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Three Things Needed from Every Power Transmission Company
(p 10)

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A Publication of
The American Gear Manufacturers Association

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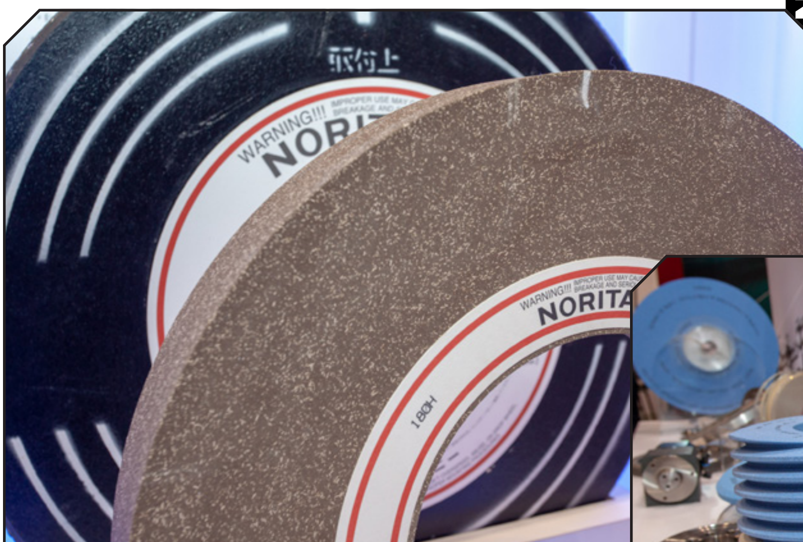

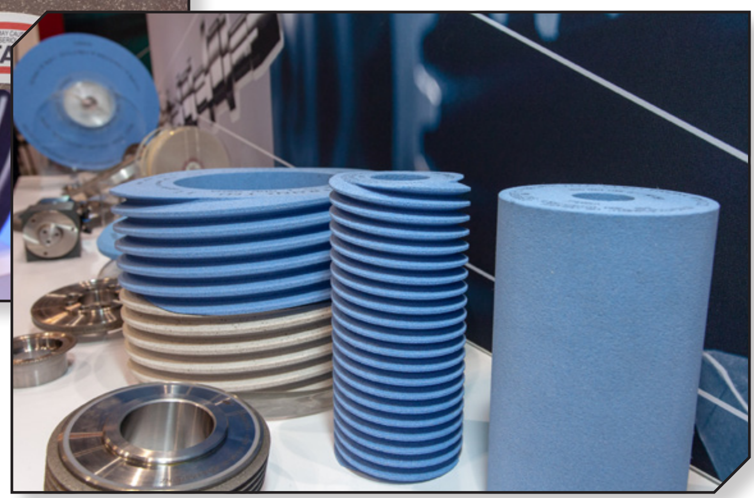

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GT Revolutions

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Felsomat Gear Honing Automation

This video examines the latest automation technologies from Felsomat for gear honing. Learn more here:

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Chamfering with Liebherr

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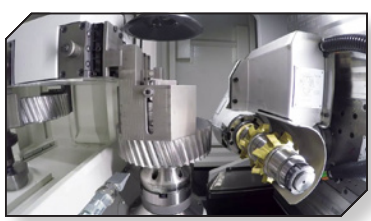

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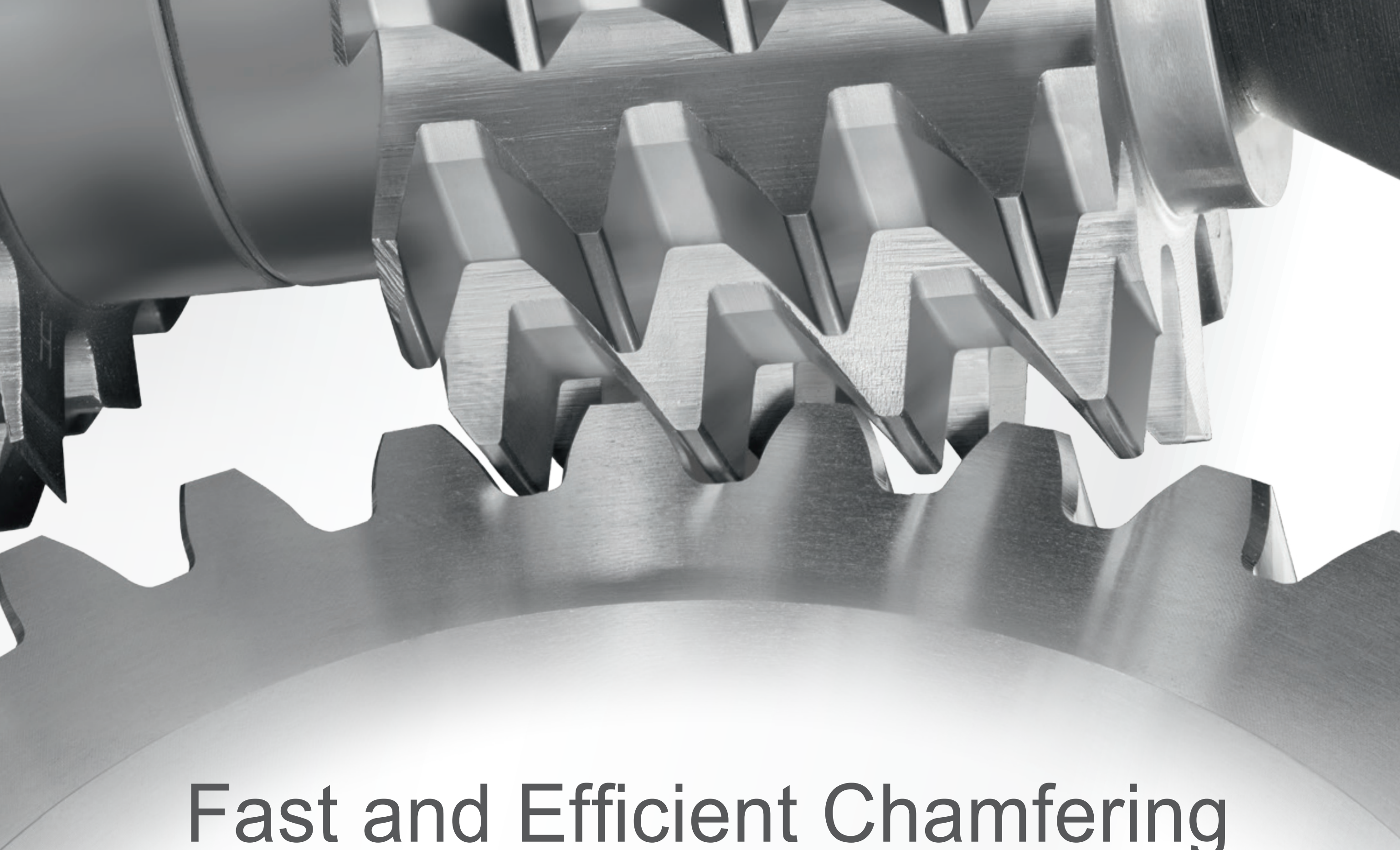
Michael Goldstein founded Gear Technology in 1984 and served as Publisher and Editor-in-Chief from 1984 through 2019. Thanks to his efforts, the Michael Goldstein Gear Technology Library, the largest collection of gear kNowledge available anywhere, will remain a free and open resource for the gear industry. 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*.



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Grinding it Out

Publisher & Editor-in-Chief
Randy Stott

My wife, Wendy, and I have been taking on a lot of DIY home improvement projects lately around the house. Our weekends have been busy with things like patching drywall, installing trim, refinishing floors, painting walls and the like. Aside from the amazing support of my partner (which goes without saying, of course), one of the things I've come to appreciate most during these past few weeks is the importance of surface finish. We've spent a lot of time scraping, sanding and smoothing in order for our projects to turn out the best they can.

In the case of our home, the surface finish is all about appearances. You can't just paint over imperfections if you want it to look right. No, you have to patch all the holes and repair all the damage that results from 20 years of living in the same place. Then, when everything is smooth and clean – with no dents or dings – it looks brand new.

But surface finish isn't just important when you're doing home repairs. It's important for gears, too. Only with gears, that surface finish isn't about appearance. It's about creating precision, quiet gears.

Today, that's more important than ever. With the automotive industry shifting towards more and more electrically-driven concepts – from full plug-in electric vehicles to hybrids driven by a combination of internal combustion and electric motors – there is also a shift in the requirements for gears.

Electric motors used in these applications run at much higher speeds than internal combustion engines. They also run much quieter. So, the transmissions that transfer power to the wheels need to accommodate those speeds without generating too much noise. Once you remove the internal combustion engine, the transmission is often the next noisiest thing in the car.

So quiet gear drives are extremely important these days, and the automotive industry is just one example. There are many other applications where gear noise has become equally important – everything from drones to wind turbines.

Quieter gears require a better surface finish, which means they need to be manufactured with additional processes like grinding and honing. That's why we've chosen surface finishing as the focus of this issue.

In Senior Editor Matthew Jaster's article on gear grinding (p. 22), he explores the ways many of the leading suppliers in the industry are improving technology to help gear manufacturers produce higher quality gears more productively.

Dr. Antoine Türich of Gleason explains how the latest gear honing processes can be extremely useful in producing gear components specific to automotive eDrives (p. 26). Gleason also contributes a second article on automotive eDrive gear noise with Dr. Hermann J. Stadtfeld's "Psychoacoustics Applied to eDrive Noise Reduction" (p. 48).

But the story doesn't end here. You should also go to *geartechnology.com* for even more great articles related to surface finishing. In fact, if you check out our *GT Extras* column (p. 6), you'll see that we've lined up some great online exclusive articles and videos from the likes of ANCA, Felsomat and Liebherr.

Also, if you're interested in learning more about how the auto industry's shift to eDrives will affect the gear industry, I highly recommend you read the AGMA's new white paper, "A Gearing-Centric Snapshot of the EV Space." The in-depth white paper, written by AGMA's Electric Drive Committee, takes a detailed look at the gearing developments in drivetrain design, the high-level technology in the machine tool market, new players in the industry, different manufacturing processes and the quest for the silent drivetrain. The paper is the result of more than six months of thoughtful collaboration and research by the committee, and it's well worth the read. It's available to both AGMA members and non-members in the store at *www.agma.org*.

We hope you enjoy our issue on surface finishing. I have to get going, because it's already late on a Friday afternoon, and I have some surface finishing projects of my own to get to.

Randy Stott

Three Things Needed from Every Power Transmission Company

Greg Schulte, President and CEO, Bonfiglioli USA, AGMA Chair, 2021-2022

In March, I became the Chair of the American Gear Manufacturers Association (AGMA).

Like many in the gearing and power transmission industry, I grew up in it alongside my father for some years before writing my own journey. My wife recently reminded me that is has been 11 years since our first AGMA annual meeting, which really isn't that long considering our association is 106 years old.

I began by getting involved with the Foundation and had the opportunity to chair the fund-raising committee, where we leveraged donations to support AGMA education efforts. I was also an active participant in the scholarship program to support the education of our young people wanting to get into the gear industry, where we have found 86% of scholarship recipients ultimately join the industry. While I was a Trustee, we also launched the successful Get into Gears campaign, which has supported many AGMA member companies in workforce recruitment. It was great to be part of a group that was trying new and different approaches to solving our industry challenges.

I then had the opportunity to join the AGMA Board of Directors, where we have guided the development of an IACET-accredited training program for your team members. Besides the online learning courses and four new operator classes we developed, we have also created the AGMA National Training Center at Daley College that will hopefully be operational later this year, giving operators real-world experience with current-technology machines. We adjusted the focus of Gear Expo to Motion + Power Transmission Technology Expo to recognize the trend in total systems approach that end user customers are focusing on. And, last year, AGMA Media was born through the acquisition of *Gear Technology* and *Power Transmission Engineering* magazines, giving us a direct voice to our industry and association.

Ironically, some of the challenges we face today might be similar to those of our earlier days: education, promotion and technology innovation. However, the response strategies necessary to solve our strategically similar industry challenges today are quite different.

I bring up just a few of the things we are doing for three reasons:

1. To remind everyone our industry is ALIVE and ever changing. Your voice is heard, and the Association is always there to support and address the obstacles we are facing (workforce recruitment, education, global trade, new technologies, and the list goes on). Put another way, we listen and TAKE ACTION.
2. I ask for your support to get involved. Do not be a passive participant—get involved, and get your team involved. If you look at the successful AGMA companies, they are the ones that are involved, networking, voicing issues they have in their business and solving problems.
3. I also encourage you to be "ALL IN" for MPT Expo this fall. As business leaders, we need to LEAD and get back to business, which includes face-to-face interaction. The AGMA Board and Show Committees are "ALL IN", and we're ready to produce a world-class event this fall, but we need you to be an active supporter of getting our world back to relative normal with your attendance.

> ***"In our association, we might be suppliers, partners, customers or competitors, but in the end, we are one industry—and now is the time when we need to come together and move the industry forward."***

Let's face it…we have a lot impacting our industry.

The fact that we spent most of the past year on Zoom + including our recent Annual Meeting + is a clear indication the world is not the same as it was, and it's moving at light speed. Therefore, as an association, we need to keep our gears moving, staying relevant with technology and keeping up with industry changes…and we can only do that together. In very simple terms, this means we need to show up!

In our association, we might be suppliers, partners, customers or competitors, but in the end, we are one industry—and now is the time when we need to come together and move the industry forward.

I will serve as Chair for two years, and I will do my best to continue the success of our association and focus on the value that everyone can realize in their business. This starts with all of us actively communicating, participating and being stewards for our companies and association.

As I begin this effort, I want to thank our outgoing chair, John Cross of ASI Drives, for his support and leadership over the last two crazy years and his predecessors: AGMA Old Goats Jim Bregi of Doppler Gear and Dean Burrows from Gear Motions, along with Mike McKernin from Milans Machining and Todd Praneis of Cotta Transmission, who have served with me on the Executive Board. These leaders were all once strangers to me, but after working side by side with them on important AGMA business, we have become friends; they have welcomed me into the association while also challenging and guiding my path until today.

I close repeating the three things we need from AGMA members in 2021:

1. This industry is alive but constantly changing. AGMA and its members need creative solutions to respond to our transient environments. Working together, we can accomplish anything.
2. It takes a leader's stewardship and time to make the most out your AGMA membership. Get your employees involved, join committees, and make AGMA a staple for your team.
3. Get "ALL IN" with AGMA and make your plans to attend MPT Expo this September.

Contact me directly if you have thoughts, ideas or want to get involved.

My email address is: *greg.schulte@bonfiglioli.com*

Greg Schulte
President and CEO, Bonfiglioli USA
AGMA Chair, 2021-2022

Liquidtool Manager

MONITORS COOLANTS USING INTELLIGENT TECHNOLOGY

With the Liquidtool Manager, Liquidtool Systems introduces the first intelligent, IoT-based solution for monitoring coolants. It is the first product ever to combine a plug & play solution and a cloud-based platform with intelligent, automated and reliable measurement into an innovation that takes metalworking companies a step closer to Industry 4.0. The Liquidtool Sensor, which is also available, makes data collection easy. Thanks to plug & play, sensor commissioning is simple and intuitive business: the highly integrative sensor is magnetically mounted on the machine to be monitored, connected to the company's WLAN or LAN internet connection and operated with the corresponding app via tablet, smartphone or PC.

Automatic measurement and evaluation of the coolant

The sensor for metal cutting machines is compatible with coolants of all manufacturers and monitors them automatically. The Liquidtool Sensor regularly takes coolant from the machine tank and measures the sample with the built-in refractometer and thermometer. It stores the data gathered securely on the corresponding platform, allowing deviations to be detected at an early stage. Users can add additional values such as pH, nitrite and water hardness manually. Reliable, regular measurement forms the basis for stabilizing and optimizing processes, increasing efficiency and identifying problems early on. This in turn can reduce machine downtime and contributes to a longer service life of the coolant and tools.

Cloud-based platform for maximum monitoring flexibility

The data collected by the sensor is stored and analyzed in the cloud-based Liquidtool Manager. The Manager provides secure access to all current and historical measurement data — in real-time and from various devices, such as smartphones, tablets and computers. The stored data can be displayed directly in the Liquidtool Manager via various graphics, statistics and reports. In addition, users can exchange experiences with other users worldwide in the Liquidtool Community.

"Digital first" — including in sales

The Liquidtool Manager is developed and sold by the Swiss start-up Liquidtool Systems, a sister company of Blaser Swisslube AG, which has been a leader in the production of lubricants for over 80 years. "With the Liquidtool Manager, we are proud to offer our customers a product that makes a significant contribution to the progressive digitalization of the metalworking industry," says Daniel Brawand, head of sales and marketing at Liquidtool Systems. "The Manager and the associated Sensor are installed and operated easily and intuitively, allowing users to take reliable measurements with minimal effort. Based on this, they can optimize their processes and minimize maintenance costs. We are very excited to launch the product in the spring of 2021. Our focus is also on digital technology when it comes to sales: both products will be available online via the Liquidtool website."

www.liquidtool.com

Marposs

ANNOUNCES MERLIN PLUS STANDALONE GAUGING SOFTWARE

Marposs has announced the standalone availability of Merlin Plus gauging software. Formerly only embedded in Merlin hardware devices, this software is now offered for use on any PC running Windows 7 or Windows 10 operating system. Aimed at optimizing industrial production analysis and control, Merlin Plus software combines flexibility and ease of use for managing simple measuring and manual bench applications. It is well-suited for fixture builders and makers, as well as end-users that want to configure their own measurement applications.

Merlin Plus software offers multiple measurement and statistical displays with numeric and graphic layout, trend limits, data traceability, batch management, part counters, and data storage; exporting in CSV or Q-DAS format. It can handle up to 250 different measurements, 1,000 different part programs and offers connection to several type of devices with built-in drivers.

Merlin Plus software also comes with a free add-on called Merlin Designer, which allows users to create customized pages using graphical representations of measurements such as bars and images, as well as imported CAD, JPG, and GIF files. In manual applications this feature allows to easily guide the operator in carrying out the inspection sequence of any component.

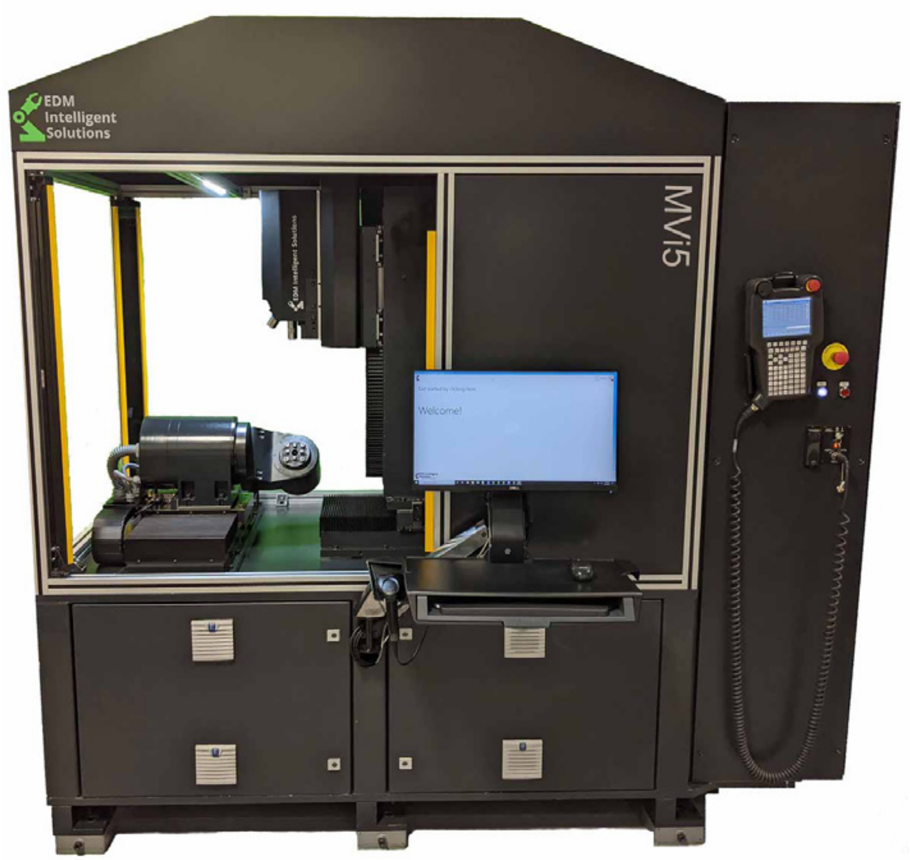
With a set of predefined I/O configurations, the Merlin Plus software can also comfortably satisfy the need of simple automatic applications requiring to interface with a PLC.

The standard network capabilities of a full Windows system combined with the built-in data segregation features makes it a perfect platform for efficient data collection in compliance with company standards.

www.marposs.com

EDM Intelligent Solutions

CREATES 5-AXIS 3D METROLOGY CENTER



EDM Intelligent Solutions (EDMIS) is pleased to announce the release of their new MVi5 – 5-Axis 3D Metrology Center joining FANUC CNC controls with advanced 3D metrology sensors to create an industry ready multi-sensor metrology and measurement platform. The company provides a unique level of expertise for the automation and industrial metrology requirements of OEM and research and development customers within the major aerospace, automotive, communications, defense, medical, and scientific industries.

EDM Intelligent Solutions automation group has developed a unique, 5-Axis 3D Metrology Center based on a machine tool motion system with fully integrated high-resolution 3D metrology sensors. Utilizing industry proven FANUC CNC controls and servomotors, the MVi5 offers the reliability and long-life performance that users in the aerospace, automotive, mechanical engineering, medical, plastics, and semiconductor technology industries have come to trust.

The robust machine tool base houses a top-of-the-line motion system with linear travels of 300 mm on the X, Y and Z axes along with integrated glass scales on each. The heavy-duty rotation and tilt unit features an enhanced payload of 20 kg with a B-Axis tilt range of ±120° and continuous C-Axis rotation of 360°, with both axes having integrated absolute encoders.

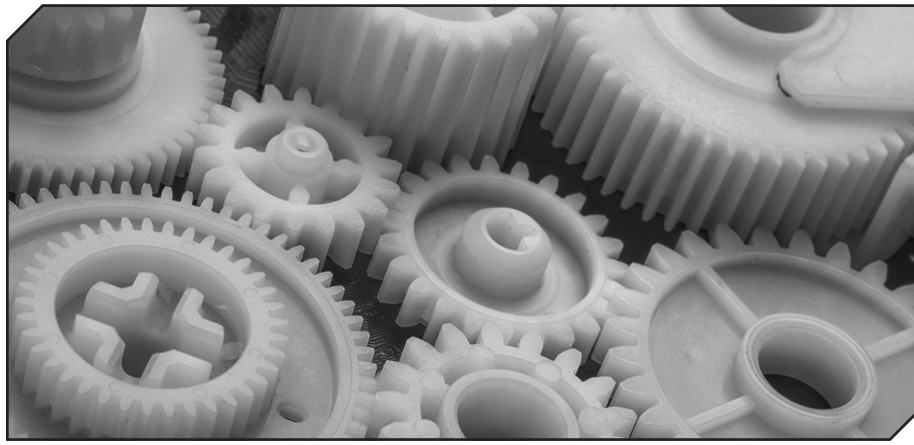
Advanced 3D metrology sensors featuring measurement speeds of up to ≤ 1.7 million points per second and high-resolutions' of 10 nm allow the MVi5 to measure form, distance, height, surface roughness, true position, scan vs. CAD model differences and scan vs. scan differences all in one rugged multi-sensor platform that is ready to be installed directly on the manufacturing production floor.

The need for hands on, complex programming of the measurement and inspection tasks have been virtually eliminated and replaced with a user friendly, menu-based programming interface found in the Foundation Programming Environment from EDMIS. Customized 3D model-based measurement and inspection programs are automatically generated off the 3D solid model design of the part to be inspected. The user simply uploads the solid model, selects the areas to measure and a program is created. Offline measurement and inspection programming is also offered through integration with various CAD/CAM software packages common within industry. Operation of the MVi5 5-Axis 3D Metrology Center is quick and simple via the touch screen optimized EDMISi human machine interface with native barcode compatibility. User access controls and permissions allow operators to only select and run approved inspection programs while Engineering and Administration staff have full access to create and modify programs and to administer all features and functionality of the machine.

www.edmdept.com

Helios Gear Products

INTRODUCES HOBBING SOLUTIONS FOR PLASTIC GEARS



External plastic gears, like their metal counterparts, use the hobbing process for productive manufacturing. However, the difference in material leads manufacturers to key considerations to ensure successful hobbing applications. Plastic gears tend to be ultra-fine- (finer than ~64 DP) to fine-pitch (finer than 20 DP); their material strength can be compromised; order volumes tend to be high; chip evacuation requires a special system; and burr mitigation is a must. Decades of experience from Helios Gear Products address these issues as follows.

