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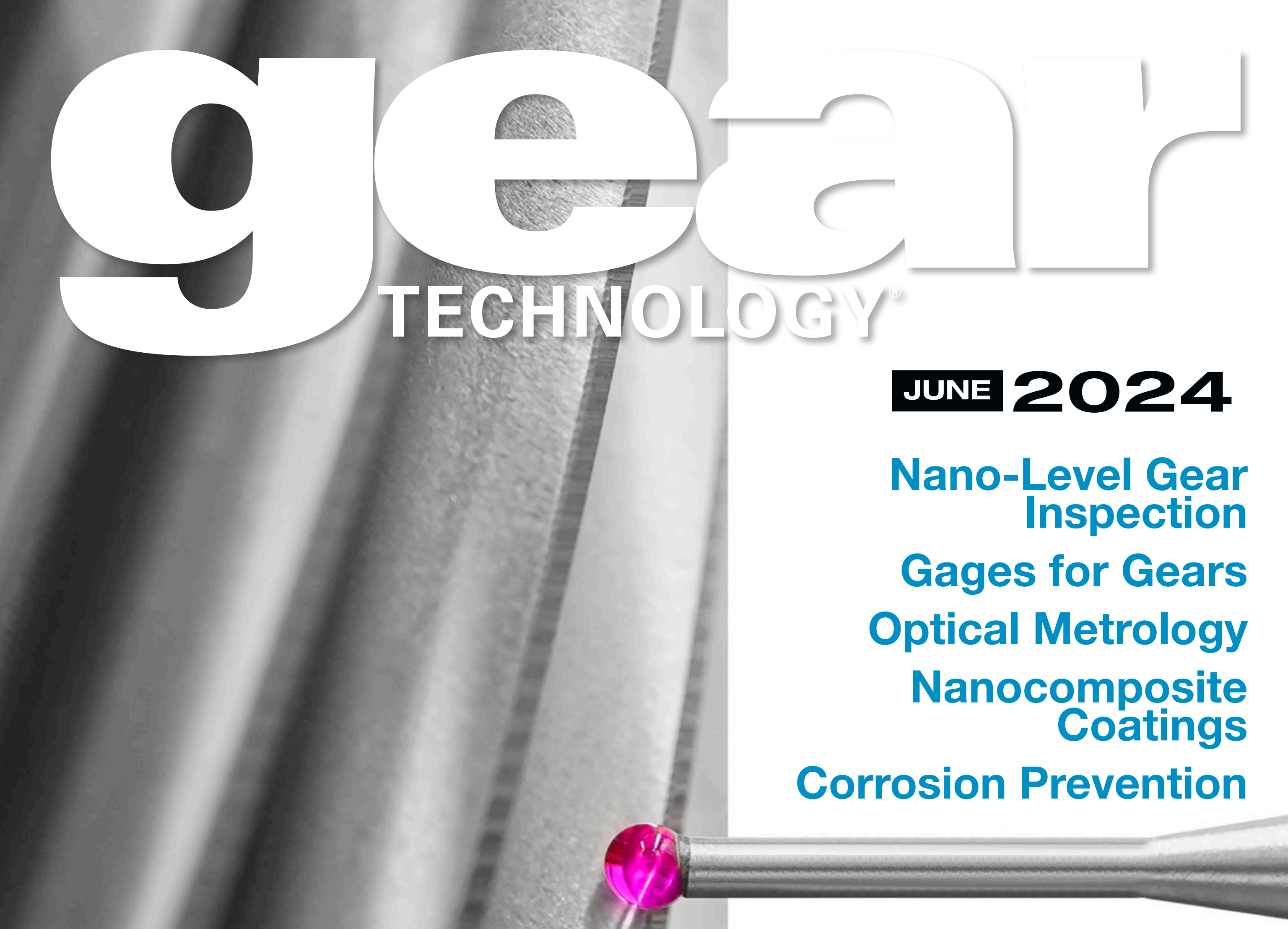

JUNE 2024

Nano-Level Gear Inspection

Gages for Gears

Optical Metrology

Nanocomposite Coatings

Corrosion Prevention

TECHNICAL

Nonlinear Analysis of Gear-Fatigue-Damage Under Variable Load

AGMA

Gear Technology is POWERED by The American Gear Manufacturers Association

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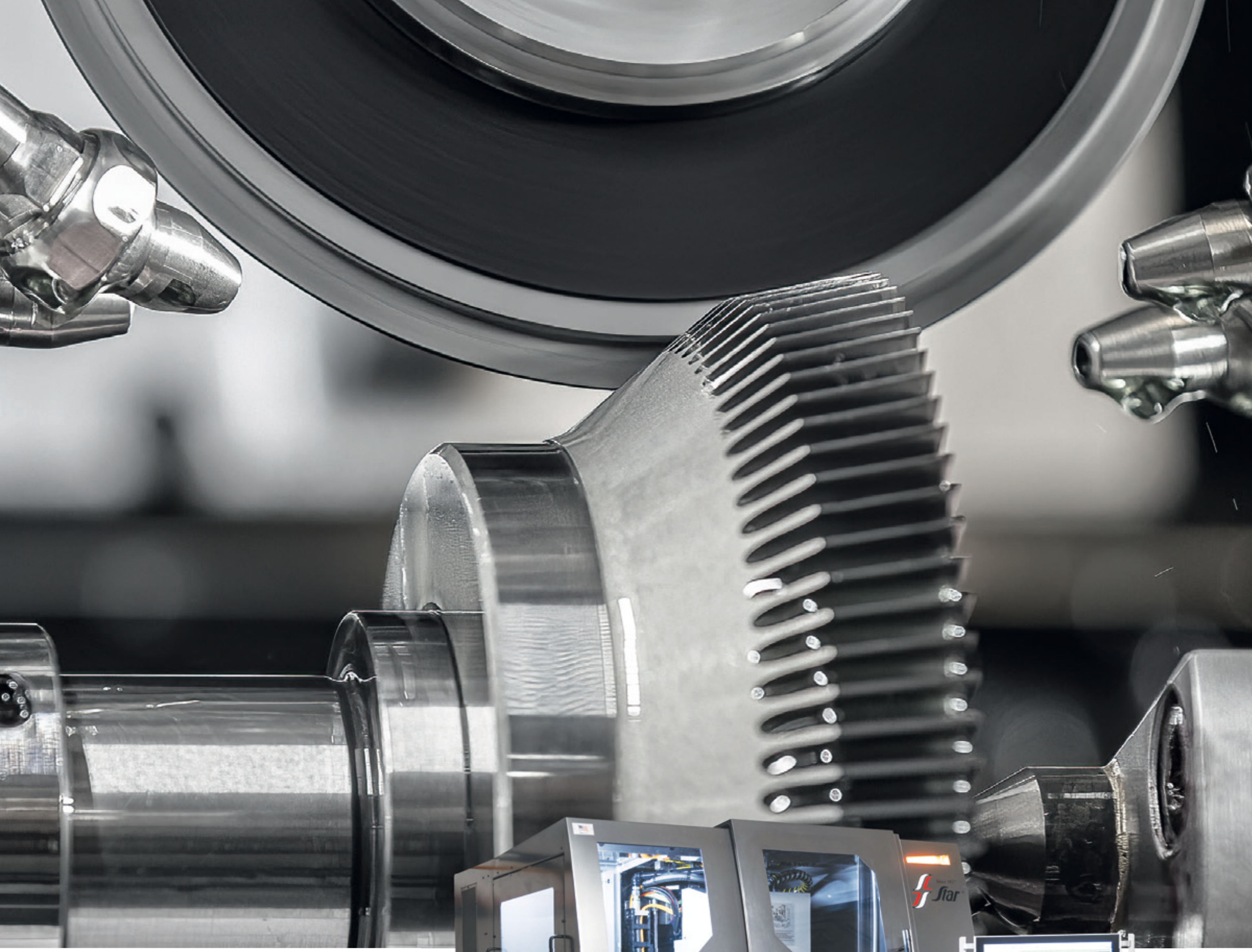


