quasi-static and dynamic gear excitation, a shift of the significant excitation minimum for µVarOpt is also visible for the psychoacoustic metrics tonality and loudness.

In the case of loudness, similar courses of the 5% percentile N_5 are shown compared to tonality. However, the variants fp_µVarOpt and µVarOpt are partly louder. The variant fp_Random is quieter than the reference at every load level and is on average 8.3% quieter. The variant fp_µVarOpt is on average 2.3% louder and the variant µVarOpt is 1.5% quieter. In the design moment of µVarOpt, the loudness could be reduced by 11.6%.

Summary and Outlook

In this report, a simulation model was generated to model the quasi-static excitation behavior of cylindrical gears with stochastic deviations over the circumference of the pinion and gear. The simulation model is capable of realistically modeling the loaded transmission error (LTE) of cylindrical gears with a stochastic pitch error curve as well as a stochastic scattering of the micro geometry. The simulation results were validated on the basis of tests on the test rig. With this validated simulation model, more in-depth investigations could be carried out to build up an understanding of the effect of stochastically scattered geometric deviations on cylindrical gears on the excitation behavior. It was shown, for example, that for the gearing and a torque range up to $M_2 = 500$ Nm, a stochastic scattering of the pitch error with a maximum amplitude of the IT6 quality class is significantly improved noise characteristics. It was shown that a stochastic pitch error course in low load range up to $M_2 = 60$ Nm generated a stronger reduction of the amplitude of the first gear mesh order 1.fz of the loaded transmission error than that of a micro geometry scattering in the same IT quality class. The positive effect of a stochastic pitch error decreases with increasing load. From a load of $M_2 = 60$ Nm, the variant with a micro geometry scattering shows greater effects for increasing the gear mesh order 1.fz of the loaded transmission error $\Delta\varphi_{LTE,1.fz}$. The combination of stochastic pitch error curve and a micro geometry scattering shows the best results for improving the noise characteristics. This phenomenon was also observed in test rig investigations. The experimental results