To productively manufacture fine- and ultra-fine-pitch gears + which plastic gears often are + the hobbing machine must offer high speeds. Contemporary hobbing platforms for these types of gears offer hob spindles up to and exceeding 10,000 rpm. At first thought, this may seem excessive, but speed requirements stem from surface speed requirements. For instance, when using a carbide hob, a common starting point for speed may be 250 m/min (820 sfm). Consider that some contemporary CNC hobbing platforms offer only 2,000 rpm tool spindles; the following chart demonstrates how this limits achievable speeds when using hobs less than approximately 40 mm diameter. Thus, to ensure productive manufacturing of ultra-fine to fine-pitch plastic gears, high-speed tool spindles are a must, such as those offered on the hobbing models Hera 30 (10,000 rpm) or the Monnier + Zahner 500 D-drive (12,000 rpm).

The material of small parts can be easily compromised under clamping pressure when mounted for hobbing. Hydraulic pressure is typically needed, but when trying to avoid part slipping, such clamping forces can crush, mushroom, or unacceptably deform a workpiece. Dual direct-drive work spindles offer help to alleviate this problem. With this ability, the machine's work spindle (headstock) and tailstock are both directly driven by CNC motors that are kept in a synchronized timing. This helps remove frictional forces during clamping, which allows easier fixturing with less clamping force. Consequently, dual direct-drive work spindles allow fixturing of very small workpieces with reduced clamping force.

Because plastic gear orders are often large-volume, manufacturers must consider automation capabilities of the hobbing machine. Small (or very small!) workpieces require a variety of automatic loaders depending on their geometry. Although robots are prevalent today, they typically lack the dexterity and/or clearances to handle these parts. As such, manufacturers must familiarize themselves with more specialized automation systems, such as gantries, bowl feeders, magazines, conveyors, line feeders, and more. Each system offers benefits and limitations for the manufacturer to weigh for his applications, so he must speak with the applications engineers from the machine tool's factory to learn more. Less ideally, a third party automation solution can also be considered, but this will add complexity to the hobbing solution.

As with metal gears, burrs produced by the hobbing operation must be removed. Most hobbing machines offer a dedicated deburring disc that shears away burrs during the hobbing cycle. Because this adds no time to the machining cycle, it should be used whenever possible. However, such discs may still leave micro-burrs, which may not be acceptable for the finished gear. Thus, more sophisticated methods may be employed for deburring, such as single- and two-hob deburring. If the machine tool allows a negative center distance + i.e., the tool spindle can reach "over" the work axis + then the same hob that performed the hobbing operation can also deburr the same gear. This is performed on the hobbing machine (such as those offered by Monnier + Zahner), with the same clamping, within the same cycle, which is a huge benefit gained at the cost of a few seconds of cycle time and a bit of extra programming during setup. Machines that cannot hob "beyond zero" (for one-hob deburring) may offer sufficient hob shifting with special software to use two-hob deburring.

In this operation, two hobs are mounted on the same hob arbor, each performs a typical hobbing cycle, but the second hob cuts and feeds in an opposite direction. As a result, each hobbing pass pushes chips toward the middle of the part, thus avoiding burrs. As with one-hob deburring, two-hob deburring uses the same clamping within the same cycle as the hobbing process, so it is a very productive means of deburring plastic gears.

An example of two-hob deburring can be seen at *heliosgearproducts.com/two-hob-deburring-plastic-gear-hera-30/*. Other means of deburring are available but may require additional machines and/or operations. Such complexity can be avoided by choosing a hobbing machine with "built-in" deburring abilities.

Applications engineers from Helios Gear Products discuss the above strategies with manufacturers when they choose an optimal hobbing platform for plastic gears. Such decisions consider key factors such as the machine's ability to effectively clamp small workpieces by using dual direct-drive work spindles. Because plastic is not a ferrous material, the hobbing platform must adequately handle chips without a traditional magnetic conveyor.

Automation systems and their versatility should be discussed for the manufacturer's particular applications, as should deburring methods. Finally, choosing a hobbing solution with high-speed spindles will help future-proof the platform to handle a wide range of applications, and it will future-proof for tomorrow's more aggressive cutting tool materials and coatings.

Heliosgearproducts.com

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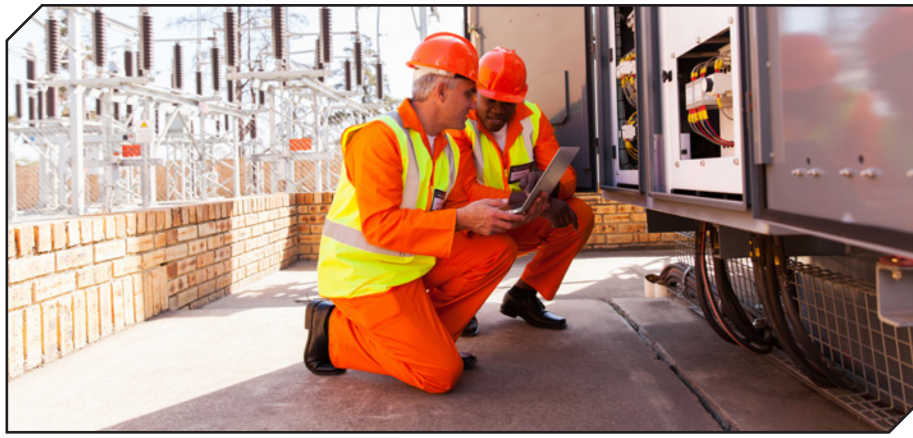
Shell

ANNOUNCES GLOBAL PORTFOLIO OF CARBON NEUTRAL LUBRICANTS



Shell has announced it will offer customers carbon neutral lubricants across a range of products for passenger cars, heavy duty diesel engines and industrial applications. Shell aims to offset the annual emissions of more than 200 million liters of advanced synthetic lubricants, expecting to compensate around 700,000 tonnes of carbon dioxide equivalent (CO_2e) emissions per year, which is equivalent to taking approximately 340,000 cars off the road for one year.

"Shell has set a target to become a net-zero emissions energy business by 2050, in step with society and our customers," said Carlos Maurer, executive vice president, global commercial at Shell. "We know our customers are looking for ways to reduce their net carbon footprint, and as the world's leading lubricants supplier we have an important role to play. That is why I am pleased to announce the largest carbon neutral program in the lubricants industry, and one that compensates for the full life-cycle emissions of our products. From today, our consumers, commercial drivers and industrial customers can now enjoy the benefits of improved engine performance and better fuel efficiency in a carbon neutral way."

This represents a key milestone in Shell Lubricants' multi-year strategy to help customers manage their sustainability needs and its ambition to reduce the carbon intensity of its products by avoiding, reducing, and offsetting emissions. Since 2016, Shell has reduced the carbon intensity of its lubricants manufacturing by over 30%, and over 50% of electricity used in its lubricant blending plants now comes from renewable sources. Shell is also reducing packaging waste from lubricants products at scale by increasing the use of recycled materials and exploring more sustainable packaging solutions across its supply chains.

While measures to avoid and reduce emissions offer the best way to tackle emissions in the long term, until scalable solutions are deployed, carbon offsetting programs provide an immediate solution to balance CO2e emissions across Shell's portfolio and value chain. Shell's global portfolio of nature-based carbon credits will compensate CO2e emissions from the entire lifecycle of these products, including the raw materials, packaging, production, distribution, customer use and product end of life.

Shell's carbon neutral lubricants will be available in key markets across Europe, Asia-Pacific, the Middle East and North America. Shell will offset the emissions from a mix of advanced synthetic lubricants in these markets, including Helix and Pennzoil for passenger cars; Rimula and Rotella for heavy duty diesel engines, and a wide range of premium industry lubricants, including Shell Omala in the wind sector, Shell's range of eco-Label products "Shell Naturelle", and the Shell Gadus greases product range.

www.shell.com/naturebasedsolutions

KISSsoft

FITS INDIVIDUAL SOFTWARE NEEDS WITH CUSTOMIZED OPTIONS

One of the key aspects in modern software development is to give end users sufficient freedom to adapt their working environment to individual needs. This ensures simple and intuitive handling, which in turn leads to efficient work processes. In KISSsoft, various options are available for personalizing the user interface and tailoring it to your own requirements.

User-defined tools and other entries can be added to the KISSsoft database, for example. Custom reports are also easy to implement or edit, and manufacturing drawings can be modified within wide limits. Creating user-defined rules and output files simplifies the entire workflow. In addition, KISSsoft calculations can be easily integrated into other programs.

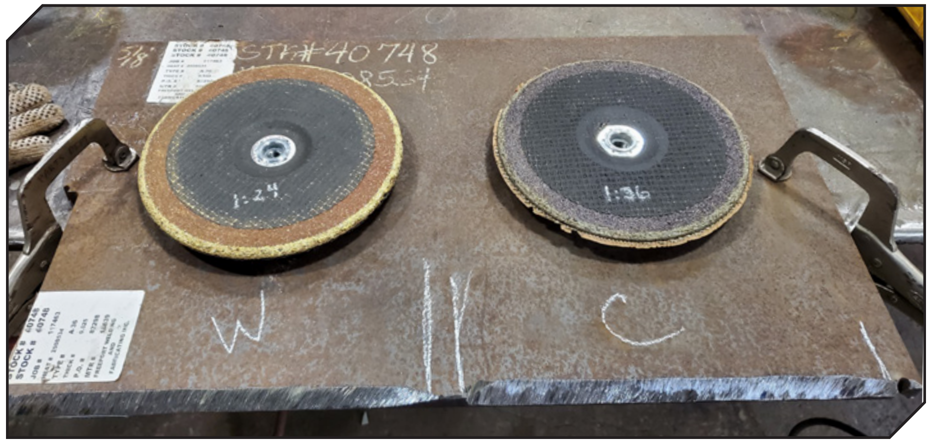
www.kisssoft.com

Weiler Abrasives

CREATES PRODUCTIVITY PROGRAM

Weiler Abrasives is offering its Weiler Consumable Productivity (WCP) program to help end users better manage their abrasives costs and increase productivity. The WCP program tests and evaluates abrasives to compare product life, reduce cycle times and increase efficiencies.

"The WCP program can bring real value to end users, especially if they are experiencing bottlenecks in their operations, have short abrasive life and want to improve performance," says Ron McCarthy, abrasives specialist, Weiler Abrasives. "Our goal is to set them on a path of cost savings and better productivity + and we're confident we can do that. One of our most recent WCP participants saved $62,000 annually, so our customers are finding significant value in this program."



The program involves time studies and observation of abrasive usage to gather quantitative data that can be measured and verified, leading to a repeatable solution. Weiler Abrasives representatives look at how abrasives are used, how long they last and how productive they are. It involves five steps:

1. Evaluating the value related to purchasing the abrasives
2. Real-life testing at the company's facility
3. Establishing a baseline through testing
4. Collecting data and establishing averages through product evaluation
5. Reviewing findings and creating an actionable plan

By comparing several products throughout the process, Weiler Abrasives provides a recommendation for the best, most productive abrasive for the application.

weilerabrasives.com/Multipass-Consumable-Productivity

FANUC CNC and Robotics Integration

SIMPLIFIES MANUFACTURING OPERATIONS

FANUC America introduces the next step in complete robotics and CNCs integration for more efficient operations. FANUC CNCs now have the ability to control connected FANUC robots providing machine tending or other assistance through its Quick and Simple Startup of Robotization (QSSR).

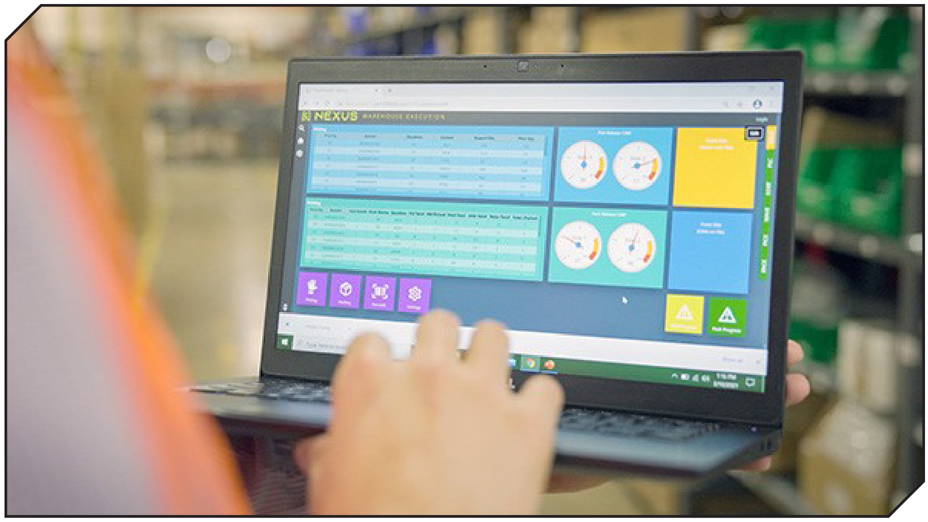
More manufacturing operations are taking advantage of adding more robotics to execute repetitive tasks previously manually performed. Advanced automation offers a competitive edge and greater profit margins to shops of all sizes.

QSSR is a complete package that simplifies the connection of a FANUC robot to a FANUC controlled machine tool. The new QSSR G-code feature allows operators and machine tool builders to program robots easily through the FANUC CNC in ISO standard G-code format. Those unfamiliar with robotic programming language will no longer require additional training or specialists because the programming can be performed with G-codes. A reliance on a separate teach pendant for the robot is also greatly reduced with the capability of robotic programming and operation through the CNC user interface.

www.fanucamerica.com

Matthews Automation Solutions

INTRODUCES WAREHOUSE EXECUTION SYSTEM SOFTWARE



Matthews Automation Solutions, a provider of warehouse automation systems and software, is introducing their new NEXUS Warehouse Execution System (WES). A warehouse execution system connects diverse automated processes in a distribution center and manages them as a centralized, integrated material handling system. Matthews NEXUS WES unifies data, operations and material handling equipment, enabling them to function collaboratively and increase throughput and material flow throughout the facility. The software features a new web-based front end for improved usability and visualization on desktop and mobile devices.

Matthews Pyramid Director and CORS (Compass Order Routing System) software platforms have helped leading brands in retail, food and beverage, parcel handling and other industries elevate their omnichannel and ecommerce order fulfillment capabilities since 1994. In 2019 the Pyramid and Compass teams joined together in Pyramid's expanded Cincinnati, OH campus. The combined teams and technologies have now produced NEXUS.

"Matthews NEXUS Warehouse Execution System dynamically balances work and synchronizes real-time resources to optimize how orders flow through a facility," shared Gary Cash, senior vice president and general manager for Matthews Automation Solutions. "NEXUS provides the visibility, flexibility and on-demand performance companies need to meet the growing volume and complexity of omnichannel and ecommerce order fulfillment."

NEXUS uses real-time data and adaptive learning to continuously monitor and adjust automated subsystems throughout the day to maintain balanced operations based on rate and projected workflow. Matthews' new WES was also developed with a completely new web-based front end.

"The responsive user interface was designed to provide an intuitive, configurable workspace with end-to-end system visibility and control," said Dann Woellert, WES product manager for Matthews. "Being web-based, NEXUS can be accessed on all devices — from PCs to tablets to phones — regardless of operating system."

Dann continues, "The NEXUS architecture was developed on the foundation of Matthews' proven Pyramid Director and CORS solutions, and offers more robust capabilities, improved usability and enhanced security."

Support will continue for Pyramid and Compass customer installations through Matthews' Cincinnati team, who will also offer virtual demonstrations of NEXUS to end users and partners.

matthewsautomation.com

Making Room for Productivity and Quality Requirements in Gear Grinding

Matthew Jaster, Senior Editor

Gear grinding comes with unique production challenges today. Customers often request higher and faster speeds for continuous generation gear grinding. They also struggle to find a balance between productivity and quality requirements. While many applications are utilizing *less* gears in their equipment, the quality and production values continue to increase. Therefore, the gears found in the automotive, aerospace and industrial segments in 2021 need to cost less, reduce gear noise and work as efficiently as possible. As with any other area of manufacturing, gear manufacturers are going to need the right tools—in this case grinding wheels, spindles, hobs, etc.—to meet greater production demands in 2021.

The 3M Nano 2.0 Series features a newly developed bond system that allows the company to reduce the amount of unloved bond volume.

Norton | Saint-Gobain Abrasives Develops Grinding Innovations

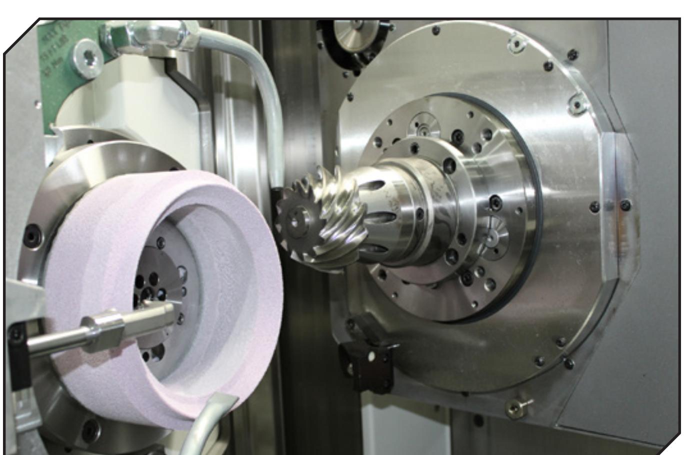
Norton | Saint-Gobain Abrasives has been developing innovations in grinding wheel technology, including advances in abrasives and bond technology. The global company is able to leverage the technical expertise from its R&D facilities around the world. Developments include new advancements in grain, bond and porosity technology.

"To meet the changing and ever stringent demands on the gear industry, we have invested heavily in our production lines for gear grinding wheels at our plant in Worcester, MA U.S.A. High wheel speed at 80 m/s has become the industry standard, and OEMs are providing grinding machines at even higher speeds. Each worm wheel follows the strictest quality control procedures to deliver perfect geometry, balance, and safe grinding at high speed," said Andrew Biro, senior applications engineer, Norton | Saint-Gobain Abrasives.

With the electrification trend gaining momentum, the transition to hybrid and electric vehicles will create new challenges for the gear industry.

"Our customers are often struggling between high productivity and high quality. Both are desired, but not always achievable together," said Josh Fairley, product engineer, Norton | Saint-Gobain Abrasives. "Our experienced Norton teams are trained to help customers meet their stringent quality standards as well as productivity goals at the best total cost."

With the Norton Dual Worm wheel, for example, cycle times can be pushed faster while maintaining the mirror finish that customers are looking for. With the new TQX and Quantum Prime grain



Norton | Saint-Gobain has been developing innovations in grinding wheel technology, including advances in abrasives and bond technology.

With the Norton Dual Worm wheel, cycle times can be pushed faster while maintaining the mirror finish that customers are looking for.

technologies, Norton is able to achieve high material removal rates. These new technologies combined with the knowledge and support from grinding experts, allows Norton to help customers convert from traditional methods of gear shaping (such as milling and hobbing) to grinding from solid, which has significant economic benefits on both tooling spend (cost) and equipment requirements.

To increase diamond dressing roll life, customers require open porosity, easier to dress bond systems and grain technology that requires less frequent dressing. Quantum Prime/Vit CBN can improve diamond dressing roll life. In addition, gear manufacturers and end users are continuously working to improve the efficiency and life of gearboxes.

Many are also working to reduce the noise generated from the gearbox. These goals are driving advances in gear form tolerances and target surface finishes to be even tighter. To address the stricter form deviation requirements, ffα, Norton offers abrasive grinding products that can maintain strong form holding, while achieving productivity goals. When gear makers are targeting a finer than standard finish, different types of Norton Dual grit products are specifically designed to quickly rough grind out the stock material and leave the desired surface finish with a finish grind, according to Fairley.

Cycle times can be pushed faster with Norton's Dual Worm wheel technology. Here's a quick rundown of some of Norton | Saint-Gobain Abrasives latest product innovations:

Continuous Generation – high speed, dual grit

The worm wheels are made in Worcester, MA and have speed capabilities up to 80 m/s.

Quantum Prime is a new, proprietary, nano-crystalline ceramic grain from Norton | Saint-Gobain Abrasives. Due to its unique micro-fracturing properties, Quantum Prime delivers excellent grinding efficiency, significantly longer wheel life, while ensuring outstanding part quality. In addition, TQ is the newest elongated ceramic grain in the industry, optimized to achieve the highest material removal rates and coolest cut. TQ technology is offered in the fastest worm wheel on the market, which also reduces power draw, increases parts per dress and form holding.

"Continuous Generation Dual wheel technology enables manufacturers to reach finer surface finishes. It combines a bonded vitrified section to grind and a fine grit section to superfinish the gear teeth. This is a new solution from Norton designed to provide stronger transmissions in trucks and quieter gear redactors in electric vehicles due to the extremely fine surface finish it provides. We developed the polishing section in hard resin where the elasticity of the resin is controlled to make sure there is no expansion of the resin during grinding. This results in no deformation of the gear and provides a high level of consistency in surface quality to achieve a mirror finish on the polished gear," said Fairley.

"We have also made smaller diameter worm wheels available worldwide. These worm wheels are able to grind gears directly on the shaft or countershaft, avoiding the need for welding. The wheels will also allow gear makers to transition discontinuous generation operations to a continuous generation process, greatly increasing productivity," added Biro.

Gear grinding technology today must provide a higher level of consistency in surface quality.

Profile – TQ/TQX from solid, Quantum Prime grain for form holding & cycle times

With the new TQX grain technology, fast grind cycles are achievable. When there is a significant amount of overstock that needs to be removed from the gear, or if the gear manufacturer is grinding gears from a solid blank, TQX is the ideal solution. This is the newest and longest shaped ceramic grain available, exclusive to Norton.

"When form holding, surface finish, and overall gear quality are more critical while still requiring higher removal rates, our Quantum Prime grain technology combined with Vortex grain and Vitrium3 bond provides the most cost-effective solution. Quantum Prime provides unparalleled sharpness and cutting efficiency because of unique micro-fracturing properties. This allows for increased MRR and faster overall cycle times. The free cutting grain also breaks down more consistently, leading to improved part quality, geometry, and better surface finishes even at high MRR's," Fairley said.

As the transition to hybrids and electric vehicles moves forward, the demand for noise level reductions will increase.

"This will lead to tighter tolerance and surface finish requirements throughout the industry. Norton will continue to develop products that meet these tighter tolerances as well as maintain productivity goals," Fairley said.

"There will also be vehicles that will transition to electric at a slower pace, such as large commercial trucks and agriculture equipment," said Biro. "Gear manufacturers will be more focused on increasing the fuel efficiency and overall life of those gearboxes. We anticipate more widespread adoption of the dual grit technology as a solution."

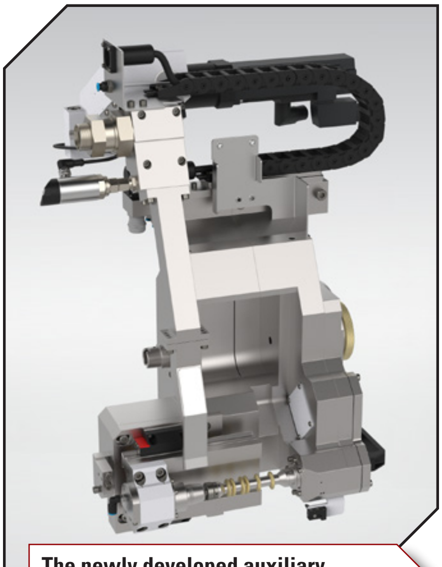
www.nortonabrasives.com

Flexibility in Aerospace Applications with Liebherr

The machining of gears with interfering contours for the aerospace industry places the highest demands on the grinding tool and often cannot be carried out with standard grinding heads due to the small tool diameters. Liebherr has developed an auxiliary spindle for these applications which can be retrofitted. This enables the production of challenging aerospace components on existing LGG gear grinding machines. They recently discussed this innovation during Liebherr's Performance Days 2021.