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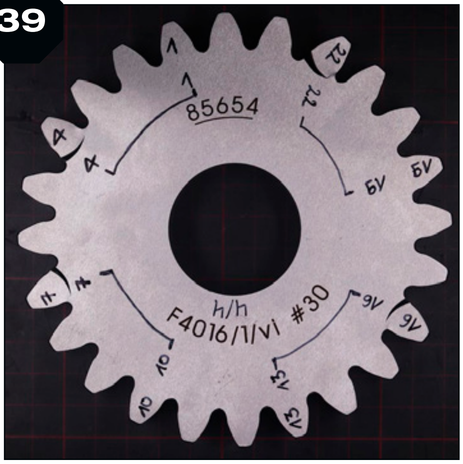

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Vol.41. No.4 GEAR TECHNOLOGY. The Journal of Gear Manufacturing (ISSN 0743-6858) is published monthly, except in February, April, October and December by The American Gear Manufacturers Association, 1001 N Fairfax Street, Suite 500, Alexandria, VA 22314, (847) 437-6604. Periodical postage paid at Arlington Heights, IL, and at additional mailing office (USPS No. 749-290). The American Gear Manufacturers Association makes every effort to ensure that the processes described in GEAR TECHNOLOGY conform to sound engineering practice. Neither the authors nor the publisher can be held responsible for injuries sustained while following the procedures described. Postmaster: Send address changes to GEAR TECHNOLOGY. The Journal of Gear Manufacturing. 1001 N Fairfax Street, Suite 500, Alexandria, VA 22314.

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Vol. 41. No. 4

Photo courtesy of Gleason

gear TECHNOLOGY

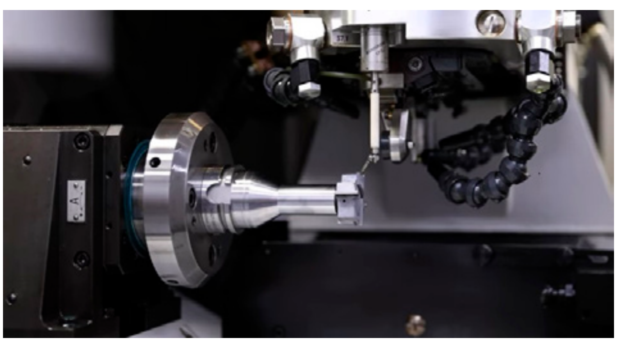
GT VIDEOS

Hera 90 Specification

The Helios Hera 90 CNC gear hobbing machine combines advanced technology, precision components, and economic pricing to enable profitable production of high-quality spur gears, helical gears, straight bevel gears, and other hobbed profiles.

geartechnology.com/media/videos/play/277

Star SU and Neher PCD Reconditioning



Neher's comprehensive line of diamond tools, including finish reamers, combination tools and PCD/CBN inserts, compliments Star SU's cutting tool offering to provide a full-service turnkey solution.

geartechnology.com/media/videos/play/276

AS SEEN IN *PTE*

Master Power Transmission's Automation Transformation with Ready Robotics

In the highly competitive gear manufacturing industry, Master Power Transmission (MPT) recognized the need for innovation. To achieve this, MPT partnered with Ready Robotics, undertaking a transformative journey into advanced automation through their Automation Readiness Assessment (ARA).

powertransmission.com/articles/9749-master-power-transmissions-automation-transformation-with-ready-robotics

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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 38 years' worth of technical articles can be found online at *geartechnology.com.* Michael continues working with the magazine in a consulting role and can be reached via e-mail at *michael@geartechnology.com.*

THE GEAR INDUSTRY'S INFORMATION SOURCE

geartechnology.com

Gears Have to Engage

A single gear, by itself, doesn't do much good. No matter how brilliant its design or how superb its quality, it has to mesh with another gear to achieve anything useful. The transfer of torque, the change of direction and the increase or reduction of rotational speed only occur when two or more gears come together.

The same is true of you.

As a member of the gear industry—whether you're a machinist, engineer, salesperson or CEO—you're just like that single gear. In order to achieve success, you have to engage.

Our organization (both the publication staff and the AGMA at large) produces a lot of information, between the magazines, newsletters, blogs, social media pages, and so on, and we organize a lot of events—everything from specific gear-related education to management-level webinars and in-person events. We publish standards and information sheets, and we convene the technical minds of the gear industry at conferences like the Fall Technical Meeting (coming in October to Rosemont, IL).

It's easy for a newcomer (or even an old timer) to be intimidated and to feel like an outsider at first. But don't just stand on the sidelines and watch. All those other gear experts are actually a pretty welcoming bunch, generous in their information sharing and interested in helping lift the industry as a whole through collaboration.

"Wallflower, Wallflower, won't you dance with me?"
—Bob Dylan (Lyrics from "Wallflower")

The gear industry is calling you to step out onto the dance floor. So don't be shy: Come join, participate and get involved.

It's easy to get started. In fact, *Gear Technology* has prepared a "Start Here" page on our website (*geartechnology.com/start-here*). The page provides a broad overview of all the ways you can engage with the gear industry, along with a list of handy links to help you stay informed, stay connected, learn, conduct business and even contribute your time, knowledge and experience.

Even if you've been in the industry for a while, I think you might be surprised by the vast amount of information and opportunities that are available to you, as well as the variety of ways you can access them. Sure, we'd love for you to stay connected via our magazines, websites, videos, social media and more. But we also hope you'll find and explore how AGMA brings our community together both online and face-to-face.

So please stop by the "Start Here" page to explore how you can engage.

Randy Stott

Publisher & Editor-in-Chief
Randy Stott, Vice President Media


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HWR Workholding

INTRODUCES NEW PRODUCTS FOR LARGE PARTS AND INCREASED FLEXIBILITY

HWR Workholding USA has announced multiple new additions to its SOLIDLine family of innovative zero-point workholding. Available immediately, the new products include SOLIDGrip MAXX for large workpieces, SOLIDBolt FLEXX for direct integration with pallets and tables of select machine tool builders, pyramids for increased capacity in 5-axis machines, and mounting plates to streamline tombstone setups.

"Since formally establishing a US-based subsidiary in 2021, HWR has partnered closely with manufacturers to better understand the current workholding needs in North America," says Thomas Saur, CEO of HWR Workholding USA. "Our most common requests are for solutions for larger parts, products that increase flexibility and products that facilitate automation. Each of our latest introductions addresses one or more of those demands."

With a maximum clamping range of 800 mm (31.5 in.), SOLIDGrip MAXX offers extremely secure holding of large parts. The product capitalizes on SOLIDGrip's modular design, allowing two standard vises to be quickly converted to one large-capacity vise and back again in minutes. For parts that are large in both width and depth, two SOLIDGrip MAXX vises can be applied as a pair. Vise jaws are available in smooth, serrated, and heavy-duty toothed versions to ensure an optimal match to every application.

Developed to simplify and streamline operations, SOLIDBolt FLEXX allows workholding components to be quickly and easily installed. The system enables pull studs to be secured directly to the existing hole pattern on a machine's table or pallets. Following this, the integrated zero-point plate on SOLIDGrip products allows for fast installation of a wide range of workholding products, including vises, risers, chucks, pyramids and more. SOLIDBolt FLEXX is currently available as a standard product for select machine tools from Makino, Matsuura, Mazak and Yasda. HWR will be expanding the product to machines from other builders, and also offers customers custom versions tailored to their specific machine make and model.

For 5-axis machining applications, HWR has launched a series of pyramids that can hold up to three workpieces at a time. Standard products can mount either 46 mm (1.8 in.) or 77 mm (3.0 in.) vises, accommodating a maximum vise length of up to 120 mm (4.7 in.). The pyramids can be directly mounted to a machine's table or pallets, and they significantly reduce non-cutting time caused by loading and unloading workpieces from the work area.