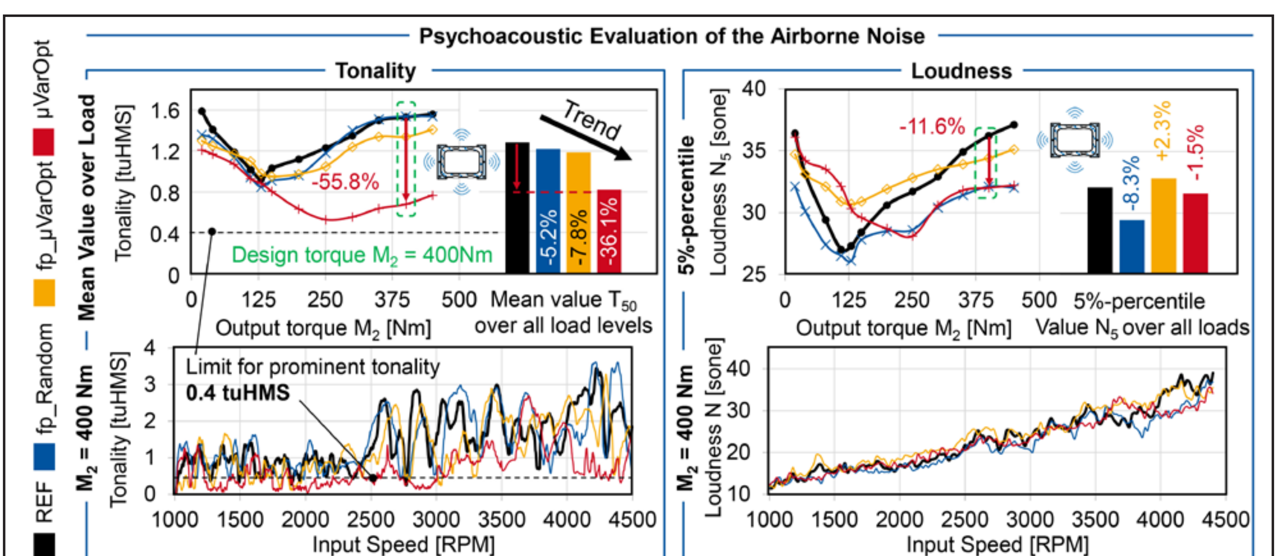


Figure 13 **Psychoacoustic evaluation of the airborne noise.**

of the noise behavior show that a stochastic pitch error curve can reduce the tonality of the airborne noise by 7.8% on average and the combination of chaotic scattering of the pitch and the micro geometry by up to 36.1% on average. On mean, the loudness increased by 2.3% for the variant with only stochastic pitch error and decreased by 1.5% for the variant with stochastic pitch and microgeometry scattering. "Controlled chaos" can significantly improve the noise characteristics of gears. In general, both the simulation results and the experimental results show that an increase in stochasticity in its expression and amplitude for deviation at the pinion and gear goes is related to with noise-optimized excitation. However, the simulation results also show that an oversized stochastic pitch error curve can also cause a decrease in the amplitude of the first gear mesh order 1.fz of the loaded transmission error $\Delta\varphi_{LTE,1.fz}$. In conclusion, when optimizing the noise characteristics of cylindrical gears by a stochastic scattering of the target geometry, it is important to control the generated chaos. The limits of reliability must be designed precisely so that it leads to an improvement and not to a deterioration of the noise characteristics.

In future work, the possible advantages and disadvantages of micro geometry scattering with regard to tooth flank load capacity must be analyzed in experimental studies. For this purpose, gears with and without targeted micro geometry scattering will be examined in the back-to-back test rig for their pitting load capacity. In addition, future continuous manufacturing processes will be modified so that targeted micro geometry scattering can be produced.

Acknowledgement

DFG	The authors gratefully acknowledge financial support by the German Research Foundation (DFG) [BR2905/82-1] for the achievement of the project results.
Seit 1956 Since 1956 WZL Getriebekreis Gear Research Circle	The authors gratefully acknowledge the WZL Gear Research Circle for providing the financial means for the development of the FE-based tooth contact analyze ZaKo3D and the manufacturing simulation GearGen.
HEAD acoustics	The authors gratefully acknowledge the support of HEAD acoustics for providing the software platform ArtemiS SUITE for sound and vibration analysis.

References

1. Reitz, A. Problemorientierte NVH-Abstimmung des Antriebsstrangs bei leichten Nutzfahrzeugen. In: Brill, U.; Laschet, A. (Hrsg.): Systemanalyse in der Kfz-Antriebstechnik. Renningen: Expert, 2005, p. 208–224.
2. Rau, G. Akustik- und Schwingungsoptimierung an Getriebeträgern. In: ATZ - Automobiltechnische Zeitschrift, 107. Jg., 2005, Nr. 7, p. 594–598.
3. Steinberg, K. *With All Senses. The First Book on How To Eliminate Interfering Sound in The Car*. 1st edition. Eching: wjr-Verl., 2007.
4. Carl, C. Gehörbezogene Analyse und Synthese der vibroakustischen Geräuschanregung von Verzahnungen, Diss. RWTH Aachen University, 2014.
5. Klocke, F. and C. Brecher. Zahnrad- und Getriebetechnik: Auslegung – Herstellung – Untersuchung – Simulation. Carl Hanser Verlag, Munich, Germany, 2017.
6. Kasten, M.; Brecher, C.; Löpenhaus, C.: Einfluss einer gezielt aufgeprägten Mikrogeometriestreuung auf das Anregungsverhalten von Kegelradverzahnungen, In: Forschung im Ingenieurwesen, 21. Jg., 2018, Nr. 2, S. 239.
7. Geradts, P.; Brecher, C.; Löpenhaus, C.; Kasten, M.: Reduction of the tonality of gear noise by application of topography scattering. In: *Applied Acoustics*, 148. Jg., 2019, S. 344–359.
8. Kasten, M.; Brecher, C.; Löpenhaus, C.; Lemmer, A.; Bläse, W.; Schalaster, R.: "Reduction of the Tonality of Gear Noise by Application of Topography Scattering for Ground Bevel Gears," *AGMA Fall Technical Meeting 2019, Detroit USA, Technical Paper 19FTM09.*
9. Kasten, M.; Brecher, C.; Brimmers, J.; Bläse, W.; Lemmer, A.; Schalaster, R.: Reduzierung der Tonalität des Getriebegeräusches einer leichten NFZ-Starrachse In: *WZL-Seminar 'Innovationen rund ums Kegelrad," 2020 S.43-57.*
10. Hellmann, M. Fertigungsabweichungen in der Auslegung von Zahnflankenmodifikationen für Stirnradverzahnungen, Diss. RWTH Aachen University, 2015.
11. Cylindrical gears - ISO system of flank tolerance classification - Part 1: Definitions and allowable values of deviations relevant to flanks of gear teeth (DIN ISO 1328-1:2018-03).
12. Acoustics - Determination of sound power levels and sound energy levels of noise sources using sound pressure - Engineering methods for an essentially free field over a reflecting plane (DIN ISO 3744:2011-02).
13. Sottek, R. Modelle zur Signalverarbeitung im menschlichen Gehör, Diss. RWTH Aachen University, 1993.
14. DIN 45631/A1. Procedure for calculating loudness level and loudness, German national standard, Berlin, Germany, Beuth Verlag, 2010.
15. Zwicker, E. Psychoakustik, Berlin: Springer, 1982.
16. Standard ECMA-74. "Measurement of Airborne Noise emitted by Information Technology and Telecommunications Equipment," 17th Edition 2019.
17. HEAD acoustics. Lautheits- und Schärfeberechnung in der *ArtemiS SUITE*, Application Note HEAD acoustics, 2018.
18. HEAD acoustics. Einzahlwert-Berechnung in der *ArtemiS SUITE.*, Application Note HEAD acoustics, 2018.