The greatest possible flexibility, even for special applications, by means of simple conversion or retrofitting of the necessary tools: Liebherr has been successfully pursuing this approach for several years with its adaptable internal grinding arms. With the existing range of internal grinding arms, a machine can be converted from external grinding to profile grinding of internal gears in a short time. Why shouldn't this proven concept also work for the external grinding of special aerospace components? Following this thought, Liebherr developed an auxiliary spindle as an optional accessory that can be offered for LGG gear and profile grinding machines and can be retrofitted to existing machines.

With the auxiliary spindle, the user can use the Liebherr LGG gear grinding machine to produce aerospace components with interference contours.



The newly developed auxiliary spindle is part of a machine purchase that was recently handed over to Liebherr-Aerospace Lindenberg GmbH.

"We view our standard products as the basis for flexible solutions that are always geared to our customers and their requirements," says Thomas Breith, head of product management gear cutting machines at Liebherr.

The newly developed auxiliary spindle is part of a machine purchase that was recently handed over to Liebherr-Aerospace Lindenberg GmbH. This sophisticated new development is designed in close cooperation with the user so that the practical needs of machine operators can be incorporated into the design at an early stage. This applies to setup procedures and service tasks, in particular. A typical aerospace application is profile grinding of what is known as a 3-stage planetary gear, which is required for the wing flap adjustment. Due to the weight-optimized, compact component geometry, only small CBN grinding wheels are technically possible for final hard gear finishing.

With the auxiliary spindle, the user can use the LGG gear grinding machine to produce aerospace components with interference contours, along with their special technical challenges, in small batch sizes without having to invest in an expensive, possibly under-utilized, special machine. The geometrically demanding components can thus be manufactured with high gear quality and surface quality. This expands the range of LGG grinding applications to include an additional option for critical, very small and high-quality components.

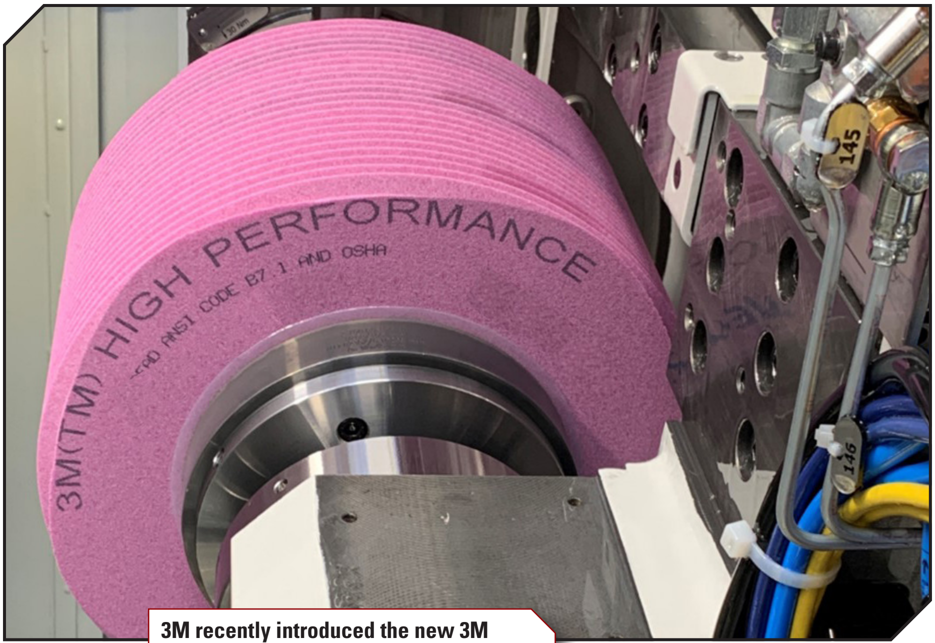
The auxiliary spindle — just like the internal grinding arm — can be mounted on all new Liebherr grinding heads with counter bearings via a changeover interface, which ensures short setup times. The additional functions of the grinding heads, such as an inductive meshing sensor, a movable cooling lubricant nozzle and a swiveling measuring probe, can also be used in combination with the auxiliary spindle.

Machining parts with very small grinding discs requires high spindle speeds to ensure the required cutting speeds of at least 30 m/s. At speeds of up to 30,000 rpm, the auxiliary spindle must meet the highest requirements in terms of vibration behavior and temperature resistance. A bearing on both sides ensures high rigidity, a stable concentricity and additionally allows the use of a longer grinding arbor, which is the technical prerequisite for the safe mounting of several grinding discs. This enables up to two duo roughing discs and two finishing discs with increased feed rates to be used, significantly reducing machining times.

Liebherr has over 30+ years of CBN expertise. For this reason, a sophisticated development project was started for the extremely small CBN profile grinding discs, in order to galvanize the extremely fine CBN grains (grain size ~25–35 µm) onto the high-precision main bodies, so that the narrow gear tolerances and high surface qualities can be ensured with the finest CBN coatings.

"Liebherr aims to be able to supply all the key components from a single source in order to offer customers the best possible solution in gear grinding machines with accessories, technological expertise as well as tool design and production," according to Breith.

www.liebherr.com



3M recently introduced the new 3M High Performance 91VX Nano+ Series.

3M Expands and Diversifies Gear Grinding Portfolio

Gear grinding requires high precision throughout the process, and it is important to use the right grinding wheel for the application. The selection of abrasive material and wheel configuration depends on the base alloy, tooth geometry, and size of the production run, among other factors. 3M's recently expanded abrasives portfolio can help you meet the growing demand for tighter dimensional tolerances and shorter production schedules, even with difficult-to-grind materials.

"We have innovated and extended the diversity of our gear grinding portfolio for the new challenges in the changing automotive (special focus on e-Drives) as well as the wind power industry (offshore)," said Juergen Hechler, global application engineering leader, transportation at 3M Abrasive Systems. "Our customers will be served with the perfect product for their specific situation. We have introduced, for example, a new innovative solution for achieving much higher surface roughness without significant performance redundancies. This is possible with the 3M 91VX Nano 2.0 Series featured by a newly developed bond system that allows us to reduce the amount of unloved bond volume. Less bond with higher grain retention force, higher abrasive content and more flexibility in the design of the pore spaces for cooler grinding, higher cutting performance, longer lifetime of the grinding wheel and dressing tool and the highest possible process stability and quality in terms of geometry and surface quality."

For achieving high surface roughness's with the need to achieve the maximum of performance at the same time, 3M has introduced the new 3M High Performance 91VX Nano+ Series where this newly developed bond systems meets 3M Precision-Shaped Grain with a "plus" of performance.

"The requirements of the automotive industry of the future were the basis for the development of our Nano 2.0 series," Hechler said. "That means increased requirements for profile accuracy and surface quality, grinding of asymmetrical gears with different engagement ratios of the grinding wheels and topologically correct gear grinding. All of this without taking into account the process costs by reducing the cost per part of the abrasives and dressing rollers by significantly increasing the lifetime."

The increasing requirements with simultaneous cost pressure are an enormous challenge for our customers, according to Hechler. "The processes are of the highest level. Be this in terms of the quality of the components to be ground, but also in terms of process time and tool life. We are constantly busy designing our customers' processes to be even more efficient."

Hechler believes the gear market is in the middle of complex changes.

"Smaller machine series are becoming the rule," he said. "There are more complex controls for even more complex machining processes. You need a higher degree of process monitoring far beyond pure geometry control. The entire process chain is evolving from incoming inspection of the gears, process monitoring of the dressing and grinding process, to the monitoring and evaluation of all axis movements of the machine including the assignment to each individual component. The first gears are already marked with QR codes from which this entire process chain can be documented and analyzed."

www.3M.com/precisiongrinding

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Driving Down Gear Noise in E-Mobility

Gleason Combi Honing System Meets eDrive Transmission Standards

Dr. Antoine Türich, Gleason Corporation

As the automotive industry moves toward E-mobility, transmission manufacturers are faced with new challenges. Larger gear ratios are necessary to reduce the high input speeds of electric motors to the required speed of the drive wheels. At the same time, gear noise that was concealed by the sound of a combustion engine is now evident, presenting completely new challenges for acceptable transmission noise levels. Finally, there are the special requirements to consider for the various new transmissions developed specifically for eDrive application. A common solution for eDrive transmissions are planetary transmissions using "stepped pinions."

In specific planetary gear applications, the two gears on the stepped pinion are synchronized to fulfill an exact timing within very tight tolerances.

Due to the noise sensitivity of such components, hard finishing by grinding or honing is indispensable. Gear honing proves to be particularly advantageous, since honed components have a proven lower noise behavior than ground components due to their specific, curved surface structure. Gear honing is also a requirement for machining gears with interfering contours, as is the case with stepped pinions. This is due to the small cross axis angle between the honing tool and the component and the fact that, unlike grinding, no tool overrun paths are required.

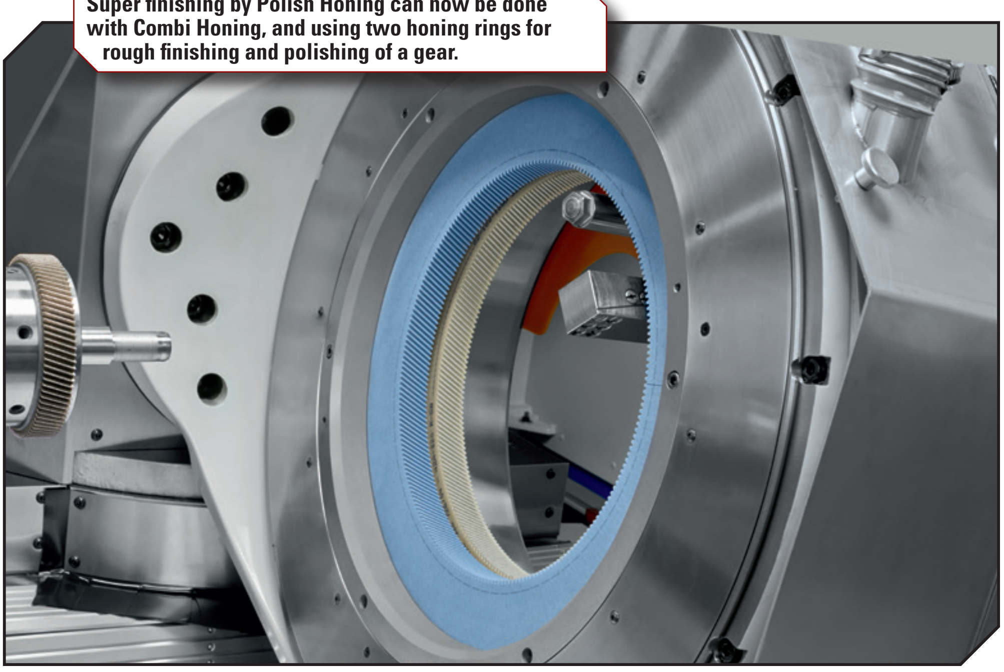
With the acquisition of the Faessler gear honing business, Gleason has added a unique process to its gear hard finishing portfolio that makes it possible to hone synchronized stepped pinions in one clamping with extremely tight tolerances and the highest quality. This so-called Combi Honing system uses two honing rings. The honing head of a Gleason 260HMS Honing Machine, for example, can clamp two honing rings in parallel. The resulting eccentric offset of the honing rings is compensated for with a B-axis (swivel axis). In addition, flank line modifications such as crowning can be realized with the B-axis during the honing process.

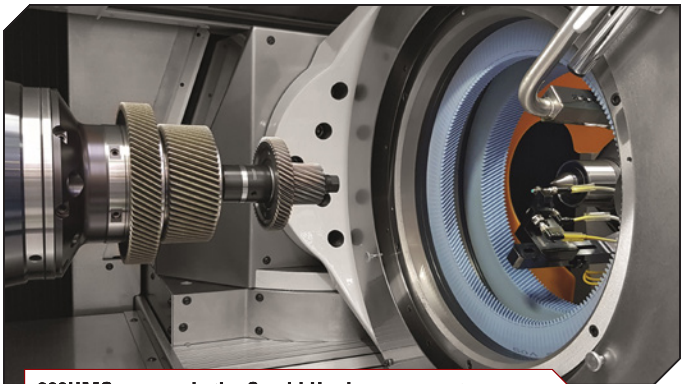
The Combi Honing process starts with honing ring 1 honing the larger gear, and then honing ring 2 honing the smaller gear, all in the same clamping. Although this may sound trivial, this process has decisive and unique advantages, especially with regard to finished quality. While this specific component could also be machined in two separate set-ups, e.g. grinding the larger gear and honing the smaller one, the quality of the resulting gear would not be the same, particularly the angular synchronization of both gears. When finishing both gears in one clamping, non-productive time for loading/unloading as well as indexing (centering tools and gears) occurs only once and not twice per component.

The Combi Honing Process on the 260HMS was specially developed for synchronized stepped pinion applications. A particular challenge was achieving the reliable and accurate positioning of the synchronized gears in relation to the honing rings. When indexing, i.e. centering gear teeth and tools, both teeth of the large and the small gear must be detected while corresponding exactly to the required angular offset and the tolerances of the index hole on the face side of the gear. The latter guarantees the final correct installation position of the stepped pinion in the planetary transmission. Three indexing sensors are used to measure the position of all teeth of the large and small gear as well as the position of the index hole on the face side. A corresponding algorithm calculates the correct position of the gear teeth in relation to the honing rings. Parts with excessive hardening distortions, which can't be honed in exact tolerances to the index bore, are automatically ejected.

Another important feature determining quality is the fixed

Super finishing by Polish Honing can now be done with Combi Honing, and using two honing rings for rough finishing and polishing of a gear.





260HMS can apply the Combi Honing process to produce stepped pinions reliably and at the quality levels needed to ensure the correct installation position in the planetary transmission. Integrated sensors measure the position of all teeth on both gear as well as the position of the index hole on the face side.

position of the two diamond dressing tools on the work spindle. The location of the dressing tools ensures that the position of the teeth on the honing rings does not change either absolutely or relatively — even after dressing of the honing rings. Loading/unloading of dressing tools to the work spindle, as is often the case in other honing applications, cannot reliably achieve this important quality aspect.

Another advantage of the Combi Honing process is the possibility of super finishing gears with Polish Honing. The requirements for increased transmission efficiency and reduced noise levels demand a superior surface quality of hard-finished components. While Polish Grinding using a two-zone polish grinding worm is a proven approach, a similar process has not, until now, been possible with gear honing.

With Combi Honing, however, it is now possible to use two honing rings in one clamping and thus use two completely different tool specifications for rough finishing and polishing of a gear. This makes it possible to achieve the surface qualities of Rz ≤ 1 µm typically required for polish grinding by means of gear honing — but with the added benefit of achieving the surface structures typical for the gear honing process.

Dr. Antoine Türich is director product management — hard finishing solutions at Gleason.

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Gear Noise Cause of a Different Stripe

QUESTION

"It is very hard to find out any paper regarding 'tiger stripes' failure, created by electrical discharge current over the gear teeth." I wish to have some more information on this issue + how it affects the vibration / noise signatures; why does it creates the tiger stripes profile; how deep are the pittings; why does it create the noise and the possibility of running a gear with this failure?"

Expert response provided by Andy Milburn, Robert Errichello and Rainer Eckert.

The questioner is correct that there is not much published information regarding electrical discharge damage on gear teeth. We assume that they have already looked at (Ref. 1), since that is the only paper, we could find that uses the term "Tiger Stripes" for this failure mode (See Figure 1). The good news is that the reason there are not many papers on the subject is likely because it is not a common failure mode for gears. It is however very similar to "fluting" damage caused by electrical erosion on bearings and is much more common in bearings. Reference 1 does not directly address the questions above, so we will attempt to address them here.

First, we will discuss what the failure mode is. Tallian provides a good definition in (Ref. 2), "Electric Erosion is damage to contact surfaces caused by the passage of electric current." Other names used for the same failure mode are electrical pitting, electric current damage, current erosion, spark erosion, and electrical discharge damage (EDD). The damage can appear in two distinct forms; as periodic damage such as fluting or "tiger stripes" on gears, or as random distinct pits over an area of the surface (See Figure 2). For the remainder of this article, we will be concentrating on the first periodic form.

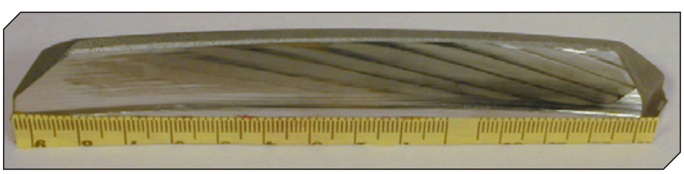

Figure 1 An example of tiger stripes failure (this image appeared as Fig. 2a in Ref. 1).

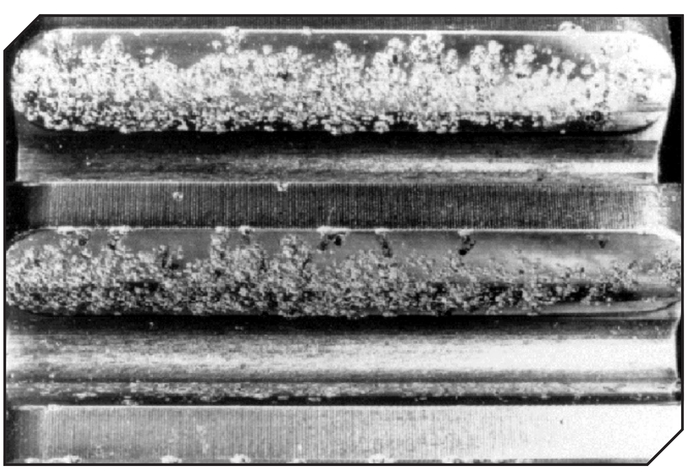

Figure 2 Electrical discharge damage can also appear as random distinct pits over the area of the surface (this image appeared as Figure 20 in Ref. 3).

The basic mechanism is the same for gears and bearings and can occur while they are static or rotating. Mating gear teeth and bearing component contacts consist of Hertzian contacts that are separated in some cases with a full EHL film and in many cases a partial EHL film plus some asperity contacts. Full EHL contacts and limited diameter asperity contacts result in resistance to the flow of electrical current and act as a capacitor. If an electrical charge builds across the contacts and reaches sufficient magnitude, the charge will jump from one component to another as a spark with sufficient energy to vaporize and melt one of the components. As the process continues, many small micropits are randomly generated on the surface. The morphology of the damaged surfaces generally consists of micropits with melted bottoms and globular material indicative of melting (See Figure 3). The critical magnitude of voltage differential across the contacts does not have to be large. Reference 4 states "Some sources (EPRI, etc.) suggest that voltages greater than 5V will result in EDM bearing damage." As more and more micro craters are created the surface to the unaided eye can appear frosted and the damage at first glance can appear to be micropitting, fretting damage or debris dents. To confirm that the damage is due to electrical erosion, the damage should be examined with a Scanning Electron Microscope (SEM) for the presence of melted material as shown in Figure 3. This same mechanism is used in Electrical Discharge Machining (EDM) to intentionally remove material to manufacture parts. The severity of the damage appears to be a function of the current magnitude and the time of exposure to the current. Cross sections taken through bearing races containing EDD (Refs. 5 & 6) indicate the pits are approximately 15 to 25 µm deep and there can be a heat affected zone with tempering up to 90 µm deep and in some cases re-hardened areas up to 50 µm deep. The re-hardened areas can be prone to cracking.As the process continues, the damage can develop into equally spaced valleys that on gear teeth appear as distinct lines parallel to the lines of contact (See Figure 1) and in bearings as periodic valleys transverse to the direction of rolling, which are called flutes (See Figure 4). The reason EDD eventually manifests as fluting is not kNown but it may be a combination of the electrical charge-discharge frequency in conjunction with the mechanical vibration that develops as the size and depth of the damaged areas increase.

The sources of the electrical current that cause EDD are many and varied but can be any source that generates a voltage difference across a bearing or gear. One of the main sources of bearing fluting damage are bearings in electrical motors that are controlled by Variable Frequency Drives (VFD) using Insulated Gate Bipolar Transistors (IGBT) for pulse width modulation of the frequency. These controllers vary the speed of AC motors by converting 60Hz current into current at different frequency, which varies the speed of the AC motor. However, the high frequency switching process can generate unbalanced voltages between the motor stator and rotor that then spark across the bearings supporting the rotor. These unbalanced voltages can also be transferred to connected equipment such as gearboxes. Other electrical sources that can generate damage are improper grounding during welding, lightning strikes, and static electricity generated by fans, belts, clutches, or oil filters.

The feasibility of continuing to run a component that has experienced EDD is dependent on several factors. The most important one being the consequences of a catastrophic failure. A component in a helicopter is much more critical than say a fan drive in an HVAC system. Any highly stressed Hertzian contact such as a bearing race, rolling element, or case-hardened gear that experiences a high rate of cycles should be replaced as soon as possible since the damage is likely to progress to macropitting (Ref. 7). However, if the damage is on a through hardened gear that is not in a critical application, and the source of electricity is eliminated, then the equipment could be allowed to run with periodic inspections. Any damage that has occurred on the tooth flanks could potentially self-correct by corrective pitting and the gear set could continue to run for a long time.

Advanced fluting damage on bearing races or rolling elements can produce significant noise because the rolling elements are basically running on a washboard type surface. We cannot discuss the vibration signature of a gear with periodic EDD because it is outside our area of expertise, but a gear mesh is going to generate noise because the valleys generated at the lines of contact are periodic and will produce an impact every time the mating tooth rolls/slides over the peaks and valleys of the EDD. Fretting damage along the lines of action on the high-speed pinion of wind turbine gearboxes similar to the EDD on the pinion in (Ref. 1), produced very high noise levels and all the pinions had to be replaced. The frequency of the noise is likely to be at the mesh frequency or some multiple of mesh frequency.

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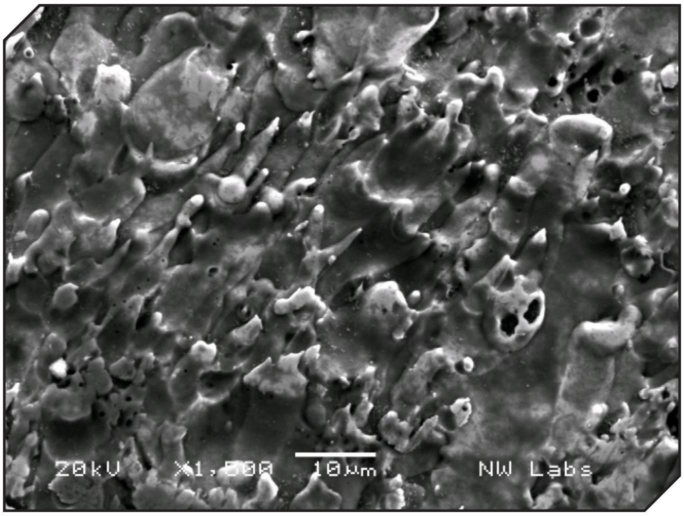

Figure 3 The morphology of the damaged surfaces generally consists of micropits with melted bottoms and globular material indicative of melting (this image appeared as Figure 2d in Ref. 1).

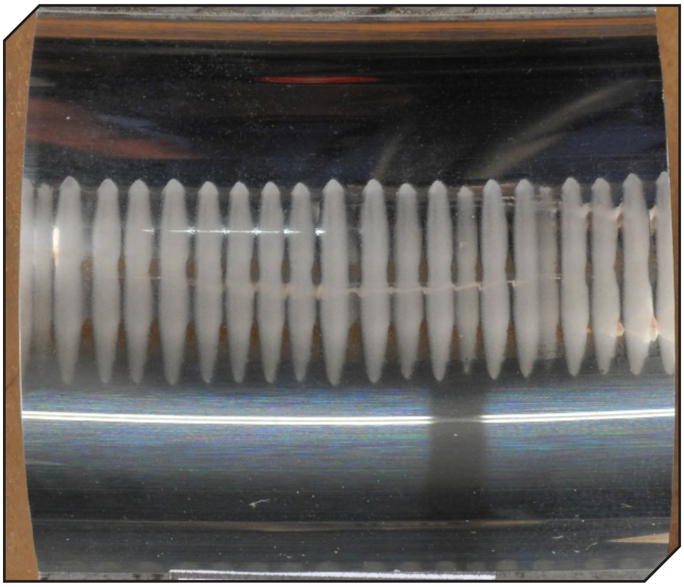

Figure 4 Fluting on the outer race of a ball bearing.