Lastly, HWR's newest tombstone plates feature imperial threaded holes. The plates are available with a 2 in. x 2 in. or 1.5 in. x 2 in. hole pattern and with 1/2–13 or 5/8–11 tapped holes. Once installed on a tombstone, these plates facilitate extremely fast changing out of workholding to accommodate a wide range of parts. These flexible products can be mounted vertically or horizontally and can easily be adapted to 3-axis and 4-axis vertical machining centers.

hwr-usa.com

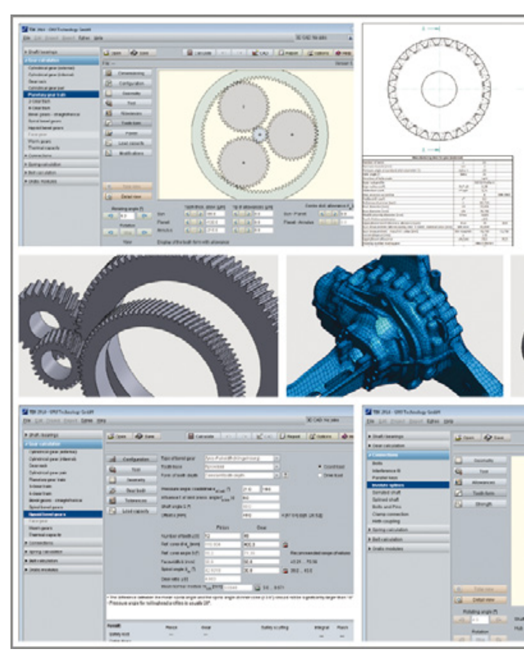
GWJ Technology

PRESENTS NEW VERSION OF *TBK* CALCULATION SOFTWARE

GWJ Technology GmbH has presented a new version of its desktop solution *TBK* with numerous enhancements, particularly in the field of gearing. The *TBK* calculation software has been used successfully worldwide for more than four decades to dimension gears, shafts, connections, bearings, and other machine elements as well as complete gearboxes. With its various interfaces to 3D CAD systems, the *TBK* software is a powerful calculation tool for development, design, work planning, production, and quality assurance.

In the latest version, the load capacity calculation according to DIN 3990 and ISO 6336 has been revised and expanded in the calculation modules for cylindrical gear pairs, planetary geartrains, 3- and 4-gear train systems and gear racks. It is now possible to individually specify additional factors such as the roughness and lubricant factor as well as the velocity or size factor. Furthermore, the calculation in the fatigue strength range has been improved.

In addition, a detailed verification of the load capacity calculation according to ISO 6336:2019 was carried out using the



eight practical examples from ISO/TR 6336-30 published in December 2022. The comparative calculations performed provide very good correlation with the examples from ISO/TR 6336-30. In all eight examples, the absolute deviation of the calculated safeties is ≤ 0.01. These results once again show the high quality of the *TBK* calculation modules.

Furthermore, the wear resistance according to VDI 2736 for dry running plastic gears was added to the cylindrical gear pair, gear rack and gear train system modules.

In response to many user requests, the old DIN 3967 from 1953 for gear tolerances and tooth width dimensions, which has been withdrawn for many years, has been integrated into the calculation modules for single cylindrical gears, cylindrical gear pairs, planetary gear trains, gear train systems and gear racks. The number of decimal places for the input fields can now also be configured individually in these modules.

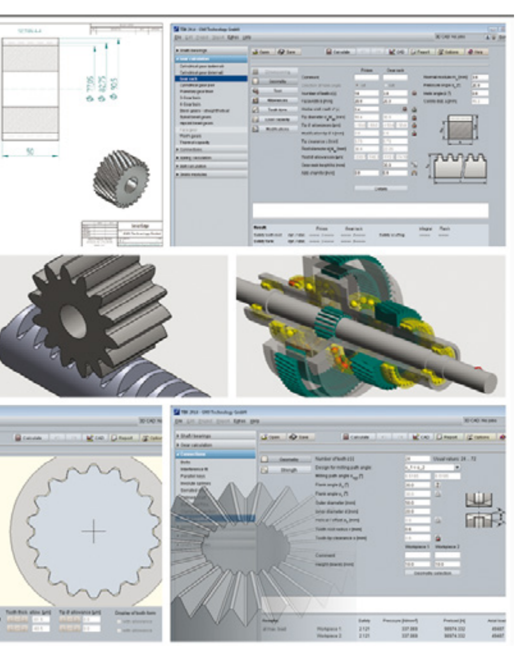
For the design layout available in the cylindrical gear pair and planetary stage modules, additional options have been implemented for the variant calculation, such as "Allow specific sliding > 3 in. or "Allow small geometry errors". The result variants can now also be exported in CSV format.

In addition to the splines according to DIN 5480, ISO 4156, ANSIB92.1 (imperial version), ANSI B92.2 (metric version) and DIN 5482, the French standard NF E 22-141 from 1955 is now also supported in the involute spline module. In doing so, the Primary Series was included as the recommended preferred series of NFE 22-141 for flank-centered splined shaft connections with a flat bottom with the associated tool reference profiles and tolerances.

The calculation of hypoid bevel gears, i.e., bevel gear pairs with offset, is now possible with a new calculation module.

In addition to the new *TBK* version, new versions of the CAD plugins for *Solidworks*, *Solid Edge* and *Autodesk Inventor* are available. Besides the additional generation of 3D rotation surfaces for tip, pitch, and root circles, these offer completely new and extensive options for the automatic generation of tables with the gear data on manufacturing drawings.

gwj.de



Speedgrip Chuck Company

DEBUTS THREE NEW PRODUCTS TO STREAMLINE MANUFACTURING

Continuing its 77-year tradition of master craftsmanship in providing high-quality clamping and gripping technologies for the manufacturing industry, Speedgrip Chuck Company, announced the availability of three new products. The company's NDS Quick-Change Mandrel, QCR Quick-Change Receiver and CSC Contactless Stroke Control improve productivity by making machine workholding changeovers faster and more reliable. Visitors to IMTS 2024 can see these products firsthand in booth #432268 at McCormick Center, West Building, Level 3, in Chicago, Sept. 9–14.

"Our new products build on Speedgrip's heritage and expertise as a leading innovator and producer of standard and customized workholding solutions for the full range of machining applications," said Speedgrip President Matthew Mayer. "At the same time, they integrate new concepts and technology that keep pace with advanced manufacturing, automation and Industry 4.0."

As a portfolio company of Stratford-Cambridge Group, Speedgrip Chuck Company provides manufacturers the means to improve efficiency and productivity by reducing cycle times while featuring affordability and durability. For versatility and efficiency, the NDS Quick-Change Mandrel uses a

unique rear bayonet mount that pulls and secures the workholding collet from behind, eliminating the need for draw screws. The no-draw-screw (NDS) configuration improves workpiece accessibility to quickly and efficiently combine outer diameter (OD) and inner diameter (ID) turning, facing and grinding into one operation with minimal interference.

Speedgrip's patented one-piece sealed collet design outperforms the competition and does not break down with extended use under harsh machining coolants. As the most advanced workholding solution currently available, the NDS Quick-Change Mandrel allows for faster spindle speeds without loss of gripping power due to centrifugal force while significantly extending durability and service life.

The NDS Quick-Change Mandrel is highly adjustable with steering screws to compensate for total indicated runout and concentricity, providing repeatable accuracy to 0.0003 of an inch. The unit is available in seven standard sizes ranging from 0.5 to 5 in. for all standard spindle nose configurations and custom sizes are available upon request.

Speedgrip's revolutionary QCR Quick-Change Receiver is a manually actuated cam-lock receiving plate that attaches to CNC Lathe spindles and dramatically reduces the time needed to change workholding clamping devices. With the QCR Quick-Change Receiver, the time needed for operators to effortlessly switch ID/OD collets, jaw chucks or face driver workholding devices on their machines is cut from an hour to five minutes, making them well suited for just-in-time production. Similar to tool retention in the spindle, the QCR has automatic release of the draw connections.

The QCR Quick-Change Receiver is available for all standard nose configurations, for spindle sizes that run from A2-5 through A11 and flatback spindles. For added versatility, the easy-to-use QCR Quick-Change Receiver also comes in a through-hole design for through-spindle bar feeding operations.

"By engineering the receiver so that only two adapter plates are necessary, we've made the QCR Quick-Change Receiver as modular and standardized for our customers as possible," Mayer said.