Marcel Kasten is a research assistant in the gear department at the Laboratory of Machine Tools and Production Engineering (WZL) of RWTH Aachen University since January 2017. His research topic is the design of gears with a focus on the psychoacoustic optimization of gear noise. In addition, he is active in the field of testing the load capacity, NVH behavior and efficiency of gear units. He completed his Bachelor thesis, during an internship in the R&D department of BMW Group. Kasten graduated from RWTH University in Aachen with a master's degree in mechanical engineering (automotive engineering).

Dr.-Ing. Jens Brimmers is the head of the gear department at the Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University since June 2019. He gratuated from RWTH Aachen University with master's degrees in mechanical engineering and business administration. His Phd thesis focussed on beveloid gears and topological tooth flank modifications.

Prof. Dr.-Ing. Christian Brecher has since January 2004 been Ordinary Professor for Machine Tools at the Laboratory for Machine Tools and Production Engineering (WZL) of the RWTH Aachen, as well as Director of the Department for Production Machines at the Fraunhofer Institute for Production Technology IPT. Upon finishing his academic studies in mechanical engineering, Brecher started his professional career first as a research assistant and later as team leader in the department for machine investigation and evaluation at the WZL. From 1999 to April 2001, he was responsible for the department of machine tools in his capacity as a Senior Engineer. After a short spell as a consultant in the aviation industry, Professor Brecher was appointed in August 2001 as the Director for Development at the DS Technologie Werkzeugmaschinenbau GmbH, Mönchengladbach, where he was responsible for construction and development until December 2003. Brecher has received numerous honors and awards, including the Springorum Commemorative Coin; the Borchers Medal of the RWTH Aachen; the Scholarship Award of the Association of German Tool Manufacturers (Verein Deutscher Werkzeugmaschinenfabriken VDW); and the Otto Kienzle Memorial Coin of the Scientific Society for Production Technology (Wissenschaftliche Gesellschaft für Produktionstechnik WGP).

Sandvik Coromant

OPENS NEW FACILITY IN MEBANE, NORTH CAROLINA

Sandvik Coromant has opened its new Sandvik Coromant Center Mebane in the heartland of manufacturing innovation and technology, joining a global network of facilities dedicated to showcasing metal-cutting expertise and helping to solve customer challenges.

As part of its continued investment in customer experience and knowledge sharing, metal-cutting leader Sandvik Coromant has opened a new Sandvik Coromant Center in Mebane, NC. In conjunction, the company has moved its U.S. headquarters to the same location.

With approximately 170 employees, the updated 167,000 square-foot facility houses an existing production unit, the new tech center and corporate offices, all in one common location.

Mebane lies at the heart of all major aerospace and automotive customers within a 200-mile radius and is easily accessible from three nearby airports, which allows Sandvik Coromant to be close to customers and partners. In addition, Mebane is located near the "Research Triangle" in the vicinity of North Carolina State University, Duke University and the University of North Carolina at Chapel Hill.

Sean Holt, president of Sales Area Americas for Sandvik Coromant, said, "Bringing together all company functions in one location will increase internal alignment and cross-functional collaboration. With all departments present in Mebane, we can provide customers and partners with a fully integrated, state-of-the-art immersion into the latest technologies and machining applications. In addition, we anticipate additional synergies between the proximity of our production unit and the activity from our new Sandvik Coromant Center."