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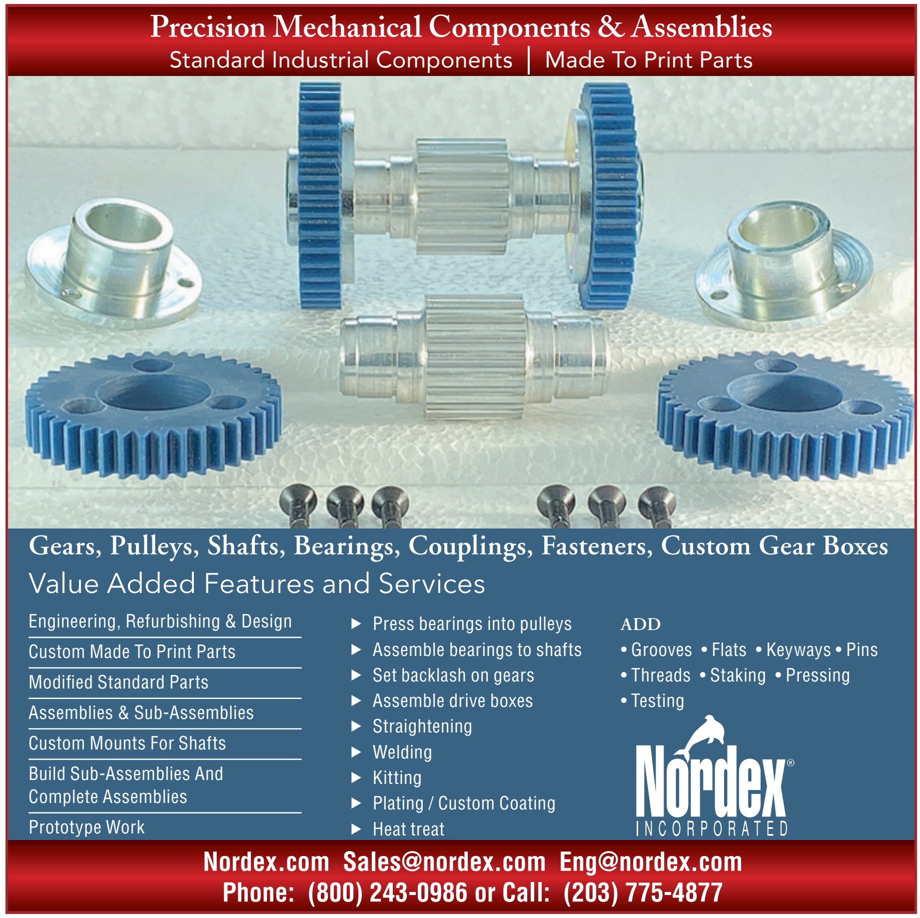
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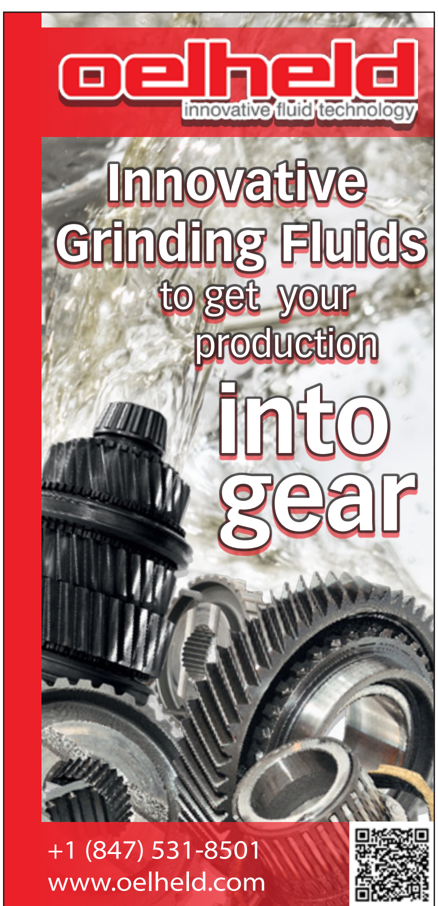
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Material Properties and Tooth Root Bending Strength of Shot Blasted, Case Carburized Gears with Alternative Microstructures

Karl Jakob Winkler, Thomas Tobie, Karsten Stahl, Christian Güntner, and Stefan Schurer

Introduction and Motivation

For most applications, components in transmissions with a high power density are case-hardened to provide a material strength which is suited to the load. The current methods commonly used for carrying out case hardening are gas and low-pressure carburizing in combination with oil or gas quenching. The heat treatment leads to a characteristic microstructure in the surface-near case layer, which significantly determines the achievable load carrying capacity properties of the gear. In the past few years, the technological development in the field of case hardening has been based on the optimization of the martensitic case layer structure. Through narrower limits and more precise definitions of the individual process steps, the range of the process outcomes has been narrowed down. Thus, the properties regarding load carrying capacity have increased within the scatter band of the achievable results, but overall, no effective growth due to the process of case carburizing was achieved.

In recent years, the main focus of the heat treatment of highly stressed, case hardened components has been on reproducibility and fulfilment of increasingly tight tolerances with regard to the carbon and hardness profile. Corresponding requirement profiles are defined in standards such as ISO 6336-5 (Ref. 11). The narrow tolerances with regard to the composition of the case layer show that the technological development of the microstructure for case carburizing is nearly exhausted. The development and testing of alternative microstructures and case layer conditions with the potential to increase the load carrying capacity have moved to the background of technological research.

In other areas of application, such as the heat treatment of rolling bearings, significant progress has been made. New impulses have been generated, for example, by the use of mixed microstructures containing bainite, martensite and retained austenite (Ref. 8) or bainitic microstructures, e.g. — "super bainite" (Ref. 3) — which have shown considerable potential for the improvement of load carrying capacities.

Most of the new approaches have improved the microstructure, which results in the increasing importance of this area of development. According to the state of the art, the essential components of the case layer should be mainly martensite and finely distributed retained austenite. But this assumption regarding case hardening is not unrestrictedly valid anymore. Preliminary tests in FVA 513 I (Ref. 14) showed that there are mixed case layer microstructures which, compared to state of the art, contained increased amounts of retained austenite of up to 60 % bainite or carbides. These mixed case layer microstructures can lead to an increase of the load carrying capacity. The application of carbonitriding as an alternative heat treatment process to carburizing has shown that the question of the stability of retained austenite is of central importance, and that the stabilization state is decisive for the strength properties of the microstructure. It should be noted in particular that microstructures with a balanced ratio of martensitic components with sufficiently stabilized austenite, bainite and retained austenite are promising.

This is the point where the research project FVA 513 III (Ref. 19) has connected. It investigated the problems identified in the literature and in the companies to develop and test new case layer microstructures. The aim of the project was to identify and safeguard increased strength properties of new case layer microstructures through heat treatment trials and structural-mechanical component tests on model samples and gearwheel tests. Selected results of this research project concerning the material properties and tooth root bending strength of shot blasted, case carburized gears with alternative microstructures are published in this paper.

State of the Art

Requirements of standards. The relevant gear standards, such as DIN 3990 (Ref. 4), ISO 6336 (Ref. 11) and AGMA 2001 (Ref. 2), respectively, and AGMA 923 (Ref. 1) specify the surface hardness and the microstructure, which have to be achieved for case hardened gears. However, these specifications are relatively brief and do not give any indication of a possible increase or reduction of the load carrying capacity, if these specifications are not complied with.

For the case hardening layer, the standards DIN 3990 (Ref. 4) and ISO 6336 (Ref. 11) intend a martensitic microstructure which must be fine-needled for material quality ME. According to ISO 6336 (Ref. 11), a bainite content of less than 10% is recommended for the material quality MQ; for the material quality ME, this limit value is a requirement. The AGMA 2001 (Ref. 2) and AGMA 923 (Ref. 1) contain separate specifications for the content of upper-bainite in the case hardening layer, for the load carrying capacities of tooth flank and tooth root. With regard to the surface durability, a maximum of 5 % for grade 2, or only traces of bainite for grade 3, are permissible. For the tooth root bending strength, these limits are slightly shifted and a maximum of 10 % bainite for grade 2 or 5% bainite for grade 3 is permissible.

According to DIN 3990 (Ref. 4), mesh and bone carbides are not permitted if they are visible at a magnification of 500 times. In ISO 6336 (Ref. 11), individual carbides with a maximum length of 0.02 mm are allowed for the material quality MQ, while only finely divided carbides are permitted for the material quality ME.

For the retained austenite content, DIN 3990 (Ref. 4) specifies a maximum amount of 30% for material quality MQ, or 20 % for material quality ME. According to ISO 6336 (Ref. 11), the maximum retained austenite content of 30 % is specified for both material qualities MQ and ME. Likewise, according to AGMA 2001 (Ref. 2) and AGMA 923 (Ref. 1), retained austenite contents of maximum 30 % are permissible for grades 2 and 3.

Research project FVA 513 I. Research project FVA 513 I (Ref. 14) is the predecessor of the research project FVA 513 III (Ref. 19), which in turn is the basis of the results published in this paper. In the research project FVA 513 I (Ref. 14) different retained austenite contents were adjusted by means of carbonitriding. The influence of the different retained austenite contents on the load carrying capacity of the tooth root and flank was investigated in comparison to case hardened reference test gears. The focus of the investigations was on the materials 20MnCr5, 18CrNiMo7-6 and 20MoCr4. The results of the investigations regarding the bending strength are shown (Fig. 1).

For the material 20MnCr5, higher tooth root bending strengths tend to result both for the non-blasted and for the shot-peened condition of the carbonitrided variant compared to the case-hardened reference. For the materials 18CrNiMo7-6 and 20MoCr4, the results show a slight decrease of the tooth root bending strength in the carbonitrided state compared to the case hardened reference. However, these results are still within a typical range for shot-peened gears and have characteristic values of the material quality MQ. In the case of the 18CrNiMo7-6 variant, it should be noted that the case hardened reference has a very high bending strength.

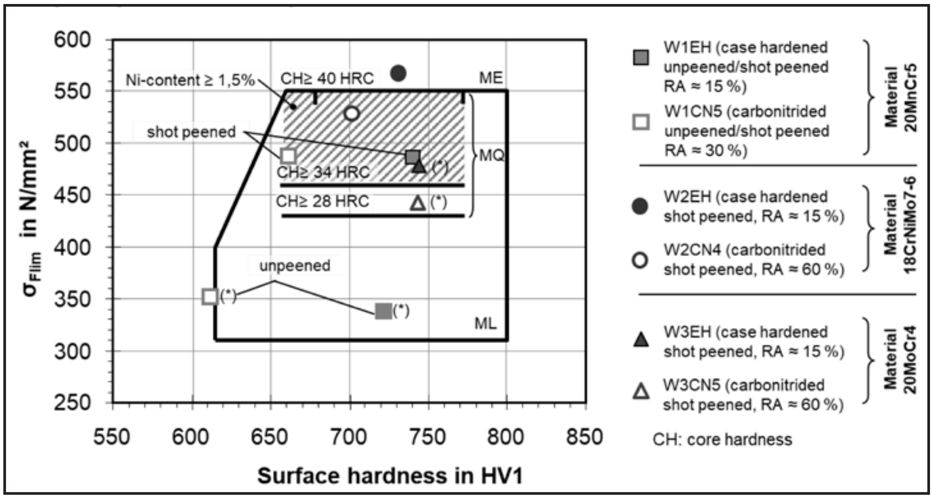


Figure 1 Classification of the determined allowable bending stress numbers for carbonitrided gears with increased amounts of retained austenite in the standard strength diagram of DIN 3990 (Ref. 4) for case-hardened gears (*reduced data points, usually about half the data points).

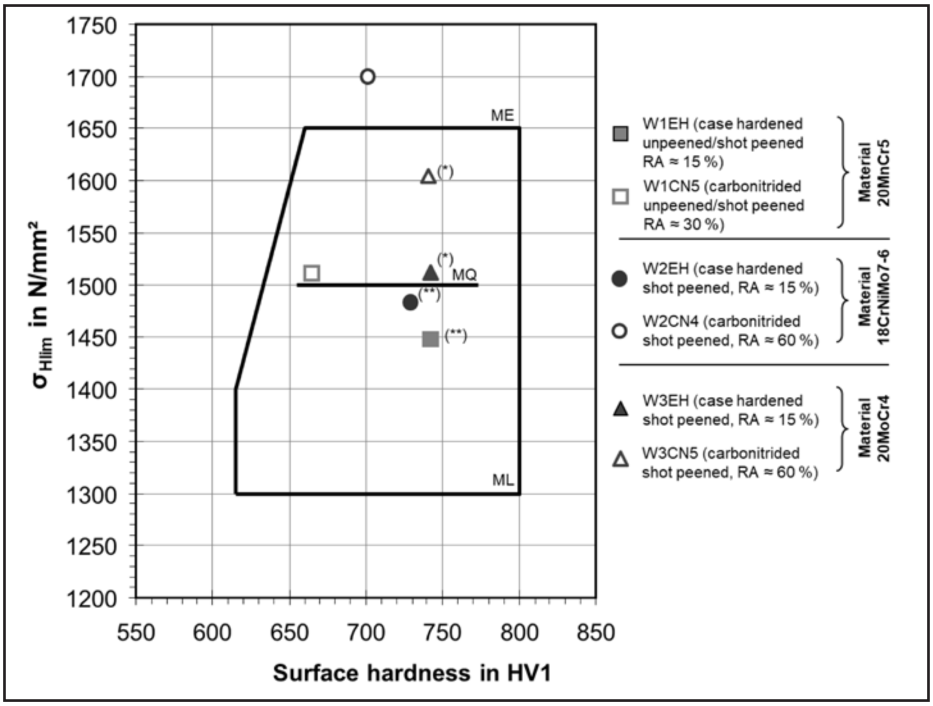


Figure 2 Classification of the determined allowable contact stress numbers for carbonitrided gears with increased amounts of retained austenite in the standard strength diagram of DIN 3990 (Ref. 4) for case-hardened gears (*reduced data points, usually about half the data points; **comparison and good correlation with results from earlier investigations (Refs. 14, 20).

With regard to the pitting load carrying capacity shown (Fig. 2), it can be seen that all variants in the carbonitrided state have a pitting load carrying capacity which is higher, and in some cases significantly higher, than the one of the case-hardened reference. The highest load carrying capacity was determined on the carbonitrided variant of the material 18CrNiMo7-6, which even exceeds the characteristic values for the material quality ME.

The results allow the conclusion that carbonitrided gears can show clear potential in the pitting load carrying capacity compared to the case-hardened reference. At the same time, the tooth root bending strength is not significantly reduced; indeed, in some cases, even a slight increase is possible.

The high-retained austenite variants of the materials 20MnCr5 and 18CrNiMo7-6 also showed promising results with regard to micropitting and wear. The scuffing load capacity was evaluated negatively, which, however, can be compensated by use of a suitable lubricant selection. Further details can be found in (Refs. 15 and 13).

Research project FVA 513 III. The publication with the title "Alternative Microstructures and Their Influence on Mechanical Properties of Case-Hardened Gears" (Ref. 10) has published selected information of the research project FVA 513 III (Ref. 19). The two variants with alternative case layer microstructures, which were compared to the reference variant, were made of the material 20MnCr5, gas carburized with different C-level and temperature controls, and mechanically cleaned by shot-blasting. Variant one had a case layer microstructure with 50% retained austenite and variant two with 30% bainite.

The flank load carrying capacity of the gears with the alternative microstructures showed a significantly increased pitting load carrying capacity in comparison to the case-hardened reference (Ref.10). The tooth root bending strength, by contrast, was not influenced in a negative way for the shot blasted gears. All in all, the results of the investigations of FVA 513 I (Ref. 14) could be confirmed, and prove that certain alternative microstructures in the case-hardened layer of gears do not necessarily have a negative impact on the load carrying capacity; in fact, they may even have a great potential to increase — especially the pitting load carrying capacity.

Retained austenite. By increasing the carbon content in a component during case hardening, it is possible to increase the residual austenite content under constant quenching conditions (Ref. 21). It can be seen from the literature that residual austenite contents of about 30% have positive effects on the flank load carrying capacity (Ref. 18) and the pitting load carrying capacity (Ref. 17) without causing a significant drop in the tooth root bending strength. Weck, Leng and Vinokur (Refs. 26–27) confirm the positive influence of highly retained austenite boundary layers on the pitting load carrying capacity, which is attributed to the good hardening capacity of austenite and finely distributed carbides. Strasser (Ref. 24) shows a small influence of the residual austenite content on the achieved tooth root bending strength of gears, whereby the effects occur less clearly in the shot-peened condition. Lechner (Ref. 12) describes the decrease of the scuffing load capacity for increased retained austenite contents due to the poorer thermal conductivity and the reduced adhesion of the lubricant in comparison to martensite. In addition, the reactivity of additives contained in the lubricant with the martensitic case layer is reduced due to increasing proportions of retained austenite (Ref. 9). Investigations of the micropitting resistance, on the other hand, show a positive influence of increasing retained austenite contents (Ref. 16).

In connection with the results from FVA 513 I (Ref. 14), this indicates that the state of the art guideline values for residual austenite contents of 25–30 % do not generally lead to the highest load carrying capacity results.

Bainite. Current developments in the field of rolling bearings (Ref. 25) indicate that a bainitic case layer can lead to improved properties concerning the load carrying capacity. A mixed structure of martensite and bainite produced by an incomplete isothermal transformation showed even stronger strength increases (Ref. 7). Similar results with partially bainitic case layers are kNown from a research project on the influence of the core hardness on the bending strength (Ref. 23).

Investigations on the tooth root bending strength (Ref. 22) have shown that a combination of too-high transformation temperatures and a clearly pronounced internal oxidation lead to a negative influence on the test results. A significant increase of the tooth root bending strength could be achieved by removal of the internal oxidation layer, as well as by shot peening. The choice of the carbon content in the case layer and the degree of bainitization are therefore of secondary importance.

Aim of Investigation

The microstructure of martensite and finely dispersed retained austenite is considered the standard for high-strength case layers. Investigations in the research project FVA 513 I (Ref. 14) have shown that a carbonitrided variant with a high content of retained austenite increases the tooth flank carrying capacity, while negative influences on the tooth root bending strength were not determined. Within a previous publication (Ref. 10) of the research project FVA 513 III (Ref. 19), the results of FVA 513 I (Ref. 14) were confirmed for two selected variants.

The aim of this report is to state the results of the investigations on further gear variants with alternative microstructures, such as material properties like hardness depth profiles, residual stress conditions and retained austenite contents, as well as their influence on the tooth root bending strength.

Test Program, Gears and Rigs

Test variants. Within the framework of the research project FVA 513 III (Ref. 19), different approaches were developed to generate alternative microstructures with the aim of raising the pitting load carrying capacity, while at the same time avoiding a negative influence on the tooth root bending strength.

The following alternative microstructures conditions were examined in detail:

- High retained austenite contents above 50% due to increased carbon or nitrogen contents, in combination with intermediate phase fractions
- Carbonitriding with optimized thermal post-treatment
- Generation of increased bainite contents of up to 30% in the case-hardening layer
- Creation of a specific variant with adjusted grain boundary carbides

Each variant with a different alternative microstructure is made of the case-hardening steels 20MnCr5 and 18CrNiMo7-6. Due to the low sulphur content in the investigated 20MnCr5 material, very few inclusion failures occur. In addition, it appears that the material achieves better results than a material with a comparatively high sulphur content. The material 18CrNiMo7-6 is strongly segregated, making heat treatment more difficult — especially during the carburization and subsequent bainitic transformation. In order to compare the heat treatment processes that were carried out, a case-hardened reference variant was developed for each test material; a summary of the test variants is shown (Table 1).

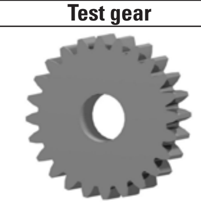
Test gears. For the pulsator test gears used in the experimental load carrying capacity investigations, there is an

Table 1 Test variants

Material	Variant	Designation	Heat Treatment	Quenching	Tempering
20MnCr5 + 18CrNiMo7-6	case carburized	R	gas carburizing	60°C, oil	180°C, 2h
	50% retained austenite gas carbonitrided	RA50GCN	gas carbonitriding	60°C, oil	180°C, 2h
	50% retained austenite carbonitrided	RA50LPCN	low pressure carbonitriding	10 bar, nitrogen	180°C, 2h
	10% bainite	B10	case austempering	T_B, salt	180°C, 2h
	50% retained austenite and optimized thermal post treatment at 150°C	TPT150	gas carboni triding	60°C, oil	150°C, 2h
	50% retained austenite and optimized thermal post treatment at 280°C	TPT280 carbonitriding	gas	60°C, oil	280°C, 2h
	grain boundary carbides	C	low pressure carburizing	60°C, oil	180°C, 2h

extensive kNowledge base at the institute, since this specific geometry has already been used in a large number of research projects. Therefore, the connection to already completed and ongoing research projects, as well as existing load carrying capacity standards, is guaranteed. The gear cutting of the pulsator test gears was carried out with the aid of a hob in protuberance design. For the correlation to industrial manufacturing processes, as well as to the specifications of the standards and their load carrying capacity values, after the heat treatment all test gears were mechanically cleaned by shot blasting in accordance with industrial practice. Neither the flanks nor the tooth root areas of the test gears were grinded after the heat treatment. An overview of the most important geometry data, as well as a geometry draft, is provided (Table 2).

Table 2 Main geometry data of the pulsator test gears

Description	Symbol	Unit	Value	Test gear
normal module	m_n	mm	5	
number of teeth	z	[-]	24	
tooth width	b	mm	30	
normal pressure angle	α	°	20	
helix angle	β	°	0	

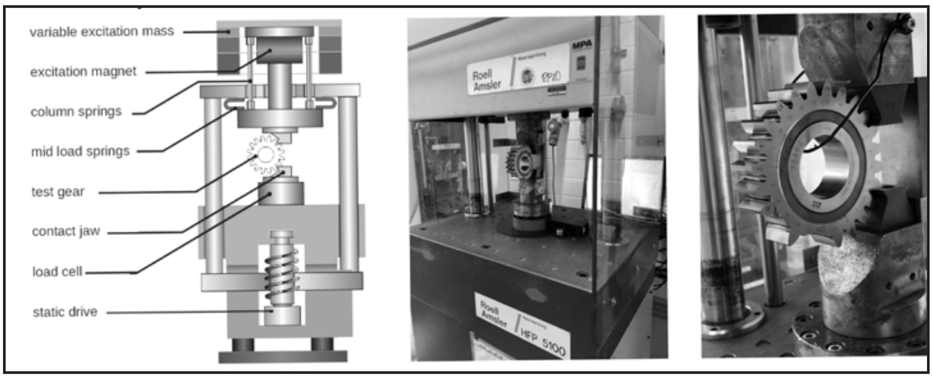


Figure 3 Pulsator test rig with exemplary gears similar to the test gears.

The case-hardening steels 20MnCr5 and 18CrNiMo7-6 were used for the investigations; these materials are commonly used steels in the gear industry. The corresponding requirements for the materials on delivery were defined as follows:

- Chemical composition and documentation according to DIN EN 10084 (Ref. 5)
- Delivery condition: verification in the form of a 3.1 certificate according to EN 10204 (Ref. 6)
- Minimum degree of deformation 4, degree of deformation 6 should be aimed at
- Limited hardenability scatter band according to H- or HH
- Material quality ME according to ISO 6336-5 (Ref. 11)

The complete manufacturing process of the test gears, as well as the initial condition of the semi-finished products of the materials, were comprehensively documented.

Test rigs. The bending fatigue tests were carried out by means of an electromagnetic pulsating test rig (Fig. 3), and described in the following, according to (Ref. 10): the test rig consists of a machine frame that incorporates test device, load cell and test gear. The pulsating load is generated by a dynamic actuator that is connected to a dynamic spring by the exciting magnet, which is directly connected with the pulsating crossbeam by two-rod springs. The test gears were symmetrically clamped and tested over four teeth between two jaws. The exact position of the test gear in relation to the clamp jaws, i.e. — the exact angle and point of load incidence — was adjusted by means of a special jig. Flank angle deviations were compensated by means of a precision adjustment so that a uniform load distribution across the whole face width can be assumed. The test gear was friction-locked between both jaws, therefore an underload was needed that was always lower than 10% of the test load. The test runs were stopped after $6 \cdot 10^6$ load cycles.