Rounding out Speedgrip's new product lineup, the CSC Contactless Stroke Control eliminates the need to manually adjust proximity switches after each workholding clamp changeover and provides fast confirmation of part-clamping position. This smart manufacturing solution automatically displays digital measurement of the cylinder stroke while clamped on the workpiece and machine feedback, stroke position and real-time workpiece dimension data during operation and sends clamp confirmation signals to machine tool CNCs.

In addition to confirming part and stroke position, the control data aids in determining whether part parameters are in range prior to machining and helps prevent scrap and tool damage if workpiece clamping is not confirmed. Plus, the simple, affordable design quickly mounts to virtually any CNC workholding device and easily retrofits to older machines.

speedgrip.com

Measuring Demands Today

Gaging evolves for precision, productivity, ergonomics and more

The L.S. Starrett Company

Precision has not always been associated with measurement. In fact, at the dawn of civilization, man began to use parts of the body to estimate dimensions, and in about 6,000 B.C. from such measurements, there evolved the inch, hand, span, foot, cubit, year, and fathom—the first standards of measurement. Of course, the tools of the past did not demand great accuracy as most products were manually and custom made, so a fraction of an inch in one way or the other made little difference to satisfactory operation.

However, mass production of today demands precision measuring because the parts in any product must be uniform to be interchangeable. Eli Whitney first conceived the basic idea of mass production through interchangeable parts, and it was only through improved methods of measurement and mechanically powered machines that would make mass production possible. There was tremendous growth in mass production of all types of goods during the 19th century. Yet, it was not until after the Civil War that machines and measuring tools approaching the accuracy of modern standards were developed. In 1877 the first combination square was invented by Laroy Starrett, founder of The L.S. Starrett Co.

For precision measuring, skilled machinists, toolmakers, and inspectors must have accurate tools and gages, produced from quality materials, carefully manufactured, and rigidly inspected, to ensure lasting dependability. Gages have evolved throughout the years beginning with mechanical, then electronic models, and now convenient wireless electronic versions have come on the scene. Each type has an important place in today's quality control and inspection processes.

Mechanical

The first precision gages were mechanical, featuring analog readout and are still widely used today. It is safe to say that one would be hard pressed to find a manufacturing operation that is not actively using a mechanical tool. Some precision tools are still only offered in mechanical versions, while many have digital and wireless versions. For linear and round measurements, gages and tools that are used vary with the size of the dimension, the nature of the work and the degree of accuracy required. Mechanical types range from a steel tape, rule, divider or trammel, to a micrometer, vernier caliper, dial indicator and many more.

Electronic

Over the last several decades, electronic gages were introduced offering digital readout and the ability to acquire measurement data for collection purposes and for Statistical Process Control (SPC), analysis and documentation. These types of gages make readings faster and easier for every machinist, regardless of experience.

Electronic gages are capable of transmitting data through cables or wireless without cables, to collection devices to provide a permanent record for SPC, required for many industries today. Properly used, the data collected can provide printouts for analysis and can help a machinist control process, as well as to predict and prevent out-of-tolerance conditions.

Wireless

Relatively recently, wireless precision gages were introduced. Key benefits of using wireless gages including using them as a gage only or within an advanced data collection system are as follows:

- The need for bulky and cumbersome hardware such as backpacks and cables which can be safety hazards is eliminated. Also, by eliminating backpacks and cables, there is less equipment to purchase, so startup costs are decreased, and related maintenance requirements are reduced within the manufacturer's shop tool calibration program.
- Collecting and transmitting measurement data is faster and less error-prone, facilitated simply by measuring and pressing a button to send the data to a mobile phone, tablet, or PC. In this way, operator subjectivity and recording measurement errors are removed, and time is saved when not manually transcribing data. Wireless provides speed, convenience, and ease of collecting and storing data.
- Wireless precision measuring tools are engineered for efficient data collection for a wide range of end uses. Whether it be for International Organization for Standardization (ISO), government, aerospace, or medical requirements, or for smaller shops, the need for accurate data is crucial for traceability to demonstrate qualified parts or to trace back any manufacturing errors. Accurate measurement data provides assurance for the end user and insurance for the manufacturer.
- By using wireless tools and an advanced data collection software system, the data can be efficiently integrated in ERP/ MRP programs. Also, wireless gages promote a cleaner work environment by removing the need for a log journal and pens/pencils, in step with lean manufacturing.
- Quality control is the last step when producing manufactured parts, so if a "bad part" slips by, problems can result in the assembly of the final product or the use of the part in the final product. Using wireless precision gages, inspectors can measure with confidence in order to qualify the part. With the simple push of a button, the measurement data is stored for future analysis or for history purposes. The time and money saved by going wireless and implementing a data collection system is incomparable. Online form-based digital calculators are available that can demonstrate this.

Refining Gage Design

Gage design is continually being enhanced and refined. The first gages, designed by pencil and paper, were bulky and cumbersome featuring crude heavy steel construction with rough edges. These initial gages earned low scores for operator comfort. Over time, gage design significantly improved for fit, size and maneuverability. Using advanced CAD programs with 3D models, gage designs are now generated faster with high accuracy. Improvements keep the operator experience as a top priority, and today's gages are constructed with honeycomb aluminum and rounded contours, making them lightweight and easy-to-hold. One person can use a gage repetitively, compared to earlier times when two people might have needed to complete the same operation due to fatigue resulting from holding and maneuvering the gage.

Special Custom Gages

Even with an extremely broad range of standard precision gages available, whether mechanical, electronic or wireless, some applications require measurements that cannot be taken with a standard gage. So, for these instances unique gages can be designed and manufactured to order. In fact, as gaging technology has advanced so has all tooling and machinery—all which have made it possible to manufacture special gages. The latest advanced gages and tooling are being utilized to manufacture custom gages. For over 50 years, Starrett has provided special gaging solutions to industries including energy, aerospace, automotive, food packaging, high-technology plastics, medical components and to NASA and over government agencies.

The Case for Multisensor Metrology Technology for Gear Parts

Multisensor technology, including vision and touch probe capability, is also a key consideration for fulfilling gear measurement and inspection needs. Having fast, reliable data acquisition in the process is important. The more complex the gear, the higher the demands are for inspection and the more important efficiency becomes.

Providing exceptional speed and efficiency, a multisensor measurement system can easily increase QC throughput by performing multiple processes on a single machine, while maintaining accuracy. For greater productivity and accuracy, more of the gear can be viewed in every image on the latest multisensor vision systems such as the Starrett AVR-FOV featuring a 0.14 magnification lens, large field-of-view of 2.36" x 1.90" (60 mm x 48 mm). and automatic part recognition. Due to "super image" technology, which allows multiple images to be stitched together to form one larger image, together with the system's touch probe technology, the AVR-FOV can accurately inspect a wide range of applications including large, complex and multiple small gears and parts.

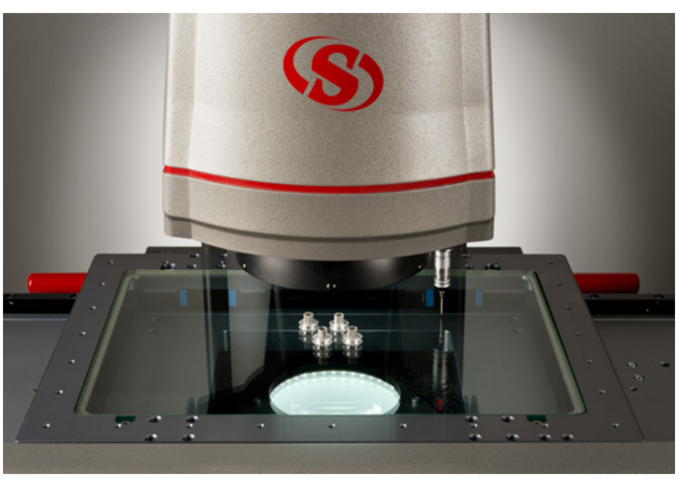
The AVR-FOV automated part programs deliver accurate results to the micron level in a matter of seconds with "Go/No-Go" tolerance zones, and data are provided in one easy-to-interpret report. Video edge detection along with touch probe capability enables measurements to be taken of discreet points along a part's profile, producing accurate profile and pitch inspection results across a wide range of gear sizes. Ensuring that gear production is reliable and consistent protects manufacturers from several issues, including excess noise, load and tooth-to-tooth challenges, as well as premature gear wear or failure.