Sandvik Coromant Center Mebane

The new Sandvik Coromant Center Mebane is a hub for training, R&D testing, customer projects, digital live machining (DLM) capabilities and, most of all, an opportunity for comprehensive customer and partner engagement with the overall Sandvik Coromant experience.

Sandvik Coromant Center Mebane allows customers and partners to fully interact with the latest technology and digital machining techniques, including Sandvik Coromant's CoroPlus, the tooling platform that brings connectivity to manufacturing. Customers can also work together with Sandvik Coromant experts, including manufacturing specialists, development and process engineers and CAM programmers to develop new ways of overcoming machining challenges.

Complete with a large auditorium, integrated showroom and modern machine tools, the new Sandvik Coromant Center Mebane also features an ITAR aerospace project area. In addition, the DLM system can be used for broadcasting training and machining demonstrations, allowing for collaboration with others around the globe in real time.

Sandvik Coromant was the first company in the cutting tool industry to establish application centers. Currently, there are 17 Sandvik Coromant Centers located across Europe, the Americas and Asia. While each facility has a physical location, they have been built with digital adaptability in mind for virtual training and events.

The interconnectivity of the centers facilitates many opportunities for problem-solving. Sandvik Coromant Centers work together, along with industry partners across the globe, to deliver webinars and digital events that tackle some of the most pertinent manufacturing concerns, such as reducing downtime, best machining practices and selecting the right tool for the job. The new Sandvik Coromant Center Mebane is part of this network.

Other Sandvik Coromant Centers in the U.S. include Schaumburg, IL, as well as two Project and Training Sites in Gardena, CA, and Brownsburg, IN. The vision for all Sandvik Coromant Centers, including the new Mebane location, is that they are permanent trade shows, where visitors will get the same immersive, state-of-the-art experience at all locations.

www.sandvik.coromant.com

Bonfiglioli

CELEBRATES 40 YEARS IN THE UK

This year marks the 40th anniversary of the establishment of the first subsidiary of Italian drive specialist Bonfiglioli Riduttori in the UK. A good reason to celebrate, as Bonfiglioli's development in the UK over the 40 years has been a true success story.

Today, Bonfiglioli UK's 2,400 m2 facility is located in Warrington, near Manchester, and is one of 21 commercial branches worldwide. As a wholly owned subsidiary of Bonfiglioli S.P.A., Bonfiglioli UK Limited is responsible for all sales activities of the Mobility & Wind (M&W) and Discrete Manufacturing & Process Industries (D&P) as well as Motion & Robotics (M&R) business units in the UK. Today Bonfiglioli UK is 23 employees strong and generated sales of £34m in the last financial year.

In the UK, all the business areas of the Bonfiglioli Group are represented. The D&P business area is active in many mechanical engineering sectors, among others, and also offers

the right solutions for almost all industrial applications. A very extensive product portfolio ranging from precision gearboxes to extremely powerful large planetary gearboxes is the basis for further growth. The M&W business unit supplies many well-known manufacturers of mobile construction machinery, cranes, and agricultural applications. In addition to hydraulic applications, Bonfiglioli accompanies the market in the electrification of these machines, doing pioneering work that demonstrates the company's innovative strength. In azimuth and pitch drives for wind turbines, Bonfiglioli has a global market share of around 35% and therefore rightly considers itself the market leader. The M&R business unit rounds off the drive portfolio with its high-performance frequency inverters and servo controllers. In the market, Bonfiglioli has built up a reputation as a reliable partner for complete drive systems with its broad product range.

The UK is an economically important market for Bonfiglioli. This is another reason why the 40th anniversary is a very special date for the company.

www.bonfiglioli.com

EMUGE-FRANKEN and GROB

ANNOUNCE STRATEGIC PARTNERSHIP

EMUGE-FRANKEN USA and GROB Systems, Inc. recently announced that the two industry leading companies have formed a strategic partnership. The synergistic alignment of EMUGE-FRANKEN, a high-performance cutting tools manufacturer, and GROB, a highly-innovative CNC machining centers manufacturer, provides powerful, advanced 5-Axis solutions, expertise and support.

Commencing the new partnership, a GROB G350T 5-Axis Universal Mill-Turn Machining Center was recently installed in the EMUGE-FRANKEN Technology Center in West Boylston, MA — a new manufacturing, research and development facility for North American manufacturers, designed to be a resource for applying cutting tool application strategies. To further reinforce the new partnership, a GROB application engineer is located and available onsite at EMUGE-FRANKEN to work together with EMUGE-FRANKEN engineers to develop turnkey 5-Axis solutions, perform customer application test cuts, conduct machining demonstrations and more.