Results

Material Properties

Microstructure. When considering the case layer microstructure in the tooth root in the non-etched state, the following is noticeable: the internal oxidation depth of the 20MnCr5 material variants (with the exception of the 20MnCr5 variant RA50LPCN, no internal oxidation due to the heat treatment process) is always higher in comparison with the variants of the material

Table 3 Exemplary comparison of internal oxidation in the tooth root, non-etched.

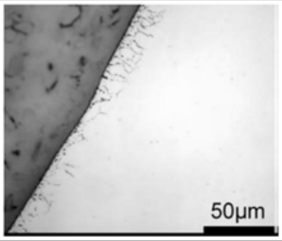
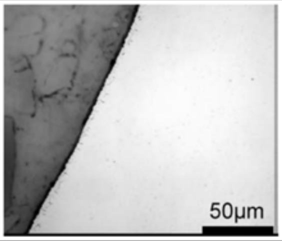
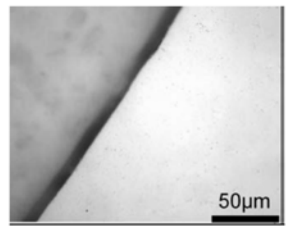
Reference – R	Reference – R	50% RA low pressure carbonitrided – RA50LPCN
		
Material: 20MnCr5	Material: 18CrNiMo7-6	Material: 18CrNiMo7-6

Table 4 Case layer microstructures of the variants made out of 20MnCr5.

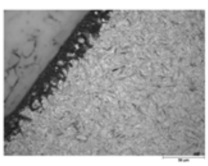
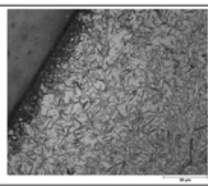
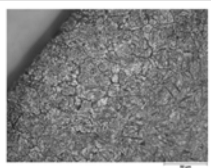
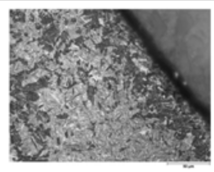
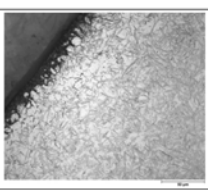
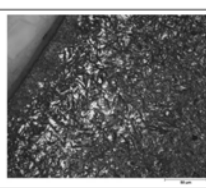
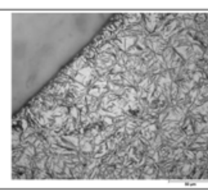
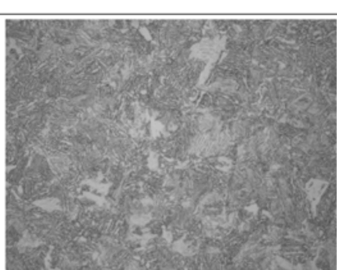
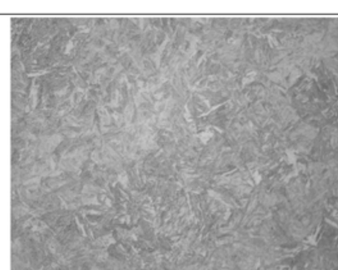
Material 20MnCr5			
Reference – R	50% RA gas carbonitrided – RA50GCN	50% RA low pressure carbonitrided – RA50LPCN	10% bainite – B10
			
martensite with 10 – 20% metallographically determined retained austenite and non-martensitic case layer microstructure	martensite with 40 – 50% metallographically determined retained austenite and non-martensitic case layer microstructure	martensite with 40 – 50% metallographically determined retained austenite	martensite with 10 – 20% metallographically determined retained austenite and non-martensitic case layer microstructure, area with locally increased bainite or troostite content
optimized thermal post-treatment at 150°C – TPT150	optimized thermal post-treatment at 280°C – TPT280	grain boundary carbides – C	
			
martensite with 50 – 60% metallographically determined retained austenite and non-martensitic case layer microstructure	martensite with 0 – 10% metallographically determined retained austenite and non-martensitic case layer microstructure	martensite with 50 – 60% metallographically determined retained austenite and carbides	

Table 5 Exemplary core microstructure of the materials 20MnCr5 and 18CrNiMo7-6.

Reference – R	Reference – R
	
Material: 20MnCr5	Material: 18CrNiMo7-6

18CrNiMo7-6. Maximum internal oxidation depths for the material 20MnCr5 varies from 15–25 µm, and the material 18CrNiMo7-6 varies from 5–10 µm. Table 3 shows exemplary photographs.

In Table 4, detailed microstructure images of the variants made from the material 20MnCr5 are shown, along with a short description of the microstructure. The variants made from the material 18CrNiMo7-6 show very similar case layer microstructures and are thus not specifically depicted. The reference R made of the material 20MnCr5 shows a case layer microstructure of martensite with 10–20% metallographically determined retained austenite and a non-martensitic case layer microstructure. This microstructure is typical for a case-hardened gear. The variants with 50% retained austenite, carbonitriding RA50GCN and low-pressure carbonitriding show high amounts of retained austenite at metallographically determined 40–50%. The case layer microstructure of the variant with 10% bainite B10 consists of martensite with 10–20% metallographically determined retained austenite, bainite and a non-martensitic case layer microstructure. The image shows an inhomogeneous microstructure and segregations with areas of locally high bainite content, as well as troostite resulting from the heat treatment. For the variant with an optimized thermal post-treatment at 150°C TPT150, the microstructure is comparable to the variants RA50GCN, as well as RA50LPCN with additionally, finely divided carbides recognizable. For the variant with an optimized thermal post-treatment at 280°C TPT280, the initially high amounts of retained austenite were converted by the thermal post-treatment, resulting in significantly lower retained austenite value of metallographically determined 0–10%. The carbides variant C shows high retained austenite amounts of metallographically determined 50–60%, as well as grain boundary carbides.

The core microstructure of the material 20MnCr5 shows for all heat treatment variants a bainitic structure, whereby more upper- as lower-bainite is present. All the core microstructures of the material 18CrNiMo7-6 show a bainitic structure, where lower than upper-bainite is present. This correlates with the different core hardness values of the two materials. Exemplary core microstructures of the reference variants R of both materials are shown in Table 5.

Hardness. The determination of the hardness depth gradients was carried out at the left and right side of the flank and root of an unloaded, non-grinded and shot blasted pulsator wheel tooth. Table 6 shows the hardness depth profiles for all variants made of the material 20MnCr5. The hardness depth profiles of the material 18CrNiMo7-6 were comparable to the profiles of the material 20MnCr5. The two main difference were that the values of the core hardness at the flank and tooth root were more comparable and did not deviate as much for the material 18CrNiMo7-6 as the core hardnesses of the material 20MnCr5, and that the values of the core hardness of the material 18CrNiMo7-6 were consistently 50–150 HV1 higher than the values of the material 20MnCr5. Both observations correlate to the higher hardenability of the material 18CrNiMo7-6, compared to the material 20MnCr5.

All variants with exception of the variant with 10% bainite B10 show steady hardness depth profiles with limited scatter. The hardness depth profiles of the tooth flank and tooth root are comparable for the variants RA50LPCN and C. For the other variants, the hardness depth profiles of the tooth root are comparable to the tooth flank near the surface, but decrease stronger towards the core. The hardness depth profiles of the right and the left side of the tooth flank and the tooth root compare very well, with exception of the variant with 10% bainite B10.

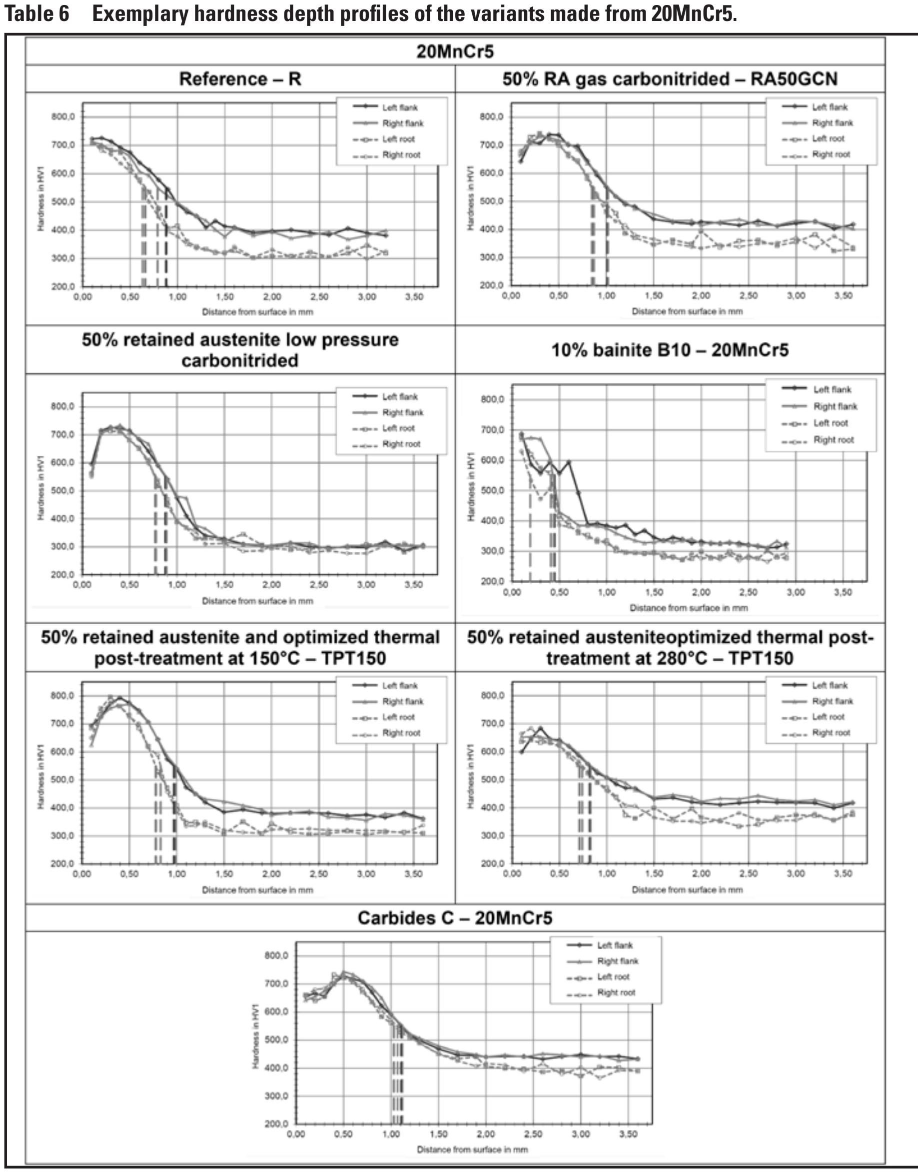
The reference R shows a hardness depth profile, which is typical for case-hardened gears of this size and material. The surface hardness measured in a material depth of 0.1 mm is approximately 700 HV1 and the case-hardening depth (CHD) with a hardness limit of 550 HV is in a range of 0.6–0.9 mm, which is inside the common recommendation of $CHD_{550HV} = 0.1–0.2 \cdot m_n = 0.5–1.0$ mm. Within the range, the tooth root shows the smaller CHD values compared to the flank. The core hardness values range from 300 HV1 for the tooth root to 400 HV1 for the tooth flank.

The variants RA50GCN, RA50LPCN, TPT150 and C all show a decrease of the hardness values towards the surface, which correlates with high-retained austenite contents. The surface hardness values range from 570 HV1 for the tooth root of RA50LPCN to 700 HV1 for the tooth flank of TPT150. The variant TPT280 with low-retained austenite contents does not show a hardness decrease towards the surface, but rather states a steady plateau at around 650 HV1. For the variants RA50GCN, RA50LPCN, TPT150 and TPT280 the core hardness ranges between 300–400 HV1, and the CHD ranges between 0.7–1.0 mm. The core hardness of the carbon variant C ranges from 400 HV1 for the tooth root values to 450 HV1 and the CHD reaches values of 1.0 –1.2 mm.

The largest differences in the measured hardness depth profiles are shown by the variant with 10% bainite B10 where, due to the inhomogeneous microstructure and segregations, strong fluctuations occur in the hardness measurements. The surface hardness has larger differences between the right and the left tooth root, where the surface hardness scatters from 630–690 HV1. The CHD is below the recommended minimum value of 0.5 mm and the core hardness ranges from 280 HV1–340 HV1.

The bar graphs in Table 7 show the determined surface and core hardness of all the variants examined. The variants of the material 20MnCr5 tend to show slightly higher-determined surface hardness in comparison to the material 18CrNiMo7-6. The highest surface hardness with values of almost 700 HV1 can be found for the reference

Table 6 Exemplary hardness depth profiles of the variants made from 20MnCr5.



of both materials. The variant with 50% retained austenite and low-pressure carbonitriding RA50LPCN shows the lowest surface hardness values for the material 20MnCr5 and for the material 18CrNiMo7-6, the variants with 50% retained austenite and carbonitriding RA50GCN, and even more the carbides variant C show a surface hardness of less than 600 HV1. For the individual variants, it is pointed out that there can be hardness reduction towards the surface. The minimum requirement for surface hardness of case-hardened gears according to part 5 of ISO 6336 (Ref. 11) is 660 HV1, which is not reached by some variants. Regarding the core hardness, the majority of the variants made of the material 18CrNiMo7-6 show an almost identical core hardness, which is about 440 HV10, and in a usual range for this material at the given gear size. The relatively low core hardness of the variant with 10% bainite B10 made of the material 18CrNiMo7-6 is a result of the heat treatment. The core hardness of the variants of the material 20MnCr5 assumes values at around 300 HV10 to 370 HV10, and is therefore always below the core hardness of the corresponding variant made of 18CrNiMo7-6. The comparatively high core hardness of the carbides variant C of the material 20MnCr5 is based on the quenching carried out (oil quenching).

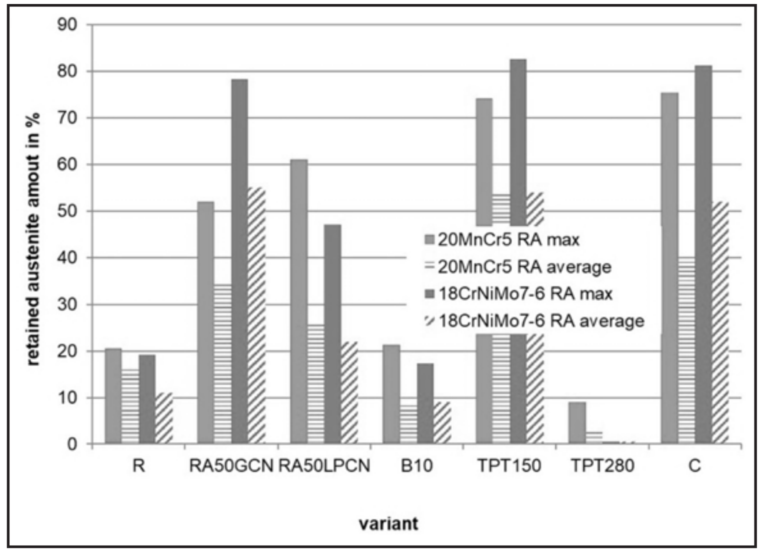


Figure 4 Comparison of the radiographically measured retained austenite amount, maximum and average values.

Residual stress and retained austenite. Table 8 shows a comparison of the residual stresses measured by an X-ray diffractometer at the surface, as well as the occurring maximum residual compressive stresses in the area of the 30° tangent in the tooth root. On the surface, all variants show residual compressive stresses, which occur in a range of −300 up to −500 N/mm². The occurring residual compressive stress maxima include a range from −450 up to −700 N/mm². In addition, for each variant the material depth position of the maximum residual compressive stress is shown in µm. It turns out that for all variants the maximum residual compressive stress is very close to the surface, which correlates with the shot blasting treatment.

Figure 4 shows the residual austenite content of the shot blasted pulsator test gears based on measurements of an X-ray diffractometer. The maximum values, as well as the average retained austenite contents over a material depth of 20–200 µm, are displayed. The first 20 µm are not taken into account for the average, since there is a non-martensitic case layer microstructure present in this surface near layer and the result would be falsified. Overall, there is a very large variation regarding the retained austenite content. The references R lie in a typical area for the present heat and shot-blasting treatment. Furthermore, the high retained austenite contents of the carbide variants are noticeable. This correlates with the increased carbon content in the case layer. For the variants with a thermal optimized post-treatment, the extreme decrease of the retained austenite content between the tempering temperatures 150°C and 280°C is remarkable. This result is the consequence of further conversion of residual austenite

Table 7 Summary of the measured surface and core hardness values.

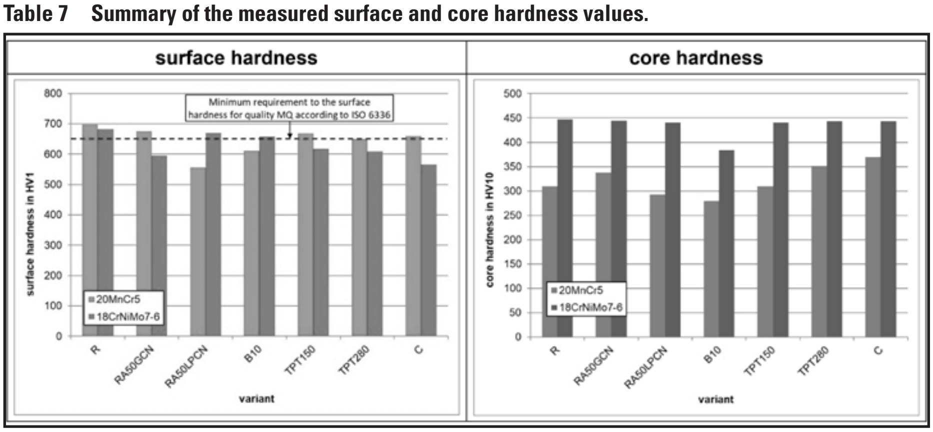
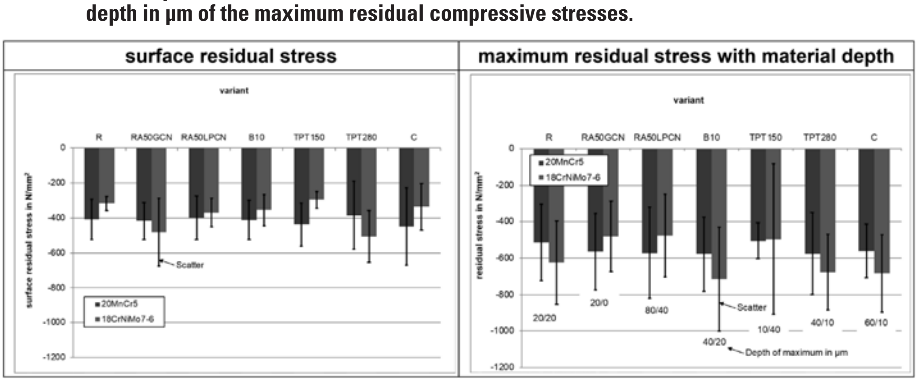


Table 8 Summary of the measured surface and maximum residual stresses as well as the material depth in µm of the maximum residual compressive stresses.



into martensite and bainite at the temperatures of 280°C, and has been confirmed in FVA 513 I (Ref. 14).

Tooth Root Bending Strength

Results of the test variants. Figure 5 shows the nominal tooth root bending strength for a failure probability of 50% ($\sigma_{F0\infty,50\%}$) of all investigated variants in a bar chart and compares the results with the case-hardened references R. In addition, the scatters of the individual variants, as well as a scattering range of ± 5% around the nominal tooth root bending strength of the case-hardened reference made of the material 20MnCr5, is depicted; it shows that the results of all variants lie within the illustrated scatter range. Furthermore, all variants show a test scattering that is still common for case-hardened gears. Overall, it can be said that the different heat treatment processes and alternative microstructures do not have a significant negative influence on the tooth root bending strength concerning long life for the shot-blasted condition. In the present case, a few variants made of the material 18CrNiMo7-6 tend to show higher scatters than the variants made of the material 20MnCr5. The higher scatters of the variants made of the material 18CrNiMo7-6 are presumably due to inhomogeneities in the base material. For all results it must be taken into account that the test gears were mechanically cleaned by shot-blasting and that the shot-blasting treatment may influence or cover up certain other effects such as different surface hardnesses or internal oxidation.

The results in the limited life range were examined more closely. Tables 9 and Table 10 show the average number of cycles to failure achieved for a failure probability of 50 % for the low and high limited life strength. In the limited life part of the S-N curve, measurements on two load levels where performed, i.e. — one measurement on a high load level with lower numbers of cycles and one measurement on a low load level with higher numbers of load cycles. The tests in the low limited life strength were performed at a pulsator normal force of $F_{Pn} \approx 80\,kN$ respectively $\sigma_{F0} \approx 1{,}350$ N/mm^2 and in the range of high limited life strength at $F_{Pn} \approx 95\,kN$ and $\sigma_{F0} \approx 1{,}600$ N/mm^2. Additionally, the logarithmic scatters s_{log} are shown. With the low as well as the high limited life strength, there are clear differences between the variants.

Most variants made of the material 18CrNiMo7-6 tend to have longer running times than the comparable variants made of the material 20MnCr5. In the area of low limited life strength, the variants with 10 % bainite B10 and the carbides variant C made of the material 18CrNiMo7-6 and for the material 20MnCr5 the variant with 10% bainite B10 have the highest numbers of load cycles. The variant with optimized thermal post-treatment at 280°C TPT280 made of the material 18CrNiMo7-6 achieved the shortest number of load cycles, whereby the very high scatter of this variant has to be taken into account. For the material 20MnCr5, the variant with 50% retained austenite and

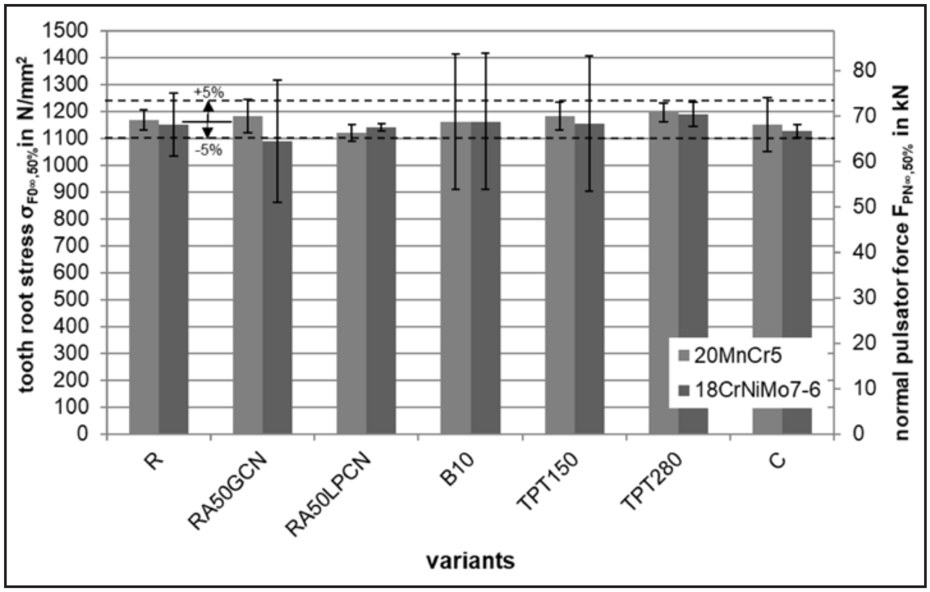


Figure 5 Results of the nominal tooth root bending strength at a 50% failure probability ($\sigma_{F0\infty,\,50\%}$) for all test variants.

Table 9 Results of the low nominal tooth root bending strength for limited life at a failure probability of 50% and the corresponding scatter for all variants.