Also, the Starrett AVR-FOV multisensor vision system is equipped with *M3* software from MetLogix which speeds inspection throughput due to features such as auto part recognition. A user can create a part measurement program that comprises the desired features of a part for inspection, which can automatically be saved in the system or to a network. Gear manufacturers can use the line, radius, and circle annotation in the software to create a part inspection program for an individual gear tooth profile or an entire gear.

Programmable light output options can be built into the program as defined steps, including being called up as the part recognition program initiates. Once the program is created, placing that part within the camera's field-of-view allows for the saved program to initiate and run the inspection. A Renishaw Touch Probe may also be utilized for quick acquisition of discreet points along a part's profile as well as Z-axis measurements.

These advancements, when combined with CNC control, advanced edge detection, and one touch measurement, facilitate what is known as "walk-up metrology". Walk-up metrology enables multiple operators, including those right on the shop floor, to utilize the same system for a variety of applications. This versatility and ease of use significantly helps with bottlenecks in the inspection process and dramatically increases speed of workflow efficiency.

starrett.com



Starrett AVR-FOV multisensor vision system offers micron level accuracy across a wide range of gear sizes.

Preventing Corrosion in Gears

Don't let rusty parts color your company's reputation

Randy Stott, Publisher & Editor-in-Chief

Gear Technology recently had the opportunity to sit down with Thomas White, Marketing Manager for Northern Technologies International Corporation, whose ZERUST line of corrosion prevention solutions includes specialized packaging, testing and comprehensive corrosion management services.

We wanted to find out more about what causes corrosion in manufactured parts and whether there were any special considerations specific to gears, splines and shafts. Here's a transcript of our conversation.

GT: What are the main causes of corrosion in cut metal parts? How much is due to manufacturing processes, parts cleaning, maintenance, packaging, or shipping conditions (i.e. overseas, long transit times, damp/humid conditions)?

TW: Raw metal components typically undergo many metalworking processes such as cutting, grinding, milling, and washing before they are formed into the final product. As a result, metalworking fluids can contain corrosion-causing contaminants that generally originate in the water sources used to prepare the fluids. Contaminants may also build over time due to drag-in and water evaporation.

Before packaging, components are commonly washed, rinsed, and dried. Washing and rinsing may remove soils and particulates, but contaminants are left behind from dirty metalworking fluids/washes/rinses. Incomplete drying will exacerbate corrosion issues, but even perfect drying will leave contaminants on metal surfaces if wash/rinse fluids are dirty.

Finished components are then packaged for shipment or storage. Corrosion can be accelerated due to fingerprints, dirt, incomplete drying or cooling, improper filtration, and direct contact with wooden containers or cardboard boxes.

Container shipments are the most common way to transport metal parts and equipment overseas. During these long journeys, shipping containers are subject to extreme environmental variations such as temperature and relative humidity. With these variations, condensation forms along the inner walls of the shipment containers. This condensation will drip from the walls and ceiling onto the packages inside the container. In addition, if the metal parts are poorly packaged, humidity can enter the packaging and accelerate corrosion.

GT: Are gears any more or less susceptible to corrosion (due to materials, heat treating processes, part geometry or other factors)?

TW: Gears are susceptible to corrosion influenced by a multitude of factors ranging from material selection to operational conditions. The choice of material plays a significant role in a gear's corrosion resistance, with options varying from various steel types, aluminum, and brass to plastics, where alloys like stainless steel are specifically designed to combat corrosion. Heat-treating processes further modify the metal's microstructure, potentially reducing its resilience to corrosive attacks, while surface treatments and coatings, including galvanizing and anodizing, offer an additional defense layer. The environmental context—marked by exposure to chemicals or extreme temperatures—also significantly dictates the rate of corrosion. Notably, the gear's design and geometry can inadvertently facilitate corrosion if it allows for water accumulation or debris retention, whereas proper maintenance practices, including regular cleaning (wash baths or single/dual stage wash), serve as critical preventive measures.

GT: Can a gear manufacturer tell if he has a problem before he receives customer complaints?

TW: Determining the presence of corrosion issues before receiving customer complaints is challenging for gear manufacturers. However, indicators can point towards potential problems, particularly if manufacturers are not adhering to stringent maintenance protocols for their metalworking fluids and are neglecting best packaging practices. Understanding the proper application of VCI technology is crucial for leveraging its full protective potential.

VCI products, available in forms such as poly bags, sheeting, kraft paper, diffusers, emitters, powders and liquids, release vapors containing corrosion inhibitors that form a protective barrier around metal surfaces. It's essential that the VCI vapors remain contained within the packaging environment to be effective. This requires that bags are sealed properly, boxes are fully closed, and metal parts are completely encapsulated, preventing the escape of VCI into the atmosphere.

The effectiveness of VCI is maximized when applied to clean and dry, contamination-free metals. Unfortunately, it's common for manufacturers to package parts without realizing they are contaminated with chlorides, bacteria or other corrosion-inducing ions, often due to fingerprint contamination, unclean workspaces, or inadequate maintenance of metalworking fluids. Moreover, for VCI to form an effective protective layer, metal parts must be fully dry before packaging. Packaging wet or damp parts can initiate the corrosion cycle before the VCI has the opportunity to act.

Another consideration is ensuring metal parts are at ambient room temperature before sealing the packaging to avoid condensation, which could lead to corrosion. This is also pertinent when unpacking metal parts, especially when transitioning from different environmental temperatures. Additionally, when configuring packaging materials, it's crucial to avoid direct contact between metal parts and potential sources of moisture and acid, such as cardboard, non-VCI paper, or wood. Proper placement of dividers or interleave sheets is necessary to not obstruct the VCI's path to the metal surfaces. In configurations involving layered or bulk packaging, additional VCI materials may be required to ensure each layer is protected.

ZERUST offers a comprehensive range of VCI solutions, alongside rust preventative coatings, rust removers, wash chemicals, and technical services. With ZERUST VCI products, manufacturers have access to an effective, environmentally responsible way to prevent corrosion, underpinned by nearly half a century of innovation and expertise in the field. By following ZERUST's guidelines and utilizing their VCI products correctly, manufacturers can significantly reduce the risk of corrosion, potentially identifying and mitigating issues before they escalate to customer complaints.

GT: What are some best practices that all gear manufacturers should be aware of?

TW: Utilizing deionized (DI) or reverse osmosis (RO) water for diluting metalworking fluids and wash chemistry is paramount, as it prevents the introduction of minerals and contaminants that can accelerate corrosion. Proper maintenance routines are essential, including accurate analysis of wash chemistry to ensure correct dilution and thorough cleaning. Effective washing, characterized by sufficient pressure to thoroughly clean parts, routine maintenance of nozzles to prevent clogging, and the use of appropriate temperatures, is crucial for removing contaminants.

Ensuring complete drying of parts is also critical; manufacturers should verify that parts are thoroughly dry, adjusting heat and drying time as necessary to prevent moisture retention. The handling of parts requires meticulous attention, with employees wearing clean and dry gloves to avoid transferring contaminants to the metal surfaces. When it comes to packaging, only clean and dry parts should be packed, with the parts' temperature closely matching that of the room to prevent condensation. VCI packages should be securely sealed using tape, heat seals, zip ties, or by folding over, and resealed after every use to maintain integrity. For added protection, especially in larger or densely packed packages, the insertion of ZERUST VCI materials as interleave can offer additional protection against corrosion. Direct contact between metal parts and materials like wood, paper, or cardboard, which can introduce moisture and acidic conditions conducive to corrosion, should be avoided. By implementing these best practices, gear manufacturers can significantly reduce the risk of corrosion, ensuring that their products maintain their quality over time.

GT: What has changed in rust prevention technology over the years?