Left to right: Bob Hellinger and Kevin Gadde.

"We are pleased to announce our strategic partnership with GROB in North America," said Bob Hellinger, president of EMUGE-FRANKEN USA. "It is a powerful and natural alliance, as both our family-owned companies already have a strong relationship in Germany where worldwide headquarters are located for GROB and EMUGE-FRANKEN. We look forward to building on each other's strengths and optimizing challenging 5-Axis mill-turn applications for industries such as aerospace, medical, energy and automotive."

"We invite manufacturers to bring application challenges to us for programming support, test cuts and efficient, comprehensive solutions. By working together, GROB's world leading 5-Axis technology and EMUGE-FRANKEN's advanced cutting tool technology produces highly efficient results such as Autonomous Automated Lights-Out Machining," said Kevin Gadde, GROB key account manager. "The new partnership also gives customers the opportunity to see demonstrations of powerful machining solutions for demanding aerospace, die and mold, production machining and more at technical seminars and events in West Boylston."

The EMUGE-FRANKEN Technology Center allows manufacturers to test new machining concepts and tools without tying up their own valuable machines and manufacturing hours. Actual machining processes are replicated and new tooling and application parameters are developed along with complete documentation. In addition, adjacent to the Technology Center, complementary training sessions and seminars are offered in an interactive classroom.

Aerospace manufacturers, as well as those with other demanding 5-Axis mill-turn applications, can collaborate with EMUGE-FRANKEN and GROB to optimize their parts and components on the high productivity, compact GROB 350T together with the full line of EMUGE-FRANKEN cutting tool solutions ranging from taps, thread mills and end mills, to carbide drills, tool holders, precision workholding/clamping devices, and other rotary cutting tools.

www.emuge.com

Mazak

MPOWER OFFERS COMPREHENSIVE MACHINE TOOL SERVICE AND SUPPORT

With the launch of its new MPower customer support program, Mazak takes complete customer care to the next level, giving manufacturers the tools they need to achieve their business goals and ensure continued success. With MPower, Mazak customers gain fast and accurate replacement parts ordering and service scheduling along with direct, real-time access to Mazak for a multitude of support benefits. Those include expert technical service through the company's Remote Assist Services and on-demand training with its Learning Management System in addition to local support from a network of Technology and Technical Centers and Mazak's cost-effective Spindle Rebuilding Services.

Through Mazak's eight Technology Centers and five Technical Centers located throughout North America, the MPower program also gives customers convenient and local access to additional support. The centers are a place for advanced applications support, education and training, new technology demonstrations and special manufacturing events.

According to Mazak President Dan Janka, MPower is Mazak's single-source, end-to-end customer support that it provides for the life of every machine. "The program helps shops save even more time and money in terms of service and support," he said, "and it demonstrates our true commitment to customers and shows that Mazak is with them every step of the way, fully invested in their success."

To streamline replacement parts ordering, MPower enables shops to digitally connect with Mazak and view an online image of the part along with its price, then easily place an order from Mazak's inventory of more than 500,000 unique part numbers in stock and receive next day delivery. In the near future, shops will be able to simply pull up their specific machine model and serial number, and Mazak will cross reference the part number to ensure the correct replacement. This information can be obtained currently with one phone call.

For machine service, shops can now log on to the new My Mazak service portal in real time to access account information, open a work order, check the availability of the next service technician or resolve the issue over the phone with tech support. When an in-person service call is scheduled, shops can check on the status of an existing work order or track when to expect the service technician to arrive.

Time is money for today's manufacturers, and Mazak's Remote Assist service shortens the mean time to repair and reduces the costs associated with in-person field service calls. Once a customer downloads a simple mobile or web app, a technician (located at one of Mazak's Technology Centers, Technical Centers or at its Florence, Kentucky-based headquarters) can then interact with the shop's connected devices to send specific work instructions and communicate with the shop just as in a face-to-face service call.

When a machine repair requires parts, shops can also use Remote Assist to identify the correct replacement so Mazak can ship it to a field service technician for direct installation. This process eliminates an in-person diagnostics visit before the parts order, saving an average of two days of downtime. In addition to combining diagnostics and part orders into a single virtual visit, Mazak's Remote Assist offers three-way connections that let service technicians collaborate on solutions with other experts.