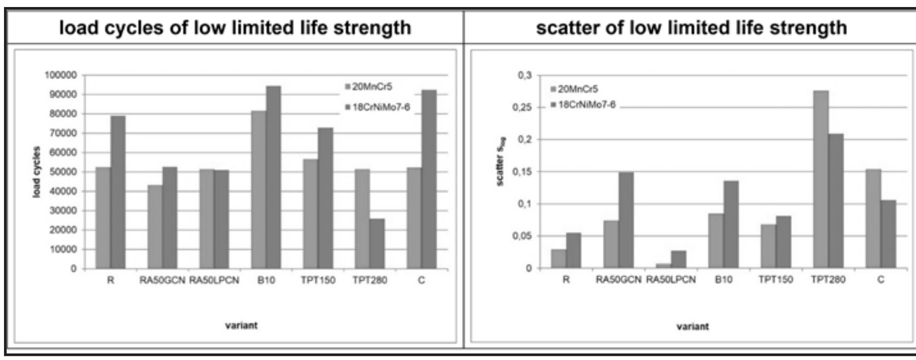
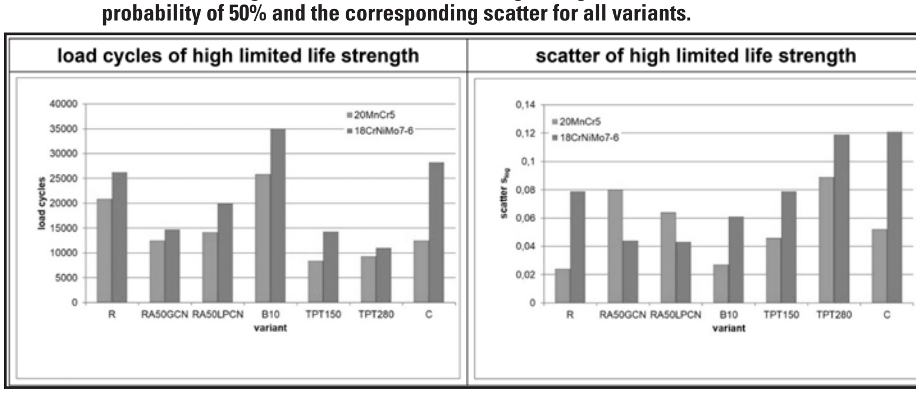


Table 10 Results of the high nominal tooth root bending strength for limited life at a failure probability of 50% and the corresponding scatter for all variants.



carbonitriding RA50GCN shows the lowest number of load cycles, while showing a scatter comparable with the case-hardened reference variant.

For the high limited life strength, the variants with 10% bainite B10 and the carbides variant made of 18CrNiMo7-6, as well as the variant with 10% bainite B10 made of 20MnCr5, have the highest numbers of load cycles. They exceed the number of load cycles of the respective case-hardened references. This characteristic can be observed at the low limited life strength as well. The variants with an optimized thermal post-treatment at 150°C TPT150 and 280°C TPT280, as well as the variant with 50% retained austenite and gas carbonitriding RA50GCN made of 18CrNiMo7-6, achieved the lowest numbers of load cycles. For the material 20MnCr5, the variants with an optimized thermal post-treatment at 150°C TPT150 and 280°C TN150, as well as the carbides variant C, showed the lowest running times with a slightly higher scatter compared to the case-hardened reference.

All the variants examined show a comparable tooth root bending strength for long life compared to the references R for both materials. However, in some cases, there are clear differences in the area of limited life strength. All variants show a nominal tooth root bending strength for long life at a 50% probability of failure, which is within the range of expectations for case-hardened, shot-blasted gears of this gear size. Taking into account the test scatter in the limited life strength range, no significant influence on the tooth root bending strength by the respective alternative microstructure states could be determined on the basis of the available pulsator tests. It should be noted, however, that all test gears examined had a tooth root area that was mechanically cleaned by shot blasting. The residual compressive stresses introduced by the shot-blasting in the area near the surface may have resulted in covering individual influences of the different microstructure variants. With regard to the conditions of the load carrying capacity according to the standard ISO 6336, part 5 (Ref. 11), it should be mentioned that the tooth root load carrying capacity values for gearwheels specified in this standard are applicable for a shot blasted condition and therefore the load carrying capacity values determined in this research work can be directly compared to the values of the standard. In the area of limited life strength, it can be assumed that the influence of the residual stresses induced by the shot-blasting decreases with increasing stress. The microstructure and hardness properties come more to the foreground as the load rises. This explains the partly different load carrying capacity properties of the individual variants in the area of tooth root bending strength for long life and limited life. It should be noted, however, that there is a statistically limited coverage, especially in the area of limited life strength. Particularly noteworthy is the variant with 10% bainite, which has a higher limited life strength for both materials than their respective case-hardened reference; this is attributed to the high toughness of the microstructure.

A detailed examination of the fractures of the carbide variants C in the cross-section shows that the crack runs along the grain boundary carbides. An exemplary crack course is shown (Fig. 6) for the variant made of the material 20MnCr5.

Classification into the State of Art and Discussion

The experimental investigations concerning the tooth root bending strength in the previous project FVA 513 I (Ref. 14) were carried out on pulsator test gears in non-blasted or specifically shot-peened condition. Among others, the case-hardened, shot-peened reference variants W1EH made of 20MnCr5 and W2EH made of 18CrNiMo7-6, as well as the carbonitrided, shot-peened variants W1CN5 made of 20MnCr5, and W2CN4 made of 18CrNiMo7-6, each with a high content of retained austenite in the case layer, were investigated. The variants made of 20MnCr5 additionally underwent investigations on the tooth root bending strength with a non-blasted condition. For the material 20MnCr5, comparable tooth root bending strength values could be determined for case-hardened and carbonitrided conditions. This applies to both the non-blasted and the shot peened condition. As seen (Fig. 7), the variants of the material 20MnCr5 investigated in the current project show almost identical tooth root fatigue strength values for case-hardened and gas carbonitrided

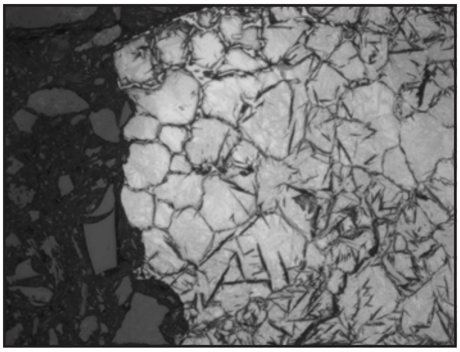


Figure 6 **Exemplary illustration of the crack course of a tooth root fracture in the cross-section of the carbide variant C made of the material 20MnCr5.**

Figure 7 **Comparison of the results of the tooth root bending strength of case-carburized and gas carbonitrided gears with different blasting treatments.**

conditions with high contents of retained austenite. The test wheels were examined in a shot blasted condition. In FVA 513 I (Ref. 14), the ned gears made out of 18CrNiMo7-6 show a slightly higher tooth root bending strength for the case-hardened material compared to the carbonitrided material. In FVA 513 III (Ref. 19), the tooth root bending strength of shot-blasted gears made out of 18CrNiMo7-6 showed that the case-hardened variant is also slightly stronger than the gas carbonitrided variant. The results prove that the tooth root bending strength of the material 20MnCr5 is almost identical for the respective blasting state in both the case-hardened and the gas-carbonitrided state. For the material 18CrNiMo7-6, it can be seen that the tooth root bending strength for the carbonitrided variants are slightly below those of the case-hardened variants. This applies to both the shot-blasting and the ning. In addition, it should be noted that the tooth root bending strength values of the material 20MnCr5 are almost identical for the shot-blasted and ned condition, whereas in the case of the material 18CrNiMo7-6 a clear increase in the load-bearing capacity is proven by ning. At the same time, a possible influence of the material and heat treatment batch cannot be excluded. Overall, it can be seen that the tooth root bending strength increases significantly as a result of a blasting treatment. The characteristic values for the long life strength lie within the usual range according to the state of kNowledge for a respective blasting state. Thus it can be shown that the results from FVA 513 III (Ref. 19) are in good agreement with the results from FVA 513 I (Ref. 14). In comparison to the respective case-hardened reference, no significant reduction of the tooth root bending strength by carbonitriding with a high-retained austenite content was found.

In Figure 8, the determined tooth root bending strength values of the individual variants are entered in the standard strength diagram according to ISO 6336 (Ref. 11). The variants marked with * are estimated strength values based on fewer data points. For additional comparison, strength values for case-carburized and shot-blasted gears made of the material 18CrNiMo7-6 and case-carburized and shot-blasted gears made of the material 16MnCr5 are given from the literature (Ref. 16). As stated, the tooth root bending strength values are all within a scatter range, which would still be common for case-hardened gears. Within this scatter range, the variant with an optimized thermal post-treatment at 280°C TPT280 made of 20MnCr5 has the highest, and the variant with 50% retained austenite and gas carbonitriding has the lowest tooth root bending strength.

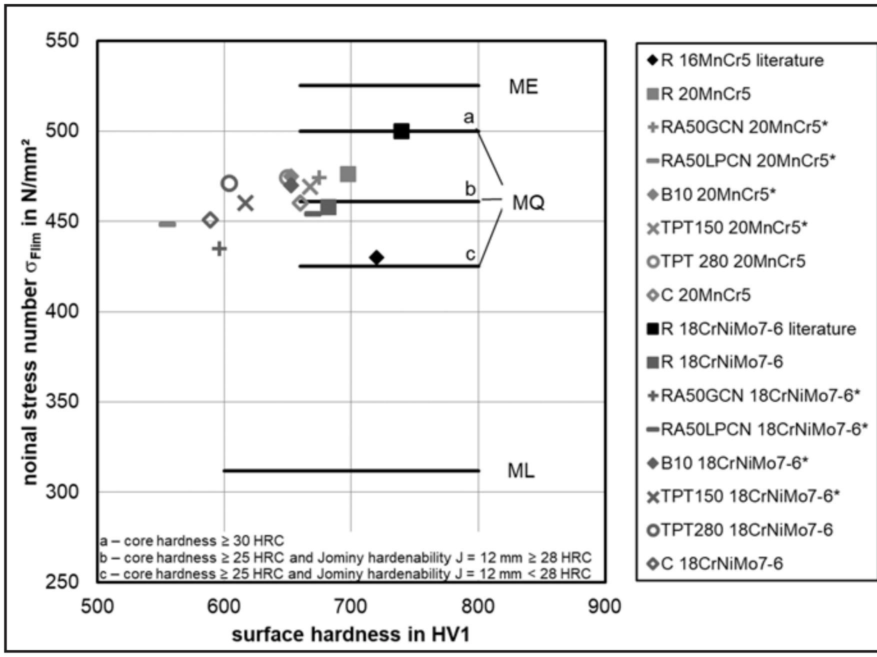


Figure 8 **Classification of the determined allowable contact stress numbers for the examined variants in the standard strength diagram of ISO 6336 (Ref. 11) for case-hardened gears (*reduced data points, additional values from literature [Ref. 16]).**

Conclusion

According to the current state of knowledge and previous experience, a case layer microstructure consisting of martensite and less than 30% retained austenite is considered highly sustainable. In the past, a lot of development work was done in the field of case-hardening with the aim of optimizing this case layer microstructure to meet the requirements of highly stressed components such as gears.

In the context of the research project FVA 513 I (Ref. 14), it was shown that a carbonitrided variant with a high-retained austenite content of up to 65% showed an increased tooth flank load carrying capacity without negative influence on the tooth root bending strength.

On the basis of these results, alternative case layers to the ones specified in standards such as ISO 6336 (Ref. 11) were specifically selected for this present paper. The shot-blasted gears with alternative microstructural conditions were investigated in detail concerning material properties and their influence on the tooth root bending strength.

The main results of these investigations are presented in the following conclusions:

- Gears with alternative microstructures that show inhomogeneities and segregations lead to unsteady and fluctuating hardness depth profiles, and possibly undesirable case-hardening depths.
- The variants with alternative microstructure made out of the material 20MnCr5 show greater fluctuations in the hardness depth profiles and values, compared to the respective variants made of the material 18CrNiMo7-6.
- The maximum residual compressive stresses of the shot-blasted gears with alternative microstructures lie relatively near to the surface.
- The shot-blasted gears of the carbides variant C did not fail prematurely, as assumed due to the internal notch effects of the carbide precipitates on the grain boundaries, but show a comparable tooth root bending strength as the case-hardened reference.
- In the limited life range of shot blasted gears, and with the exemption of the variant TPT280, the variants made of 18CrNiMo7-6 have a higher tooth root bending strength compared to the variants made of 20MnCr5.
- In the limited life range of shot-blasted

gears and comparing within one material, the microstructure can increase or decrease the tooth root bending strength significantly.

- When applying shot-blasting after the heat treatment, the examined alternative microstructures do not lead to a significant increase, nor to a decrease of the tooth root bending strength for long life.
- The tooth root bending strength values for long life are comparable and do not show any significant differences between the materials 20MnCr5 and 18CrNiMo7-6.
- Regarding the tooth root bending strength, certain alternative microstructures, which are different to the recommendations of part 5 of the standard ISO 6336 (Ref. 11), can be tolerated — especially if the gears are designed for long life. Additionally, the alternative microstructures may have a high potential to increase the tooth flank (contact) load carrying capacity.

For more information.
Questions or comments regarding this paper? Contact Jakob Winkler at *j.winkler@fzg.mw.tum.de.*

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Psychoacoustics Applied to eDrive Noise Reduction

Dr. Hermann J. Stadtfeld

Physical Effects Causing Transmission Noise

Transmissions in electric vehicles appear to require new and different mechanisms for the reduction of the high pitch noise they are emitting. If the question is asked why the frequency of the eDrives noise is significantly higher than the frequencies in conventional automotive transmissions, then the answer is that the transmission input RPM is higher by a factor 3 to 10. Basically this means the physical phenomena which generate the noise are the same phenomena that generate noise in a conventional transmission. This means the tooth mesh frequency and its higher harmonics are also responsible for the high pitch noise emitted from eDrives.

High pitch noise is recognized as more annoying than low pitch noise. Although the same effects are responsible for the noise in both conventional and electric vehicle transmissions, the same disturbance which was tolerable in a conventional vehicle with an internal combustion engine becomes now a deciding factor of why to buy one vehicle versus another. The importance of small tooth mesh impacts which were rated as acceptable in the past becomes critical in connection with an eDrive.

Cylindrical gears as well as bevel and hypoid gears have the same identical noise generation principles, and both can be reduced with the same noise reduction mechanisms.

- Chapter 9 introduces the phenomena between noise generation, analysis and recognition by the human ear. The acknowledgements and conclusion of chapter 9 are then applied to two different levels of noise reduction, Micro Topology (flank form modifications), discussed in chapter 10 and Micro Topography (surface structure modifications), discussed in chapter 11.

Main Topics of Chapter 9 are:

- Designed flank surface crowning and theoretical motion transmission
- Fourier analysis and its limits in gear noise analysis
- Gear noise and psychoacoustics
- Practical example of Fourier analysis and the residual phenomenon

Psychoacoustics. Sound is created by the vibration of mechanical elements and magnified by structures with certain surface areas and certain resonance frequency. The original or the magnified sound is transmitted through structures (structure-borne noise) and then transmitted through the air (sound pressure waves) and finally received by the human ear.

The physics of sound transmission is based on the compression and expansion of solid materials as well as fluids. The mathematical function of the compression and expansion of elastic materials is most likely always a sinusoidal function. The assumption that all sounds which are transmitted and emitted consist solely of sinusoidal elements seems reasonable.

The answers which engineers would be interested to receive from the Psychoacoustic Science regard the receiving of sound transmission by the human ear. If sound was created as a non-sinusoidal signal and also transmitted to the ear in a media which supports non-harmonic functions, how is this sound recognized by the human brain? An inverse

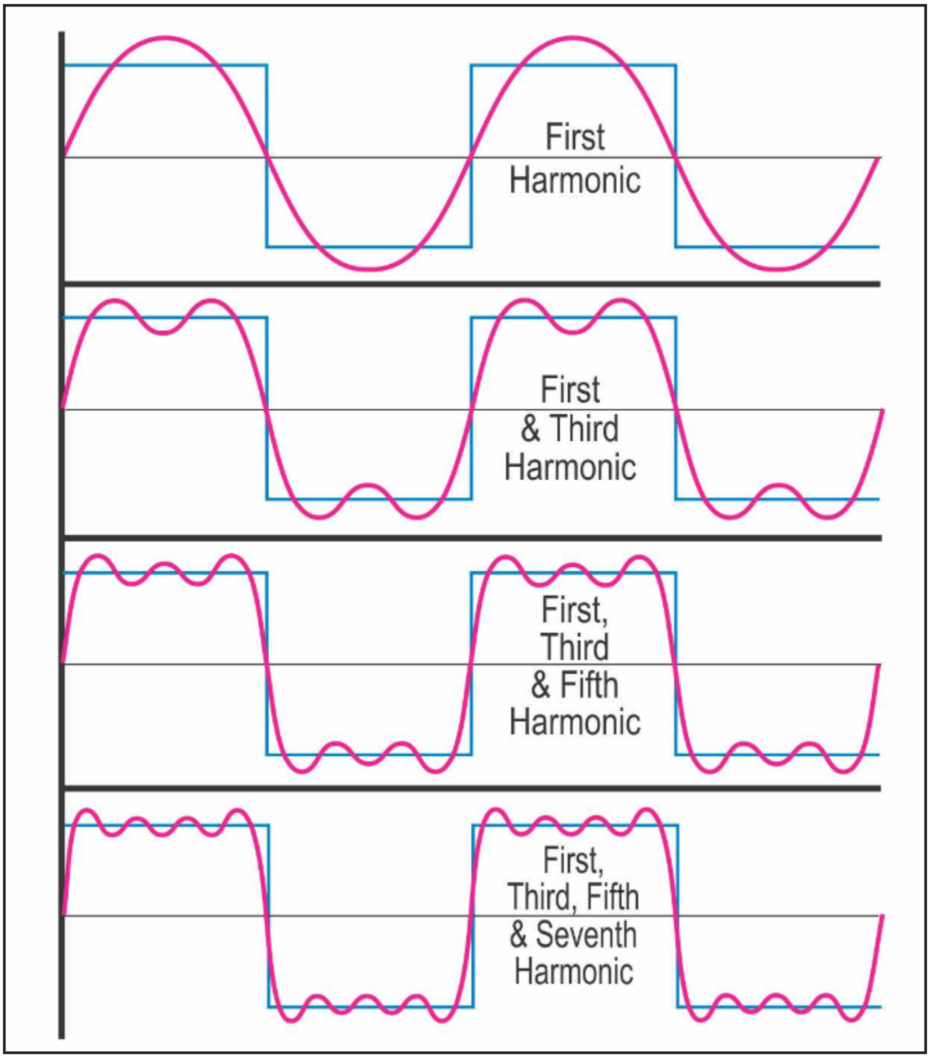

Figure 1 Fourier series development for a square wave.

question is, if our entire environment, including the laws of physics, is strictly supporting harmonic sounds. This would govern that sound sources, sound transmission, as well as the receiving and recognizing of sound by a listener, are all based on the harmonic movement of elements by certain amplitudes and with a certain frequency.

In studying the vertical sequence of the graphics in Figure 1, it is evident that according to the common acoustic interpretation a square wave would cause a listener to hear several high frequencies. This raises a number of questions:

- Is the transmission of waves through the air or other media only possible in sine waves?
- If a true square wave was received by the human ear, would the brain first recognize the received wave form and replace it with a sine wave of the same frequency and similar intensity and then substitute the higher frequencies, similar to Figure 1?
- If the human ear could hear the original square wave as a plain periodic plus-minus signal, would it sound the same as an artificial square wave which is a superimposition of four or more different frequency sine functions?

The questions above require some basic relationships between sound transmission and the psychoacoustics between the sound received by the human ear and its processing by the brain. A complete Fast Fourier Transformation (FFT) also analyzes the frequencies between the harmonics in certain Hertzian increments in order to more accurately capture the working variation. If the result of a FFT is used as the absolute measure of the noise characteristic of a gearset, then the conclusion is made that the human ear only recognizes acoustic signals or sound pressure waves in the form of true sinewaves.

The concert pitch A of 440 Hz from a tuning fork sounds different to the human ear than from a violin or from a piano. The reasons are overtones which consist of higher harmonics, side bands and/or other elements in the sound waves which might not be captured by the FFT. However, the fact that the 440 Hz can be recognized precisely by a listener is explained with the higher harmonics accompanying the fundamental frequency (Ref. 1).

The assumption that the ear tends to recognize only harmonic signals is partially correct. The outer ear acts as equalizer and compressor, which boost the sound pressure by 15 to 20 dB. The airwaves actuate the eardrum which in turn actuates the ossicles which acts as equalizer, compressor and impedance matcher such that the processed pressure waves are transferred into the cochlear fluid. The pressure waves are transmitted by the cochlea fluid to the tectorial membrane. The snail house-shaped cochlea is lined with the tectorial membrane which moves hair cells. Along the windings of the cochlea, the hair cells are sensitive to different frequencies, performing a spectral analysis of the sound signal. The hair cell neurons convert the mechanical vibration into digital electronic signals which are transmitted to the brain. The diagrams in Figure 2 show the Fourier analysis of the noise emission from a gearset and how the vibrations are converted to airborne sound which is received by the order tracking neurons in the ear. The recognized frequencies and amplitudes are similar, but different than the ones found in the Fourier transformation. One reason for this is the residual error which is not captured by the Fourier analysis.

An interesting phenomenon is that the pitch identification of ear and brain not only uses the fundamental frequency, but also employs the available (audible) higher harmonic orders. The ear still identifies, for example, concert pitch A if only the second to sixth harmonics are received, and the fundamental frequency

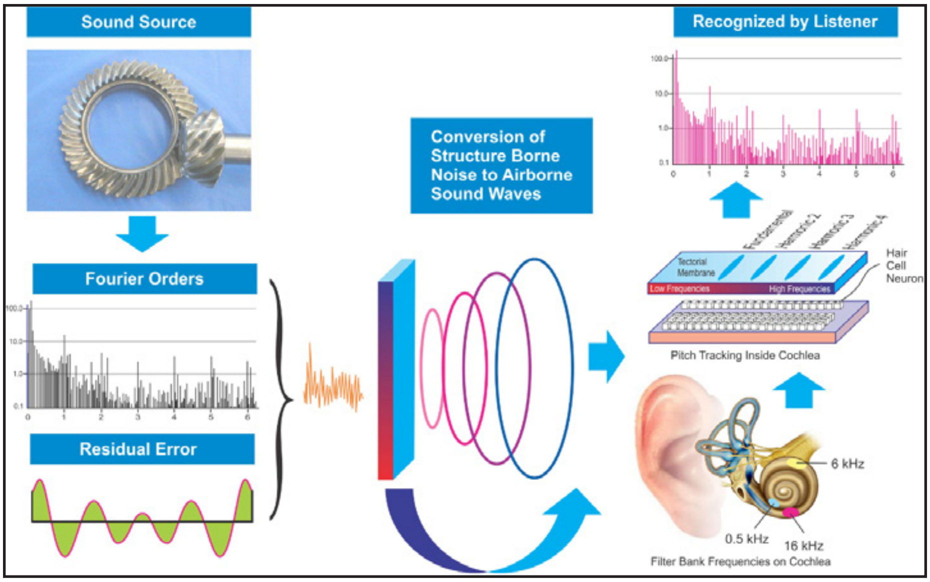

Figure 2 From sound source human recognized sound.

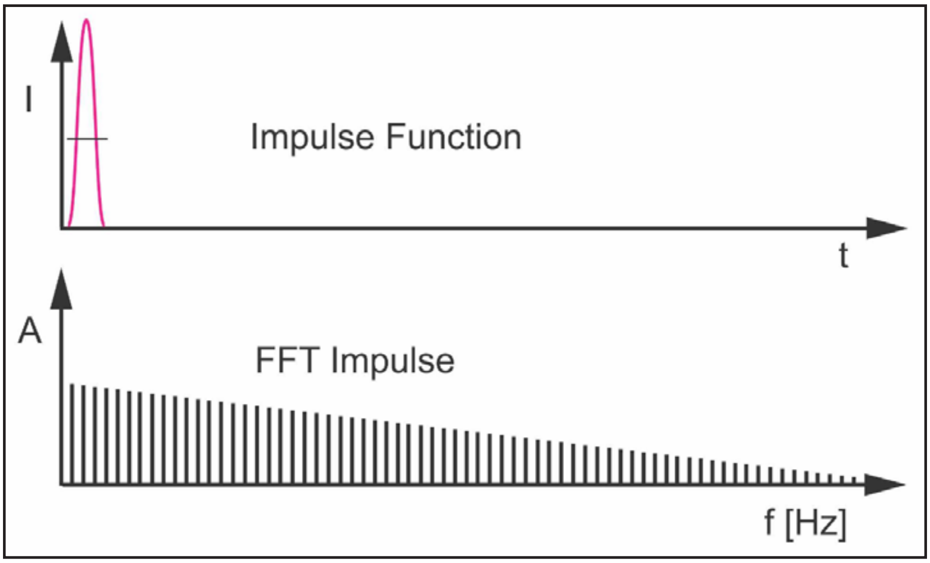

Figure 3 Impulse recognition in Fourier analysis.

is absent in the received sound signal (ghost fundamental). The "A-signal" without the fundamental sounds "smoother" than if the fundamental frequency was present.