TW: For years, rust preventive coatings have been the cornerstone of corrosion protection strategies within the manufacturing sector, including gear production and metal cutting operations. These traditional methods have provided a reliable barrier against corrosion, yet their application and removal often involve the use of hazardous materials, posing safety and environmental concerns. However, the landscape of corrosion prevention is evolving as industry increasingly recognizes the advantages of Vapor Corrosion Inhibitors (VCI) technology.

VCIs represent a significant advancement, offering a safer, more efficient alternative to conventional coatings. Unlike their predecessors, VCIs eliminate the need to introduce hazardous chemicals into the manufacturing environment, addressing health and safety concerns. Moreover, parts treated with VCI are ready to use straight out of the package, streamlining the manufacturing and assembly processes. This immediate usability is particularly beneficial for the customers of gear manufacturers, as it removes the need for any additional preparation steps before the parts proceed to assembly or further processing.

This shift towards VCI technology is driven by the realization of its benefits, not only in terms of enhancing workplace safety and environmental compliance but also in simplifying logistics and reducing overall production times. As manufacturers continue to seek out solutions that optimize efficiency without compromising on quality or safety, the adoption of VCI for corrosion prevention is set to expand, reflecting the industry's ongoing commitment to innovation and sustainability.

GT: How do ZERUST packaging solutions work?

TW: ZERUST VCI products prevent corrosion in several ways:

1. By acting as a protective barrier from external corrosive elements such as abrasion, water, dirt, and acid gas pollutants.
2. By emitting Volatile Corrosion Inhibitors that passivate the electron flow between the anodic and cathodic areas on metal surfaces and interrupt the electrochemical corrosion process.
3. By adding water repulsion properties to the metal surface, which inhibit water from permeating the metal surface and providing the electrolyte for corrosion reactions.

The vapor corrosion inhibitor portion of ZERUST VCI products is made of proprietary chemical formulations that are invisible, odorless, non-toxic, non-reactive, non-flammable, and non-allergenic. These chemical formulations release a corrosion inhibiting vapor that diffuses throughout an enclosure that either contains VCI formulations or is made from VCI materials and settles on exposed metal surfaces to form a microscopic corrosion inhibiting layer.

This protective layer will remain on the surface of the metal if there is no significant, continuous exchange of air within the enclosure. Ideally, there should be less than one air exchange per day (for example, when an electrical cabinet or package is opened briefly and occasionally). Once the metal part is removed from the enclosure, the corrosion inhibiting layer is no longer kept in place by equilibrium with the VCI source, and it dissipates from metal surfaces (typically within about an hour), leaving the metal part clean, dry, and corrosion-free.

The vapor diffusing properties of our corrosion inhibiting formulations offer an important advantage over conventional inhibitor coatings since the traces of these gas molecules penetrate hard-to-access crevices, gaps, and slots. They also cover the surfaces of complex-shaped articles that are difficult to coat. They are adsorbed onto the surface of the metal to form a corrosion inhibiting protective layer that is just a few molecules thick. ZERUST VCI products may also include acid gas absorbing chemicals in the packaging material to act as a barrier and add another dimension to the protection of the metal content. These "scavenging" chemicals react and neutralize the polluted air that may diffuse through the ZERUST VCI material. Also used are various combinations of physical barrier properties that optimize the corrosion prevention and physical protection needs of our customers. These may range from plain low-density polyethylene (LDPE) material to combinations of higher strength, higher tear resistance, higher resistance to sunlight or UV, static charge dissipation, and lower diffusion for moisture or acid gas molecules.

ZERUST VCI products offer corrosion protection without having to be in direct contact with or coated onto the parts that are being protected. Metal parts merely need to be enclosed in or with a ZERUST VCI product (where airflow is minimized) for protection to occur. With ZERUST VCI packaging, it is no longer necessary to apply messy oils, greases, and other corrosion protection compounds and incur the cost of their removal.

GT: Is the chemistry of these products inappropriate for any types of parts (due to chemistry, material or end use)?

TW: ZERUST utilizes a variety of VCI formulations to provide the best possible protection for customer's specific parts and packaging, rather than a sub-optimal one-size-fits-all solution. The selection of the correct corrosion protection products is critically dependent on various factors, including the type of metal substrate, the required duration of protection, and the specific conditions under which the parts will be stored or shipped. It's essential for customers to select the correct products or chemistry to safeguard their gears effectively.

Customers are encouraged to consult with a ZERUST/EXCOR representative to identify the most effective comprehensive corrosion management solution for their metal assets. This ensures that the chosen products are not only compatible with the parts' materials and intended use but also aligned with the environmental conditions and protection duration required, thereby optimizing the longevity and integrity of the gears and other metal components.

GT: How does a manufacturer determine the root cause of his corrosion problems?

TW: Determining the root cause of corrosion problems can be a complex process that requires a comprehensive approach to identify and address the underlying factors contributing to the issue. Manufacturers facing corrosion challenges can effectively resolve these issues by contacting ZERUST. Utilizing the ZERUST Corrosion Inhibiting System (Z-CIS), a proven methodology designed to deploy complex corrosion management systems, manufacturers can ensure the protection of their metal product shipments throughout the global supply chain.

When a manufacturer reaches out to ZERUST, the process begins with a comprehensive site visit where the ZERUST team collects product samples directly from the manufacturing site, alongside samples of all processing fluids and wash chemistry used on the production line. This step is crucial for understanding the specific conditions that may contribute to corrosion, including the evaluation of climatic stress impacts associated with shipping routes. Furthermore, the team updates process Failure Mode and Effects Analysis (FMEA) documents and reviews process control plans to gain a holistic view of the manufacturing and handling processes.

Following the collection and analysis phase, the products and fluid samples are rigorously tested in one of ZERUST's regional laboratories around the world to assess corrosion management system compatibility. Based on the results of these tests and the comprehensive analysis conducted, the ZERUST team formulates and recommends a tailored corrosion protection system, which may include one or several solutions, as outlined in the Z-CIS Deployment Recommendations document.

This systematic and meticulous approach enables manufacturers to pinpoint the exact causes of their corrosion problems and implement the most effective solutions, ensuring the integrity and longevity of their metal products.

GT: What are a manufacturer's typical objections to the various solutions? How do they justify the added cost?

TW: Manufacturers often express reservations about implementing corrosion prevention solutions, with the most frequent objection stemming from the need for approval from their clients, who are the ultimate recipients of the parts they produce. This approval process usually requires ZERUST's involvement in conducting necessary tests and demonstrations to get a ZERUST product specified or approved for use. Many manufacturers initially perceive this process as overly burdensome and time-consuming, hesitating to embark on what appears to be an extensive approval journey.

However, the reluctance typically shifts when the tangible consequences of corrosion become undeniable, often evidenced by the rejection of parts due to rust. This scenario underscores the immediate and long-term implications of inadequate corrosion protection, compelling manufacturers to reconsider their stance. The initial perception of Vapor Corrosion Inhibitors (VCI) and other corrosion prevention measures as merely an additional expense begins to wane when faced with the direct costs associated with corrosion, including rework, disposal of compromised parts, and the negative impact on client relationships.

By adopting corrosion prevention solutions, manufacturers effectively invest in the longevity and integrity of their products, realizing cost savings that far outweigh the initial investment in corrosion protection measures. This strategic approach to managing corrosion ultimately proves to be a cost-effective decision, supporting both the manufacturer's operational efficiency and their standing in the competitive market.

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Figure 1—Parts being coated using PECVD.

Nanocomposite Coatings

A new approach to reducing wear, friction, and corrosion

Olivia Fey, Technical Writer, United Protective Technologies, LLC (UPT)
Mike Greenwald, Vice President of Engineering, UPT

Wear, friction, and corrosion constantly threaten mechanical components, causing efficiency losses and decreased component life. As more efficient designs and material advancements are introduced, these threats continue to be a point of frustration for engineers and end users.

To combat these losses, protective coatings were developed including legacy coatings like nickel-boron, chrome in its various forms, and cadmium typically deposited by electrolysis. While these coatings helped reduce wear, friction, and corrosion, they weren't ideal, primarily due to the adverse health and environmental effects caused during their application and disposal. Not only that, but their performance characteristics left room for improvement and where there's opportunity, there's an engineer ready to develop a solution.