Because spindles are the heart of every machine tool, Mazak's Spindle Rebuild Department offers customers fast and precise spindle rebuilding services under the MPower umbrella. The department has the ability to refurbish over 700 machine spindle variations drawing from a more than $54 million dedicated spindle inventory. Once rebuilt, spindles are warrantied for one year or 4,000 hours.

Mazak's on-demand Learning Management System allows users to custom-tailor training programs, select subject matter from over 100 multi-level courses and schedule classes for times that suit their schedules, especially when in-person instruction becomes impossible or inconvenient. Through MPower, the system makes essential courses accessible on demand to shops anytime, anywhere.

The Learning Management System offers online instruction and virtual experiences that provide all the engagement of in-person instruction with the same standards of results. It also enables Mazak to customize its course offerings and subject matter to meet customer requests and adapt classes to suit learning levels. This ensures that shops always have access to exactly the right classes that will empower their teams to do more.

www.mazakusa.com/mpower-hub/

gear TECHNOLOGY

FREE SUBSCRIPTION

18GTPAGE

RESPONSE REQUIRED

☐ **YES** I want to receive/continue to receive *Gear Technology*

☐ **NO** Thanks anyway, but I don't need the world's best publication on gear engineering and manufacturing.

Name ______________________ Job Title ____________________
(please print)

Signature ______________________ Date ____________________
(required)

How would you like to receive *Gear Technology*?

☐ PRINT version (Verify mailing info below)
☐ DIGITAL Version (E-mail required)
☐ BOTH Print AND Digital (E-mail required)

E-mail ____________________________*

*Your PRIVACY is important to us. You get to CHOOSE how we use your personal information. The next e-mail we send you will have clear instructions.

How are you involved with GEARS?

☐ My company MAKES GEARS (20)
☐ My company BUYS GEARS (22)
☐ I DESIGN gears (23)
☐ I am a SUPPLIER to the GEAR INDUSTRY (24)
☐ OTHER (Please describe) ____________________

What is your company's principal product or service? ____________________

____

MAILING INFORMATION

NAME:
JOB TITLE:
COMPANY:
ADDRESS:
☐ Check if this is a home address

CITY:
STATE/Province:
ZIP/Postal Code:
PHONE:
FAX:

Put your business card here to make it easier!

Mail to:
1840 Jarvis Ave., Elk Grove Village, IL 60007 USA

or

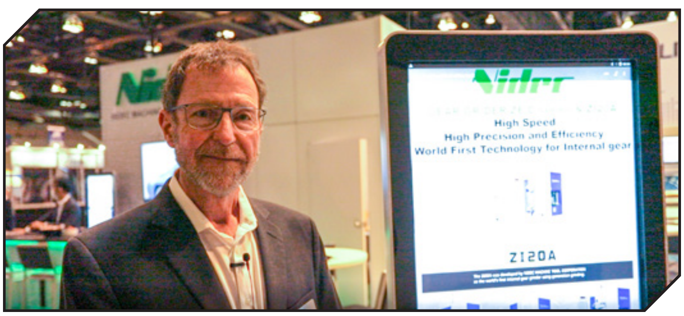
FAX to 1-847-437-6618
SCAN to: subscribe@geartechnology.com

Highlights from MPT Expo

At the recently held Motion+Power Technology Expo, we had the opportunity to sit down with a number of exhibitors to learn more about the latest in technology for the mechanical power transmission industry – including gear manufacturing machine tools, workholding, inspection equipment and much more.
All of the following videos are available on demand at *Gear Technology TV*. (*www.geartechnology.com/tv/*).

Dixitech CNC – Dr. Devin Flowers, President, talks about remanufactured gear machines and especially the niche the company has found in quench presses.

Nidec Machine Tool America – Dwight Smith, Vice President, discusses how internal gear grinding can help improve NVH for e-Drive transmissions.



Hainbuch America – Al Dopf, National Sales Manager, presents the latest in gear workholding technology.

German Machine Tools of America – Walter Friedrich, President/CEO, demonstrates how the Profilator Scudding process with a tandem tool can cut a double gear in one setup.

Wenzel America – Drew Shemenski, President, Wenzel America, talks about the company's latest technology in dedicated gear and CMM inspection.

Liebherr Gear Technology – Scott Yoders, VP Sales, discusses gear hobbing and automation.

Stay tuned to the Gear Technology e-mail newsletter for even more highlights from the show, or visit *www.geartechnology.com/tv/* to watch all of our videos.