The conclusion is that the ear as a pneumatic-mechanical-hydraulic-electronic system has masses, springs and dampening, and is created to recognize frequencies. It will mostly recognize harmonic air pressure changes which are received in a periodic signal. However, an impulse will also be recognized while ear and brain try to supplement the missing periodicity. The Fourier transformation of an impulse is shown in Figure 3. The impulse generates bars in the entire frequency range which die down in amplitude as the frequency increases. This means that all those frequencies have been found by the Fourier transformation, although the impulse was an isolated occurrence with virtually no frequency. The human ear will respond similarly because its design will cause an excitation of all hair cells along the windings of the cochlea and send signals of all audible frequencies to the brain.

Another interesting question is how a square wave sounds to the human ear compared to the results of a Fourier analysis. A perfect square wave which is approximated with a Fourier series shows an overshoot at the corners of the square (Gibbs phenomenon) (Refs. 2-3). Figure 1 shows a square wave which is approximated by a first, third, fifth and seventh order sine wave. The overshoot never dies out, but approaches a finite limit of 18% of the square wave amplitude as the number of orders increases. The question is if the human ear, because of its function, will basically send a similar exaggerated signal to the brain when it receives a perfect square sound wave. This question might be academic because no sound generating source is capable of creating a perfectly square signal without the overshoot. Besides this, the airwaves would not be able to transmit such a signal without distortion. The square wave has a ringing sound to the ear which is attributed to the overshoot. An additional peculiarity of the Fourier series of a square wave is that only the odd orders + 1, 3, 5 + are represented. The verification of the fundamental frequency of a square wave which the ear conducts with the higher harmonics in numerous distinct areas of the tectorial membrane is not given and a strange hearing experience is the result. The square wave not only rings, it also sounds "cold and synthetic."

Acoustical experiments with pure single frequency sine waves seem to confirm the theory that ear and brain will not complement the non-transmitted higher harmonic multiples of that sinusoidal sound. The pure single frequency sine wave sounds smooth and rather quiet compared to a same intensity square wave. This raises the question, if in case of a parabolic motion error, will the ear notice the same higher harmonic frequency levels which result in a Fourier analysis of such a motion error? The Fourier analysis mirrors in many cases the psychoacoustics of the human ear very well (e.g. music), but also fails in many cases to deliver representative evaluation results (e.g. disturbing mechanical noise).

Depending on the motion error characteristic, there are higher harmonics amplitudes in the FFT result and residual approximation errors which are ignored. It is assumed that certain residual non-sinusoidal waves are audible as distorted sine waves and certain harmonic amplitudes do not really exist in the sound waves received and processed by the ear. The non-existing harmonic amplitudes are merely a result of the Fourier summation scheme. It has been proposed to apply the smoother Fejér summation or Riesz summation or using the continuous wavelet transformation in order to gain more relevant dynamic analysis results.

Dynamic analysis results have commonly two applications. One is the mentioned audible experience by humans and the second is the conclusion to gear geometry-related manufacturing errors. The latter asks for a sufficient qualitative and a concrete quantitative interpretation in order to allow for corrections in the machining process. The fundamental harmonics and the side bands can give certain hints to machining errors. The harmonics above the fourth order point in some cases at surface structural and roughness problems. Especially the second to fourth harmonic amplitudes can lead to the belief that there is, for example, a disturbance which occurs 2, 3 or 4 times at each tooth mesh. As a matter of fact, this is possible, but it only might be the result of the Fourier summation process required to capture a particular motion graph, which only repeats its disturbing rotational transmission once per tooth mesh.

Example of Fourier analysis and the residual phenomenon. In order to approximate a realistic motion transmission graph, a parabola of the form $\Delta\varphi = a \cdot (\varphi - \varphi_0)^2$ as it is typical for bevel gearsets, is used in Figure 4 as the subject of a Fourier analysis.

As a starting point, a sine-function with suitable amplitude and a period of

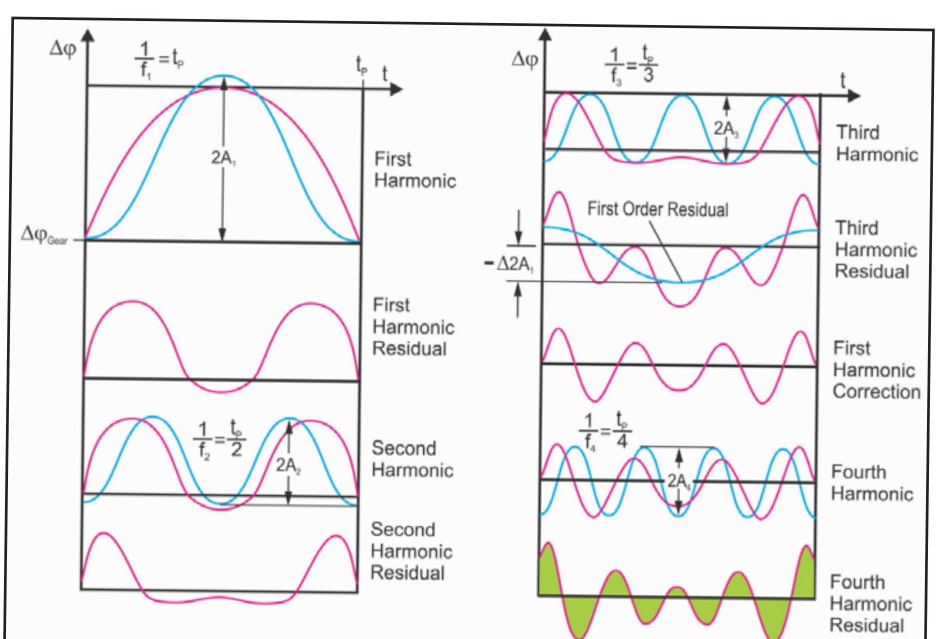

Figure 4 Fourier analysis of parabolic function.

the meshing time of one pitch are drawn into the parabola-shaped motion graph. If the first harmonic is subtracted from the motion transmission graph, the result is the first harmonic residual which has twice the frequency of the motion transmission graph itself. This does not mean that the original motion transmission graph contained any elements of double frequency, it merely means that in the attempt to approximate a parabola with a sine-function the residual will show a dominating second order. If the dynamic transmission media is capable of transmitting the original parabola-shaped sound wave, and if the receiver, e.g.— a human ear was rather capable in receiving and processing sinusoidal waves, only then would this second harmonic be noticed.

A sinusoidal function with half the period of the original function and an amplitude of about half of the residual magnitude is now used to approximate the residual function from the first harmonic. The residual from this approximation step result is shown in Figure 4 underneath the second harmonic. This graph appears to have some third- and some fourth-order elements. As a matter of fact, it requires the elimination of the third- and fourth-order harmonic elements in order to notice a visible reduction of the residual function. The unequal spacing of the waves makes it particularly difficult for a Fourier analysis to closely approximate a parabolic function. The residual error after the elimination of the third harmonic element still contains some first-order residual, which can be determined at this point and then be added to the amplitude A_1. The frequency-amplitude spectrums of the four sinewaves in Figure 4 have been plotted into the graphic in Figure 5. Although this graphic shows the amplitudes for the dynamic gearset evaluation, only the first order peak-to-peak values are relevant because they only represent the stroke of the excitation ripple and can be correlated to the transmission error. A true mechanical disturbance (e.g. + second order) would show as an amplitude above the enveloping curve (red dashed bar). There are several conclusions that came out of the experiment demonstrated with Figure 4:

- A true parabola-shaped graph was

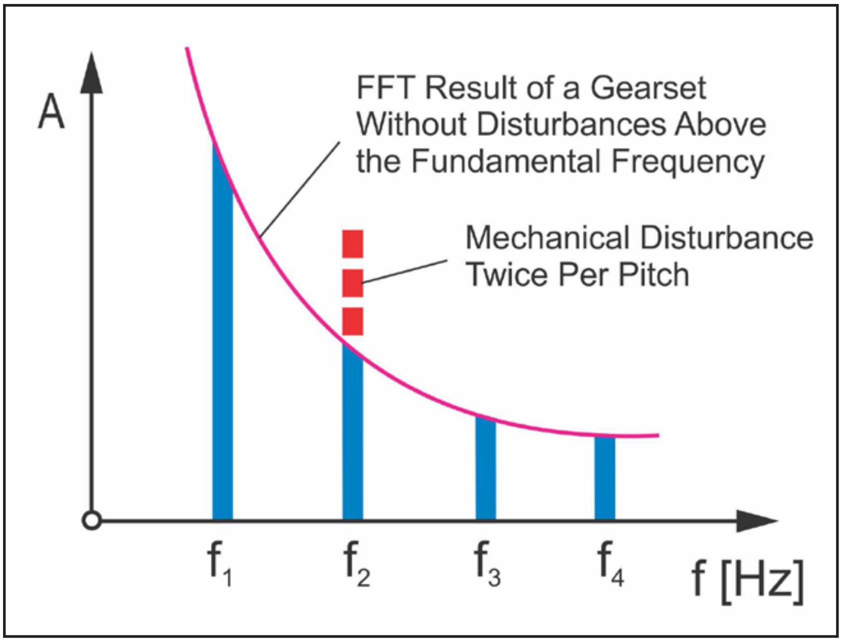

Figure 5 **Frequency-amplitude spectrum of harmonic contents of a periodic parabola.**

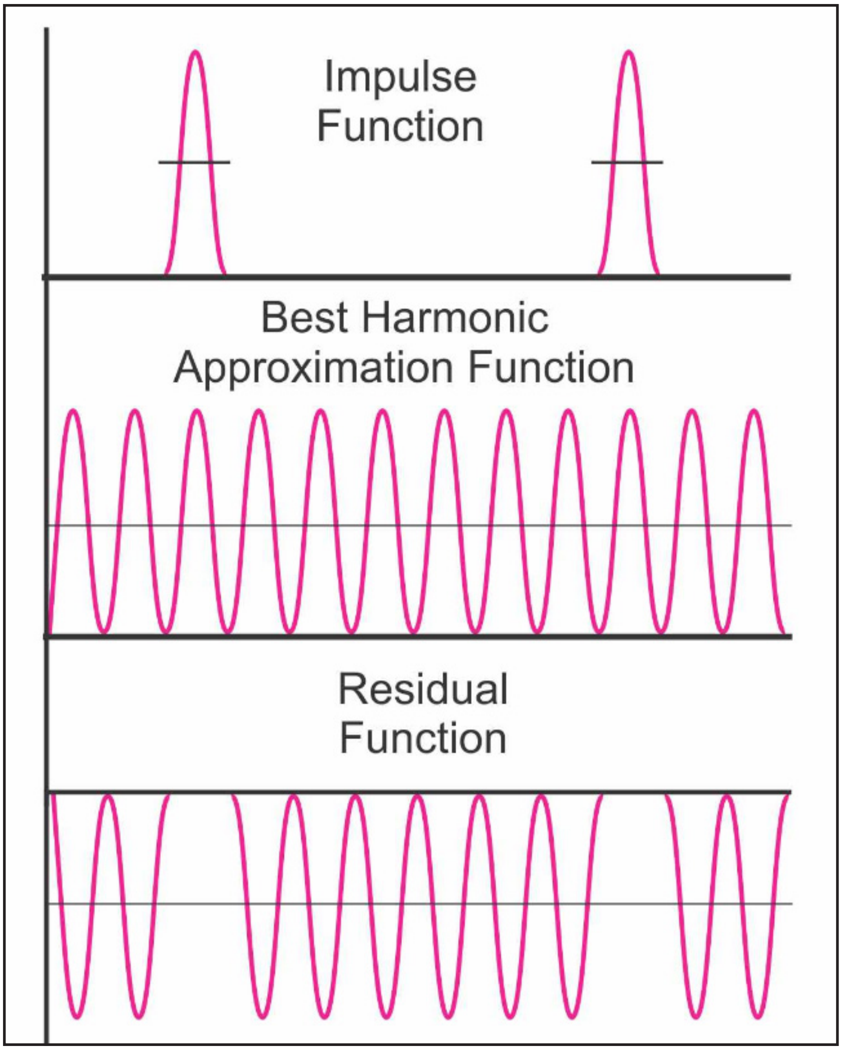

Figure 6 **Residual error in case of a periodic impulse.**

approximated. The result of a Fourier analysis of a perfect parabola-shaped motion transmission graph results in more than four harmonics of significant amplitudes. If the analysis is stopped after the four harmonic separation steps, a residual amplitude of about 50% of the original function is found.

- The value $2A_1$ is larger than the original value of the motion error $\Delta_{\varphi Gear}$
- Many gear analyses are performed with only a four harmonics analysis. The residual function is so significant for the effective noise emission of the gearset that no absolute noise rating is possible.
- FFTs have their value if they are used in the comparison of similar gearsets which have been found acceptable in their noise emission.
- FFTs are useful if the presence of low frequencies caused by pinion and gear runout should be detected. Those waves are dominated by a sinusoidal content.
- FFTs are useful if higher frequencies caused by surface texture or generating flats should be detected. Also those waves are dominated by sinusoidal contents.
- FFTs are useful in the medium frequency range (first to fourth harmonic) if the measured transmission variations have a dominating sinusoidal content.

A periodic impulse function is impossible to capture with a harmonic Fourier analysis if the width of the impulse and the period of its reoccurrence have largely different amounts, as shown on top of Figure 6. The bottom of Figure 6 shows the residual error reflects a high frequency with the amplitude of the original peak. In reality, the FFT will attempt to approximate the function and also interpret the impulse characteristic which will result in side bands in the entire frequency range.

The Physics of Sound Transmission Applied to Gears

In a constructed example, the single flank error signal in the graphic in Figure 7 consists only of sine functions. The top graphic is the recording of one ring gear revolution. In the example, a ratio of 3.00 was chosen, which means the graphs in Figure 10 will be exactly repeated for additional ring gear revolutions.

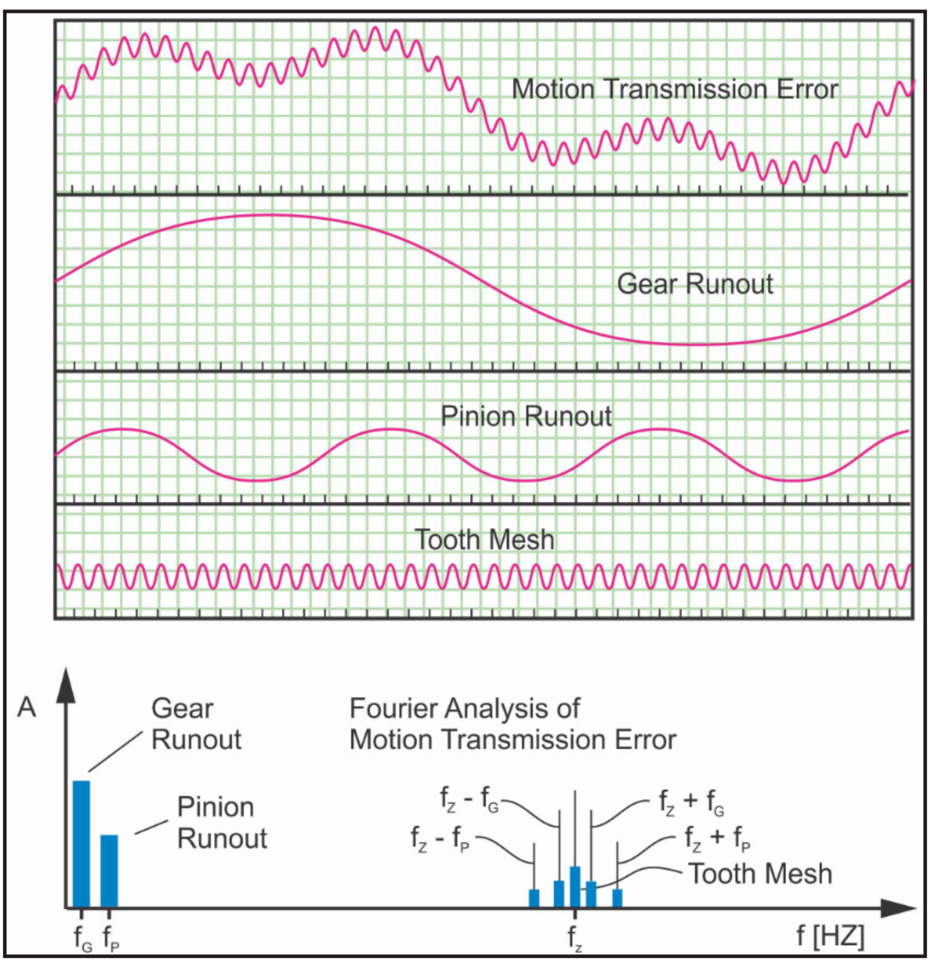

Figure 7 Separation of harmonic motion transmission elements of motion error.

Figure 7 shows how in three steps, first the gear runout, then the pinion runout and finally the tooth mesh is filtered out. In the example, no residual amplitudes are left. It can be assumed that a listener can clearly hear all three separated frequencies. At the bottom in Figure 7 the FFT result contains bars for the gear runout, the pinion runout and the tooth mesh frequency. The side bands of the tooth mesh frequency originate from the gear and pinion runout. The side bands are spaced away from the tooth mesh frequency by their respective runout frequencies. Although the gear and pinion runout and even the generating flats commonly have a dominating sinusoidal shape, the tooth mesh in most real cases is parabolic, resulting in many additional frequency amplitudes which is attributed to the transformation algorithm that is used in Fourier analysis and does not exactly represent the audible frequencies.

In Figure 8 the motion transmission error from Figure 7 is used as an example for the separation of the elements "Gear Runout," Pinion Runout" and tooth mesh. The difference with Figure 7 is the tooth mesh motion error which is parabolic in Figure 8 instead of sinusoidal. Due to the parabolic motion error not only f_z, but also the multiples of f_z are present in the Fourier analysis result. Each of these harmonic frequency bars is surrounded by side bands caused by the gear and pinion runout. Instead of ignoring the differences between parabolic and sinusoidal function, the Fourier analysis expresses the residuals between parabolic motion graph and sine function in additional sine functions of higher orders (Ref. 4).

Summary

Psychoacoustic science teaches that a sound source which initially has a non-harmonic excitation will be recognized as harmonic function with the initial frequency and a superimposition of an infinite number of higher frequencies with fading amplitudes. The reason is the ability of mechanical structures and the ability of air waves to transmit only harmonic signals. This phenomenon is also supported by the human ear, which processes received sound with a spectral analysis and therefore only recognizes superimposed harmonic sound signals + even if the sound waves would consist of a pure square function.

It is interesting to mention in this connection, that Jean-Baptiste Joseph Fourier published in 1807 his analysis method which uses an infinite number of sinusoidal frequencies in order to quantify a repeated function + even if the function has no sinusoidal elements. Fourier's analysis algorithm is employed since the 1960s as a computerized method and is used today to analyze vibration and sound for its contents of frequencies. Fourier's method is aligned with the sound transmission principle of the airwaves as well as with the function of the human ear. However, it is an approximation of signals like square waves which do not contain any harmonic waves at all, yet the result is a variety of harmonic frequencies and their amplitudes.

Conclusion for eDrive Noise Reduction

The higher input speed of eDrives implies that all noise-causing disturbances are multiplied by 3 to 10 compared to conventional transmissions. Therefore events higher than the third mesh harmonic would be above the human audible frequency. The conclusion from this would be that higher harmonics and surface structure effects have no influence on the audible spectrum and can therefore be ignored.

This conclusion is incorrect. Only the first stage of an eDrive has the high rotational speed. All conventional criteria like frequencies below and above the third mesh harmonic, as well as surface structure-borne frequencies, are still applicable to the final stages of electric vehicle transmissions. Another reason to use surface structure shifts (MicroShift) in addition to flank form modifications is based on the research results from structure shift investigations. A different amount of surface structure shift from tooth to tooth, following for example a sinusoidal function, will generate side bands with different frequency distances from the mesh frequency multiples. The side bands will change sensation of noise recognition from annoying to an un-disturbing, smooth buzzing sound.

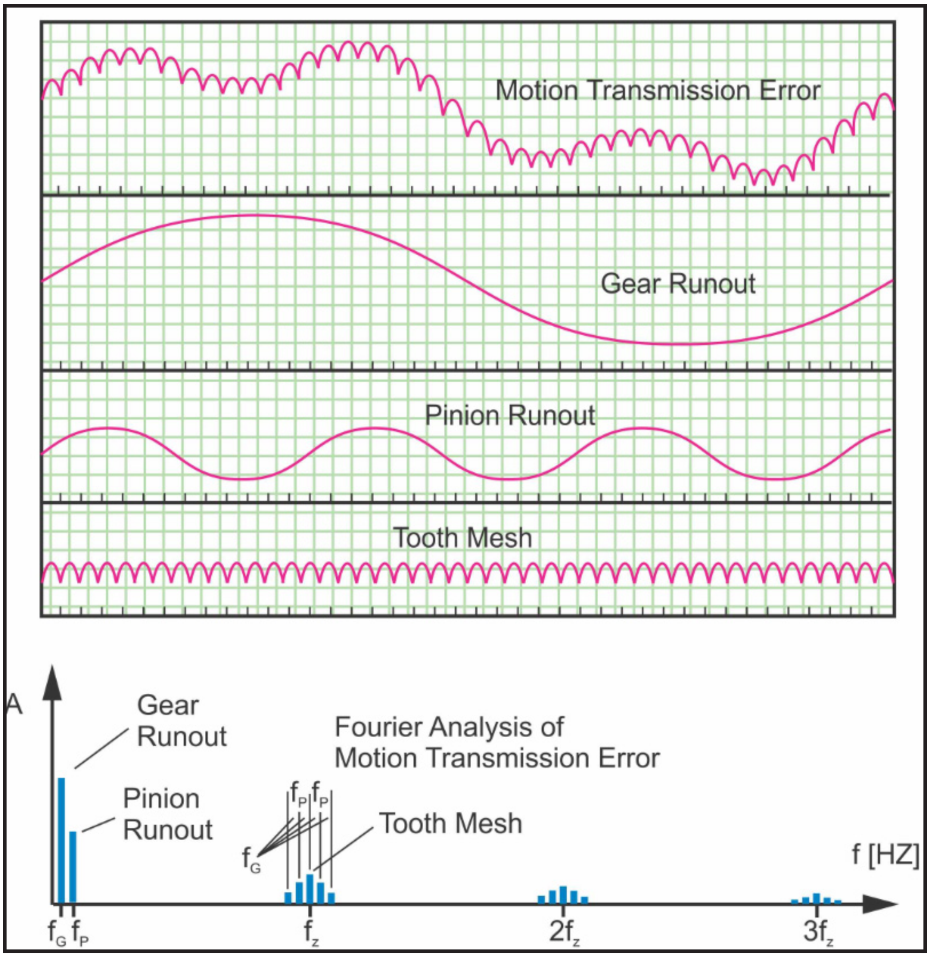

Figure 8 Separation of parabolic and harmonic motion transmission elements.