Thanks to advancements in material science and chemistry, particularly in nanoscience, a new solution has emerged: nanocomposite coatings, more broadly referred to as thin-film coatings. But how did we arrive at this point in coating development? As with many technologies, war highlighted the need for more advanced coating development eventually leading to nanocomposite coatings.

Evolution of Nanocomposite Coatings: Pioneering Materials Engineering

World War II Era

Optical Coatings: During World War II, the demand for improved optics led to advancements in optical coatings. Antireflective coatings, composed of thin films, were developed to enhance the performance of lenses and other optical devices.

Post-World War II

Thin-Film Deposition Techniques: In the post-war period, there was significant progress made in thin-film deposition techniques. Vacuum deposition methods emerged, such as Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD). These techniques enabled precise control over coating thickness, microstructure, and composition, laying the foundation for developing nanocomposite coatings.

1950s–1960s

Semiconductor Industry: The semiconductor industry's growth in the 1950s and 1960s drove advancements in thin-film technology. Thin films became integral to the manufacturing of semiconductors, with techniques like sputtering and evaporation becoming widely adopted.

1970s–1980s

Plasma-Assisted Techniques: The use of plasmas to assist in thin-film deposition gained prominence in the 1970s and 1980s. Plasma-Assisted Chemical Vapor Deposition (PACVD) and Plasma Enhanced Chemical Vapor Deposition (PECVD) techniques were developed, improving film properties and lower processing temperatures.

Late 20th Century

Advancements in Coating Materials: Continued research led to developing a wide range of coating materials. Thin films were now being applied not only for functional purposes like corrosion resistance and optical enhancement but also for novel applications in electronics, sensors, and medical devices.

21st Century

Nanotechnology and Multifunctional Coatings: The 21st century saw a convergence of nanotechnology and thin-film coatings. Nanocomposite coatings, with nanoscale materials embedded, became a focus for enhanced properties. Multifunctional coatings, offering a combination of properties such as self-cleaning, anti-bacterial, and enhanced mechanical properties, gained attention.

Diamond-Like Carbon Coatings: Engineering Marvels of Nature-Inspired Design

Amidst the evolution of nanocomposite coatings, diamond-like carbon (DLC) coatings emerged as a breakthrough innovation, drawing inspiration from the extraordinary properties of natural diamonds. Unlike conventional carbon coatings, which often exhibited limited hardness, wear resistance, and adhesion, DLC coatings offered a compelling alternative with their exceptional mechanical and tribological properties.

The genesis of DLC coatings can be traced back to the pioneering work of researchers in the 1970s and 1980s, who sought to replicate the structure and properties of diamonds through various deposition methods. By employing hydrocarbon precursor gases in a vacuum environment, researchers could generate amorphous carbon films with diamond-like characteristics, including high hardness, low friction, and chemical inertness.

The development of advanced deposition techniques, such as plasma-enhanced chemical vapor deposition (PECVD), further refined the synthesis of DLC coatings, enabling precise control over coating morphology, sp^2/sp^3 carbon bonding ratio i.e. diamond/ graphitic ratio, and internal stress levels.

As seen in Figure 1, the ratio of sp^2 to sp^3 carbon bonding has a direct effect on the properties exhibited by a DLC coating. Besides, sp^2/sp^3 ratio, hydrogen content impacts the properties exhibited.

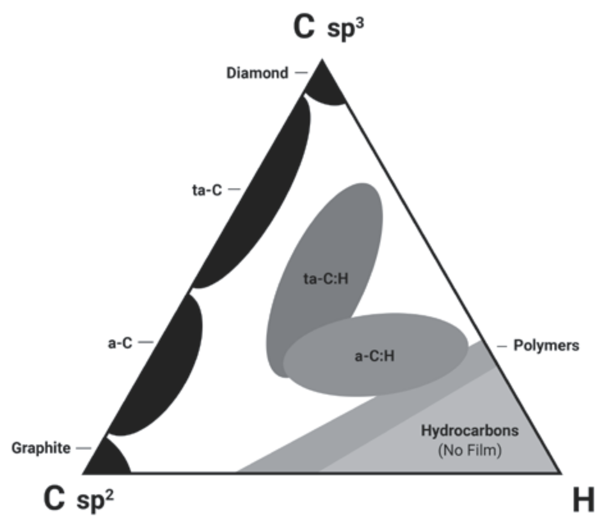

Figure 2—Ternary phase diagram for DLC thin films. Adapted from Ref. 1.

Unraveling the Enigmatic Properties of Diamond-Like Carbon Coatings

DLC coatings exhibit a plethora of exceptional properties, each contributing to their unparalleled performance in various industrial applications:

Hardness and Wear Resistance: DLC coatings boast extraordinary hardness, rivaling that of natural diamond, with values typically exceeding 20 GPa (~ 2000 HV). This exceptional hardness renders DLC-coated surfaces highly resistant to abrasive wear, adhesive wear, and surface deformation, ensuring prolonged service life and reliability in high-stress environments.

Tribological Performance: The low friction coefficient of DLC coatings, coupled with their smooth surface finish, mitigates frictional losses and wear in mechanical systems, thereby enhancing operational efficiency and reducing energy consumption. The tribological behavior of DLC coatings can be further optimized through the incorporation of dopants, such as hydrogen or silicon, to modulate surface chemistry and lubricant interaction.

Chemical Inertness: DLC coatings exhibit inherent chemical inertness, rendering them impervious to corrosive agents, oxidizing environments, and aggressive chemicals. This chemical stability preserves the integrity of coated surfaces and prevents contamination and degradation of adjacent components, making DLC coatings indispensable in harsh operating conditions.

Adhesion and Coating Integrity: The adhesion strength of DLC coatings to substrate materials is critical for ensuring long-term performance and durability. Advanced surface pretreatment techniques, such as ion bombardment or plasma cleaning, promote interfacial bonding and adhesion between the DLC coating and substrate, thereby minimizing the risk of delamination or spalling under mechanical loading.

Biocompatibility and Biofunctionality: DLC coatings exhibit biocompatible properties in biomedical applications, facilitating integration with biological tissues and implants. The bioinert nature of DLC coatings mitigates inflammatory responses and tissue rejection, while surface modifications, such as surface functionalization or bioactive coatings, impart biofunctionality for tailored biomedical applications.

Optimizing Gear Performance: Diamond-Like Carbon Coatings in Action

Now that we've elucidated the remarkable properties of DLC coatings, let's explore their transformative impact on gear applications, with a focus on electric vehicle transmissions and industrial gearbox systems.

Electric Vehicle Transmissions: Efficiency, Reliability, and Sustainability

Electric vehicles (EVs) represent the vanguard of automotive innovation, propelled by electric propulsion systems that demand lightweight, compact, and efficient transmission solutions. DLC coatings emerge as a strategic enabler for enhancing the performance and sustainability of EV transmissions:

Enhanced Efficiency and Range: The integration of DLC-coated gear components within EV transmissions yields substantial improvements in energy efficiency and range. By reducing frictional losses and wear, DLC coatings optimize power transmission, minimize energy dissipation, and extend the operational lifespan of critical drivetrain components.

Thermal Management and Durability: Lower friction results in lower thermal load leading to better thermal management within EV transmissions, thereby mitigating the risk of overheating and thermal degradation. Additionally, DLC coatings enhance the thermal stability and wear resistance of gear surfaces, ensuring robust performance under dynamic operating conditions.

Noise Reduction and Vibration Damping: DLC-coated gear systems exhibit reduced noise emissions and vibration levels compared to traditional metal-on-metal configurations. The inherent damping properties of DLC coatings attenuate mechanical vibrations, harmonics, and resonance, thereby enhancing passenger comfort and drivetrain refinement in EVs.