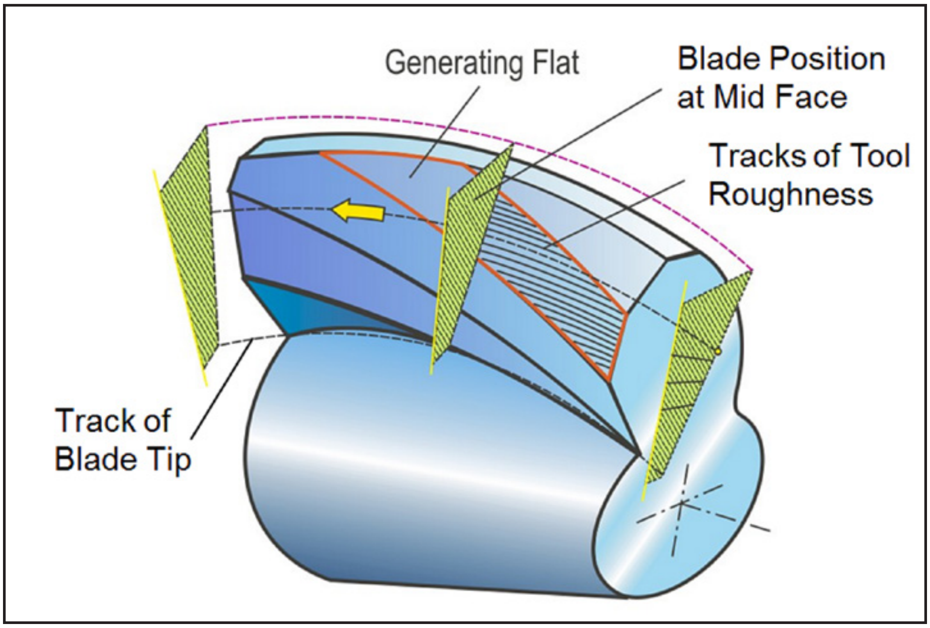

Figure 9 Noise generating flank surface effects.

All gear noise is caused from the tooth mesh impact, flank form imperfections as well as from generating flats and roughness tracks of the tool (cutting blades or grinding wheel). Generating flats and tool roughness tracks are shown in an exaggerated view in Figure 9. Depending on the direction of the contacting lines between the two mating gears and their interacting with the flank surface effects in Figure 9, medium- and high-frequency noise can be generated when the mating teeth mesh under certain, mostly low, loads.

If the tooth mesh impact and the surface effects are the cause of excitations of gearbox surrounding structures, two conclusions for their reduction or elimination are possible:

- A modified transmission function can reduce or eliminate the residuals and all higher harmonic multiples of the tooth mesh harmonic.
- Side bands surrounding the harmonic peaks will reduce the annoying character of the emitted noise.

Modifications to the transmission function can be achieved with *Universal Machine Motions* (*UMC*). Chapter 10 (see book version) discusses several possibilities of sophisticated transmission function optimizations which proved to reduce the tooth mesh impact as the major source of all gear noise.

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

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

Stadtfeld continues, along with his senior management position at Gleason Corporation, to mentor and advise graduate level Gleason employees, and he supervises Gleason-sponsored Master Thesis programs as professor of the Technical University of Ilmenau—thus helping to shape and ensure the future of gear technology.

DVS Technology Group

COMPLETES EXECUTIVE BOARD RESHUFFLE

As of April 1, 2021, DVS Technology Group/DVS Technology AG will initially appoint Dr. Christoph Müller-Mederer to the executive board as Co-CEO. As of July 1, he will then take over the duties of the long-standing CEO Josef Preis. Following the departure from the board and the company of CEO Josef Preis and his fellow board member CSMO Bernd Rothenberger, as planned, and the appointment of CFO Stefan Menz and CTDO Mario Preis, which had already taken place beforehand, this completes a long-planned reshuffle of the management of the Hessian solution provider in mechanical engineering.

Left to right: Bernd Rothenberger, Josef Preis, Christoph Müller-Mederer.

"Continuity and change"—these two words could stand as a motto over the change in the DVS Group management team, which has been well prepared for a long time. With CEO Josef Preis and CSMO Bernd Rothenberger, two personalities will leave the company in July who have shaped the group into the technological solution provider as which it presents itself today with international success. Both will remain associated with the group of companies in an advisory capacity after their active time. Following a three-month handover phase, Dr. Christoph Müller-Mederer will assume the role of CEO from this date and, together with CFO Stefan Menz and CTDO Mario Preis, will form the new, three-member executive board team.

With Müller-Mederer, someone takes the helm who combines both the classically technology-driven side of DVS Group and the recently increased focus on customer orientation and business aspects: the internationally experienced company leader has his academic roots in both mechanical engineering and economics and has shaped his professional career throughout the world of mechanical engineering.

"We are very happy to have found a successor in Christoph Müller-Mederer who understands both the rules of the game and the challenges of our industry very well, so he also recognizes the special opportunities that can be found in the current change. As a solution provider in Future Mobility, we thrive on our experience and technical know-how—but also on innovation, agility and customer focus. Our new CEO stands for both sides," says Dr. Steen Rothenberger, chairman of the supervisory board, about the selection criteria for the succession.

The focus of the new CEO's work will be on the further alignment of the DVS Group as a solution provider of future mobility with a particular emphasis on customer orientation, internationalization and digitalization.

www.dvs-technology.com

Gear Motions

WELCOMES DIRECTOR OF BUSINESS DEVELOPMENT

Gear Motions welcomes **Mike Toper** as director of business development. In this new position, Toper will be responsible for strategic business development to identify and create business markets and opportunities.

Toper brings with him 20 years of experience in the industrial sector, with proven success in strategic planning and execution, and implementing new programs. Most recently, he served as the northeast sales manager for Gerard Daniel Worldwide.

"The employee owners are excited to welcome Mike to the Gear Motions Team" says Dean Burrows, president and CEO, Gear Motions. "In this new role, Mike will bring his technical expertise and background to explore and develop new markets."

Gearmotions.com

Amorphology

OPENS WEST COAST DEMO CENTER WITH STARRAG MACHINING CENTER

Amorphology and Starrag Bumotec are teaming up to establish the only U.S. West Coast laboratory where customers of both companies can observe real-time precision engineering and machining of complex gears using amorphous metals.

Amorphology, a NASA spinoff company founded from technology developed at the Jet Propulsion Laboratory (JPL) and the California Institute of Technology, is a leader in applying advanced materials and manufacturing technologies toward improving gear production for robotics and other industrial applications using amorphous metals, also known as bulk metal glass (BMG).

The demo center will be at Amorphology's Pasadena, California, headquarters where Starrag Bumotec's s191H CNC

machine will be showcased, machining a wide variety of parts from mold inserts to rapid prototype gears, as well as other production BMGs and traditional metal parts.

"We are targeting high-precision parts with tolerances often < 5 µm on certain dimensions," said Jason Riley, Amorphology's chief operating officer. "The majority of our work is focused on rapid prototyping and production quantities in the hundreds of parts per month."

"Establishing a laboratory environment to showcase the precision, quality and capabilities of the Bumotec s191H will enable aerospace and defense engineers to experience this real-time machining that could be used in their manufacturing operations," said Greg Dunkley, Starrag Bumotec's vice president of precision engineering."

Advanced Features of Amorphous Metals

BMGs have several material advantages over traditional steel, titanium and aluminum metals and alloys. Amorphology's patent portfolio includes several patents focused on high-precision gears for space and other extreme cold temperature applications. Amorphous metals are a non-crystalline class of alloys that cut and chip differently than other materials.

"The Bumotec s191H provides mill-turn capabilities as well as a higher production capacity," said Riley. "Bumotec can take our alloys and machine single pieces. Or instead of machining one part at a time, it can produce hundreds of pieces lights-out."

Amorphology's gears are made for use in cobots, robots and medical devices. For example, most cobots use strainwave gears — the main component being a flexspline. It is complex, thin-walled and fulfills an important role — to precisely move the arm of the robot.

Many of the cobot, robot and medical device parts can be cast or injected molded but, at times, the micro-parts need to be post-processed to extremely high tolerances. "Bumotec 'cut its teeth' in designing machines for the Swiss watch industry," said Dunkley. "Bumotec has a talent for machining micro-size high-value gears."

Riley believes the Bumotec s191H will make Amorphology's own micro gearboxes without lubrication for robots and medical devices. "We will be machining our patented alloys to very small sizes where production quantities don't require our injection molding process," he said.

www.amorphology.com

Star Cutter

ANNOUNCES NEW VP OF OPERATIONS

Star Cutter Company has promoted **Mike Billiel** from corporate operations manager to vice president of operations. In this position, Billiel is responsible for planning, directing and coordinating efficient and cost-effective operational activities across the company's five manufacturing locations, helping Star Cutter meet its current and future needs.

Billiel originally joined the company in 2013 as the cutting tool operations manager and in 2019 moved to the role of corporate operations manager. "Mike has been instrumental in building uniformity into our improvement strategies, from performance targets and KPI development to budget and capital planning," said Jeff Lawton, Star Cutter president. "We're confident he'll bring even more value to this organization in this role and as a member of our board of directors."

When he joined Star Cutter, Billiel already had significant experience in quality, manufacturing, and operations management gained by working for automotive Tier 1 suppliers and other manufacturing companies. He is skilled in Lean and Six Sigma tools including DMAIC, Value Stream Mapping, Failure Mode and Effects Analysis, and more. He has an Associate of Science degree in electrical engineering technologies from the Community College of the Air Force and served six years of active duty in the United States Air Force.

www.starcutter.com

ECM USA

WELCOMES SENIOR PROJECT MANAGER AND TECHNICAL SALES ENGINEER

Many in the heat treat community may recognize one of the newer faces to join the ECM USA Team—**Juan Cruz**, of Saltillo Coahuila Mexico! With a mechatronics engineering degree from the Technologic Institute of Saltillo ITS and master's degree MBA from the Northeast Autonomous University UANE, Cruz has more than 10 years of experience in the heat treat industry. Previous roles include maintenance, sales and service in the United States, and senior management in Mexico. With international vacuum furnace experience in supporting many projects for the heat treat industry, his extremely efficient focus is and always will be on continuous improvement. In his role as ECM USA's senior project manager to Mexico, Cruz will be leading the Mexican market, projects and support for ECM customers. He will be located in Saltillo Coahuila which is in the north of Mexico.

In addition, ECM USA is pleased to announce the addition of **Gordon Banish**, technical sales engineer for the North, Central and South American thermal process markets. Banish joins ECM USA with a highly skilled background in various induction/resistive equipment systems and heat treat applications, such as large ferrous and non-ferrous alloy melting equipment up to 20 MW power. Working primarily as a national/global sales manager in Crystal Growth Furnaces (including PV/Solar) with various global companies for 20 years, including Cyberstar since 2004, his experience also expands into the automotive industry with automation systems for custom-designed tooling with induction and heat transfer applications. He is a graduate of Wayne State University (Detroit, MI) with a degree in electrical engineering.

Banish will primarily be working with ECM's Cyberstar division. Cyberstar is a manufacturer of furnaces for crystal growth equipment (Czochralski, Bridgman, floating zone, liquid phase epitaxy and mirror furnaces -infrared or laser heating-), photovoltaics (PV) Si furnaces, sapphire crystal furnaces, gamma and X-ray detectors. Their crystal growth furnaces are well known for their outstanding reliability and performance in many R&D laboratories and industrial companies in the Medical, Laser, LED and Medical Imagery fields. Additional responsibilities will be for VPA (vapor phase aluminization), VIM (vacuum induction melting), and other vacuum processing equipment sold under the ECM Group name.

www.ecm-usa.com

Solar Atmospheres of Western Pennsylvania

CONTINUES EXPANSION

Solar Atmospheres of Western PA recently took occupancy of a brand new 15,000 square foot "connector" building. This building joins the existing 80,000 square foot workspace, which houses some of the largest vacuum furnaces in the world, to its current 10,000 square foot Nadcap laboratory, testing building and vacuum oil quenching building. The primary purpose of this new building is to create a clear and defined flow of work using a pull/push system, rather than having incoming and outgoing jobs co-mingled in front of heat treating equipment. All incoming jobs will now be "pulled" from this building and completed jobs will be "pushed" back to a designated outbound area. This new space will serve as a conduit for transfer of materials from production to final testing. Finally, the four new loading bays will allow for the loading and unloading of multiple trucks at one time. A drive through feature will allow all flatbed trucks to load/unload indoors, thus keeping shipping personnel and equipment out of the harsh winter elements.

Wes Hoffman, shipping manager states, "Material handling is now thoughtful and organized throughout our 100,000 plus square foot facility. The new building has already proven to eliminate wasteful movement of material. This addition has also enhanced our overall safety. Instead of large trucks navigating our entire campus internally, we can now isolate trucks and drivers to the outer perimeter of the property. This improvement prominently positions Solar for continued growth well into the future."

Solaratm.com

Starrett

APPOINTS DIRECTOR OF SALES, METROLOGY SYSTEMS

The L.S. Starrett Company has announced the appointment of **Jim VandeHei** as director of sales, Starrett Metrology Systems. In this newly created role, VandeHei's primary responsibility will be North American sales of the company's vision systems, optical measuring projectors and force measurement systems.

"I am very pleased to announce that Jim is joining Starrett," said David Allen, vice president of Starrett Metrology Systems. "His extensive sales management and sales process skills will be key to furthering the growth of our metrology equipment products in the North American marketplace."

VandeHei has led and developed multi-channel sales teams for more than 28 years, including over 20 years of metrology sales and commercial operations management for Hexagon Manufacturing Intelligence, Carl Zeiss IMT Corp., and DW Fritz Automation. He is a graduate of the University of Wisconsin—Madison where he received a bachelor of science in industrial engineering degree, in addition to a professional development certificate for executive sales management. He lives with his family in the Chicago area.

www.starrett.com

Verisurf

APPOINTS BUSINESS DEVELOPMENT MANAGER FOR THE AMERICAS

Verisurf Software has appointed **Tara Mitchell** to the position of business development manager for the Americas. She will work closely with both customers and Verisurf regional sales managers in her new role, applying critical thinking for inspection and measurement solutions across the manufacturing enterprise.

"We are delighted to have Tara as a team leader for business development; her experience and reputation as being highly effective and customer-centric are a great fit for Verisurf," said Pat Bass, director of sales.

Mitchell's work history and ongoing involvement in metrology-related community organizations adds to her relevant expertise and provides a clear perspective on industry and customer challenges.

Previously, Mitchell was responsible for business development in the western region for Hexagon Metrology, where she sold inspection and measurement solutions, including fixed CNC CMMs, portable CMM arms, and more.

Notably, during her tenure with Hexagon, she also served on the Executive Committee of the CMSC for nearly ten years, where she pursued the organizations' goal of bringing the world of metrology one step closer to its audience. While working with the CMSC, Mitchell helped foster an educational atmosphere through programs and the annual CMSC conference that encouraged attendees to network and learn about innovations in 3D measurement solutions from the world's leading providers of metrology systems.

Mitchell is also a member of the manufacturing and fabrication technical advisory committee at Renton Technical College, Renton Washington, where she will continue her role of supporting programs designed to prepare students and incumbent workers for careers in industrial production and fabrication.

www.verisurf.com

Bonfiglioli

WINS INNOVATION 4.0 AWARD FOR IOTWINS PROJECT

The A&T (Automation & Testing) 2021 Fair in Torino recently presented Bonfiglioli Riduttori with an Innovation 4.0 award for its IoTwins project. The other winner was Rollwasch italiana S.p.a., with VibroBLAST, a patent for a revolutionary vibro-blasting technology.

The IoTwins project is led and coordinated by Bonfiglioli and involves 23 partners from 8 European countries, realizing and effective network of open innovation.

Francesco Millo, strategic planning and M&A director (left) and Fausto Carboni, CEO Bonfiglioli Group (right).

IoTwins design and implement a platform providing services to 12 test beds. The platform digitally reproduces a system (infrastructure, process, machine, etc.) together with its performance, creating Digital Twins that allow the modelling of the system and its dynamics, the prediction of its evolution and the optimization of its operation, management and maintenance. The simulations already affected and replicable involve monitoring production in industrial plants, managing the flow of crowds inside large entertainment facilities, such as the Barcelona stadium, and creating a digital twin of a wind farm by aggregating simulation models and machine learning of single turbines for predictive maintenance.

There were 51 projects selected and admitted, among which the Industrial Scientific Committee of A&T has designated eight finalists. The 2021 edition of the Prize awarded by the A&T Fair has seen a growing interest especially from companies.

"Receiving this award is a source of pride for us, proof of the importance of the IoTwins project of which we are coordinator. R&D, innovation and market orientation as drivers of our corporate activities are the elements that distinguish and guide our Group. I consider the constant development of new ideas and strategies our competitive advantage and success factor," said Fausto Carboni CEO of Bonfiglioli Group.

www.bonfiglioli.com

Tsugami/Rem

RECEIVES ISO 9001:2015 CERTIFICATION QMS

Tsugami/Rem Sales LLC, exclusive North American importer of Precision Tsugami machine tools, has received ISO 9001:2015 Certification Quality Management System (QMS) through American Systems Registrar (ASR), an ANSI National Accreditation Board (ANAB) accredited registrar.

The International Organization for Standardization (ISO) is an independent organization with the goal of developing voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges.

Valentina Ciotto, engineering project specialist at Tsugami/Rem Sales, shared, "Becoming ISO 9001:2015 certified allows us to be proactive in our approach to refining our processes, improving the quality of our support, and enhancing our overall customer service."

ISO 9001 is a set of basic business principles, written in a standard for quality management systems, that apply uniformly to organizations of any size or type of business. Currently, more than 100 countries have adopted ISO 9001 as a national standard.

"ISO 9001:2015 provided Rem Sales with the structure to focus on standard practices, business process effectiveness, and a culture of risk-based thinking and continual improvement using a team approach." explained Elaine Rampone, consultant at RAMP Enterprises, who assisted Tsugami/Rem Sales in preparing for their assessment.

While many associate the Tsugami name with Swiss turn machines, Tsugami/Rem Sales does much more than that. Alongside their distribution network, Tsugami/Rem Sales is in regular contact with their customers, whether it is the service department answering questions about alarms or other machine maintenance or the applications engineers to assisting customers in streamlining their programs.

Michael Mugno, president at Tsugami/Rem Sales commented, "Many of our end-users operate with ISO standards. By embedding the ISO process in our own company's culture, we hope that in addition to bettering our own practices, we can better understand the needs of our customers, and in turn further their confidence in the Tsugami/Rem Sales team."

remsales.com

Shell

SELECTS SIEMENS POLARION SOFTWARE FOR CAPITAL PROJECTS DATA

Siemens Digital Industries Software recently announced that Royal Dutch Shell has selected *Polarion Requirements* software as the foundation for managing and streamlining the flow of requirements across Shell's global Capital Projects ecosystem. Shell will leverage Siemens' *Polarion* to accelerate development of its digital enterprise as they further transition from document-centric communications to data-driven execution. This will improve the efficiency and flow of digital project data and integrated requirements throughout the Shell supply chain.

Shell is using *Polarion*, a contextual tool within Siemens' *Xcelerator* portfolio of integrated software and services, to enable highly effective and transparent collaboration between its project development teams. The software connects Shell's project teams as they apply Systems Engineering techniques to rapidly and efficiently gather, author, approve, manage, and audit requirements for complex systems across the entire project lifecycle.

"Shell invests billions of dollars each year in new capital projects, Powering Progress in the energy transition and working toward our climate target of being a net-zero energy emissions business by 2050, in step with society. We need trusted partners to do this — which is why we are working with Siemens on a robust, comprehensive and innovative requirements solution," said James Haug, general manager for systems engineering at Shell. "The *Polarion Requirements* software will be the lynchpin technology for advancing our digital enterprise. As we standardize on and deploy *Polarion* globally, we look forward to enhanced efficiencies and lower costs for Shell and for our supply chain and project ecosystems."

Siemens and Shell worked collaboratively to ensure that the *Polarion* solution provided was configured to accelerate Shell's digital transformation goals. The strategy involved atomizing corporate specification documents into data using *Polarion* to automatically create status reports, documents and workflows that subsequently improve the real-time availability of relevant standards content and requirements across the organization. As a result of the initiative, requirements previously managed in documents are now available as data to be modified and tracked, via a user-friendly collaborative interface, to support and deliver greater efficiency in engineering workflows across the project development lifecycle. Shell quickly expanded the use of *Polarion* to a substantial number of projects globally within the first year, following the technology's initial deployment.

"Siemens is pleased to help one of the world's foremost energy firms develop and deploy a modern, world-class digital enterprise based on the management and coordination of requirements data and other critical initiatives," said John Nixon, senior director for the energy and utilities industry at Siemens Digital Industries Software. "By implementing a unified approach to requirements management that connects all project development processes with their engineering artifacts, and improving the collaboration between the teams that originate, manage and review them, *Polarion* is helping Shell and its supply chain partners reduce their total cost of ownership, improve regulatory compliance, and accelerate time-to-value on assets."

www.sw.siemens.com

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Artwork with Gear Teeth

Joseph L. Hazelton, Contributing Editor

In Homewood AL, driving up to the Valley Hotel, you might think its 25-foot-tall sculpture is wooden, but it's not. It's metal. From a distance, it looks wooden because the metal has a thin layer, a patina, of rust. The patina is deliberate. Being outdoors, the sculpture has to withstand the elements, so "The Outpouring" is made of Corten steel, which is meant for long-term use outdoors.

The metal is designed to resist corrosion and to develop its patina over a few months outside. Once the patina forms, the metal will hold up like stainless steel, says sculptor Salem Barker.

From South Beloit, IL, Barker designed and created "The Outpouring" to be, first and foremost, a tribute to the steelmaking industry in and around Birmingham, AL. The metro area includes suburban Homewood. However, the artwork also refers to precision machining through the gear teeth that wind their way up the 25-foot-tall piece.

Once you're up close, standing in front of the sculpture, you can see it starts with a crucible pouring molten material. This outpouring flows down, then curves up, continuing upward until it's above the crucible—"that suggests technological advancement," Barker says. The material then ends with a segment that looks like part of a wing.

Barker built "The Outpouring" by welding steel panels onto a framework. Like the panels, the gear teeth are Corten steel. But, Barker says the steel for the teeth was sandblasted, treated with an adhesion promoter, then treated with an automotive clear coat: "Giving it a satin, low-luster finish." He adds that the look of the teeth suggests modern manufacturing, something "clean and finished and precision-machined."

Building the sculpture itself took three-and-a-half months. During construction, Barker recorded himself working, then created three short videos showing the building process. The videos can be seen on his YouTube channel, *youtube.com/c/SalemBarker*. The channel also includes videos of some of Barker's other sculptures. More of his sculptures can be seen on his website, *salembarker.com*. The site has a gallery of images, including a section of gear-themed pieces.

Barker knows about gears from his previous career operating, repairing, and rebuilding machine tools, including gear machine tools. He spent some of that career doing on-site machining, including work at many steel mills. Traveling to customers' sites, though, involved downtime, sitting in airports, airplanes, hotels. So, Barker used the occasions to sketch, a favorite pastime.

In 2003, though, he started moving toward a career in sculpture. That year, South Beloit was hit by a storm that blew down some large trees. Barker says he noticed one of the trees and started to cut it "with artistic intent." "I was hooked," he adds. "And I just kept doing it." In 2007, he became a sculptor, working first with wood and later with metal, too.

Then, in 2019, Barker heard from a real estate developer in Birmingham. Michael Mouron wanted a sculpture for the lobby in one of his hotels and knew about Barker's artwork. Barker took the job; created a six-foot-wide, wooden sculpture; and delivered it himself to Birmingham.

The trip was in mid-2020 and was the first time he and Mouron met in person. Naturally, they talked. "He just took a liking to me," Barker says, and "he wanted to know about my background before getting into art." That's when Mouron learned about Barker's career in manufacturing.

"The Outpouring" honors the steelmaking industry in Alabama, specifically the Birmingham area. The outdoor sculpture is in suburban Homewood and includes gear teeth that are meant to suggest precision machining (photo courtesy of Craig Roderick).

Barker describes their next comments, starting with Mouron's: "'Oh, can you work with metal?' And I said, 'Yes.'" Barker says he told Mouron he could form and weld metal and adds that Mouron replied: "'Let's go take a ride. Can you do something big?' And I said, "Yes.""

The ride led to a construction site, to the shell of a building. Barker says Mouron now had a new question: "What do you think would look good in the front corner of this building?"

Today, "The Outpouring" stands outside that building, the Valley Hotel, paying tribute to the steelmaking industry in the Birmingham area.

Barker himself describes the sculpture as "a new plateau" in his artwork, given that it's twice the size of his other pieces. Moreover, he gained knowledge from making the piece. "I learned so much doing this one," he says. "I could do the next one in half the time."