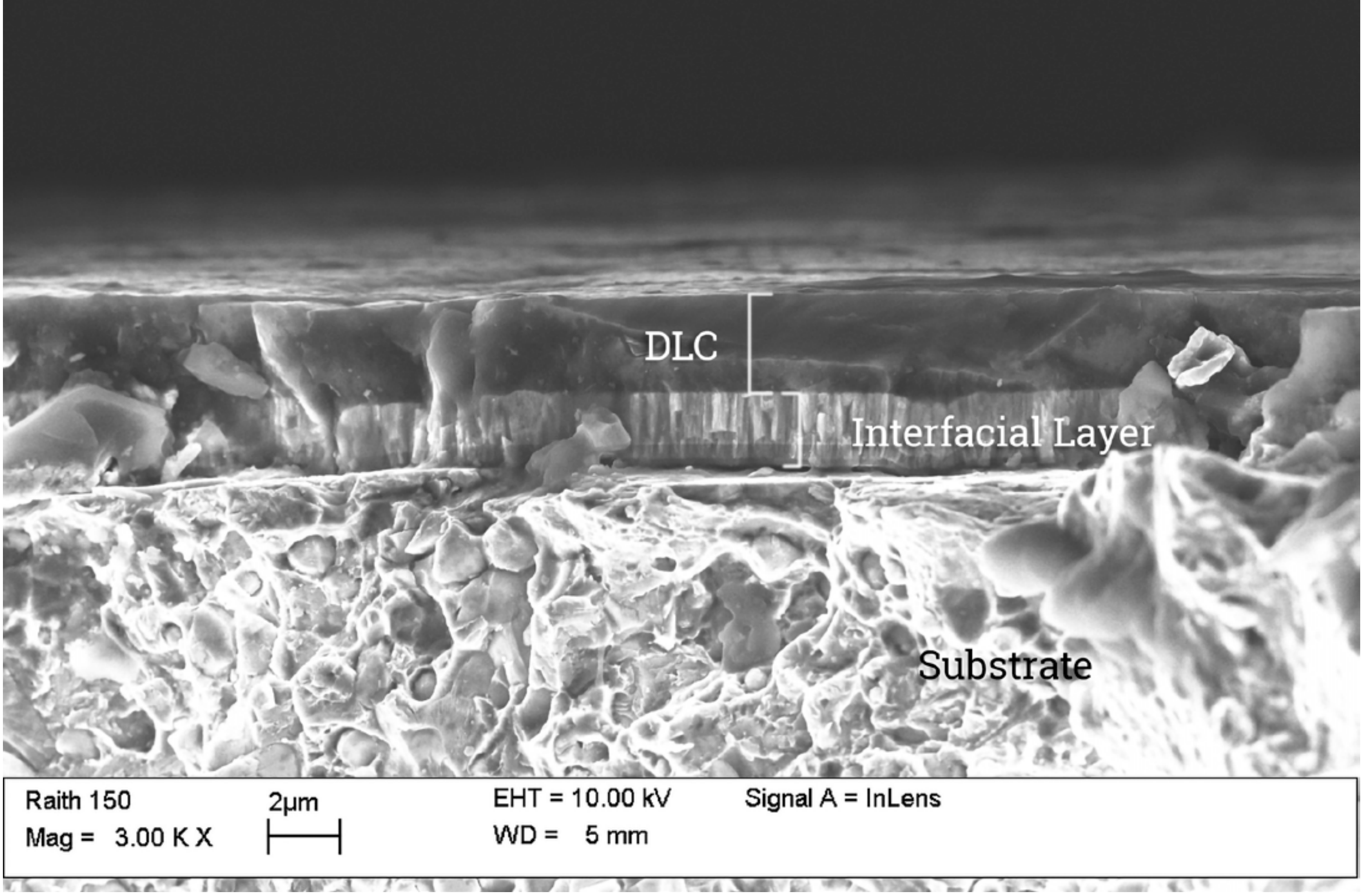

Figure 3: SEM micrograph of Nanocomposite coating.

Industrial Gearbox Systems: Productivity, Reliability, and Maintenance Optimization

In industrial settings, gearbox systems serve as the mechanical backbone of machinery and equipment, facilitating power transmission, speed reduction, and torque amplification across diverse applications. DLC coatings emerge as a strategic asset for optimizing the performance, reliability, and maintenance requirements of industrial gearbox systems:

Enhanced Load-Bearing Capacity: DLC-coated gears exhibit superior load-bearing capacity and fatigue resistance, enabling them to withstand the rigors of heavy-duty industrial applications. The exceptional hardness and wear resistance of DLC coatings mitigates surface damage, pitting, and micro-fractures, thereby prolonging the service life of gearbox components.

Efficiency Optimization and Energy Savings: Industrial gearbox systems often operate at high torque levels and rotational speeds, necessitating efficient power transmission and minimal energy losses. DLC coatings reduce frictional losses, improve gear meshing efficiency, and optimize lubricant retention, resulting in energy savings, reduced operating temperatures, and enhanced gearbox efficiency.

Maintenance Interval Extension: DLC coatings mitigate the need for frequent maintenance interventions and lubricant replenishment in industrial gearbox systems. The self-lubricating properties of DLC-coated surfaces, combined with their resistance to abrasive wear and surface oxidation, contribute to extended maintenance intervals, reduced downtime, and enhanced equipment availability.

Advanced Applications and Emerging Trends in DLC Coatings

Beyond conventional gear applications, DLC coatings are finding novel applications and driving innovation across diverse industries:

Aerospace and Defense: DLC coatings enhance the performance and durability of aircraft components, such as gears, bearings, and actuators, in demanding aerospace environments characterized by high speeds, loads, and temperatures.

Renewable Energy: DLC coatings optimize the efficiency and reliability of wind turbine gearboxes, hydroelectric turbines, and solar tracking systems, thereby contributing to the expansion of renewable energy sources and sustainable power generation.

Medical Devices and Implants: DLC coatings exhibit biocompatible properties and wear resistance, making them ideal for orthopedic implants, surgical instruments, and medical devices requiring prolonged contact with biological tissues.

Microelectromechanical Systems (MEMS): DLC coatings provide lubrication and wear protection for MEMS devices, such as accelerometers, gyroscopes, and microvalves, enabling miniaturization and improved performance in microscale applications.

Challenges and Future Directions in DLC Coating Technology

Despite the myriad benefits offered by DLC coatings, several challenges and opportunities exist on the horizon:

Optimization of Deposition Processes: Enhancing the deposition efficiency, uniformity, and scalability of DLC coatings through advanced deposition techniques, such as plasma immersion ion implantation (PIII) and hybrid deposition methods, to meet the demands of mass production and high-throughput applications.

Tailoring Surface Properties: Engineering DLC coatings with tailored surface properties, such as tunable friction, wear, and adhesion. This is accomplished through the incorporation of dopants, nanocomposite additives, or surface functionalization techniques, to address specific application requirements and performance objectives.

Multifunctional Coating Systems: Developing multifunctional coating systems by integrating DLC coatings with complementary materials, such as diamond nanoparticles, metal oxides, or polymers, to synergistically enhance mechanical, thermal, and electrical properties for multifaceted applications.

Sustainability and Environmental Impact: Exploring sustainable sources of precursor materials and renewable energy sources for DLC coating deposition processes and advancing recycling and reclamation technologies for reclaiming and reusing DLC-coated components to minimize environmental footprint.

Conclusion: Harnessing the Power of Diamond-Like Carbon Coatings

In conclusion, diamond-like carbon coatings epitomize the convergence of cutting-edge material science, nanotechnology, and engineering innovation. Their exceptional hardness, tribological performance, chemical inertness, and biocompatibility render them indispensable in various industrial applications, particularly in gear systems where durability, efficiency, and reliability are paramount.

Embracing the transformative potential of DLC coatings unlocks new frontiers in performance optimization, sustainability, and technological advancement. By integrating DLC-coated components into gear assemblies, you not only elevate the operational efficiency and longevity of machinery but also contribute to the broader objectives of energy conservation, emissions reduction, and sustainable development.

In the ever-evolving landscape of materials engineering and surface technology, diamond-like carbon coatings stand as a beacon of progress and possibility, empowering industries to surmount challenges, transcend limitations, and redefine the boundaries of what's achievable. These goals drive the continuous innovation here at United Protective Technologies (UPT). For more than two decades UPT has researched, developed, and applied advanced surface solutions for demanding applications. Our nanocomposite coating innovations are used to enable advancements in industries from aerospace to automotive, medical to metalworking, weapons systems to oil and gas.

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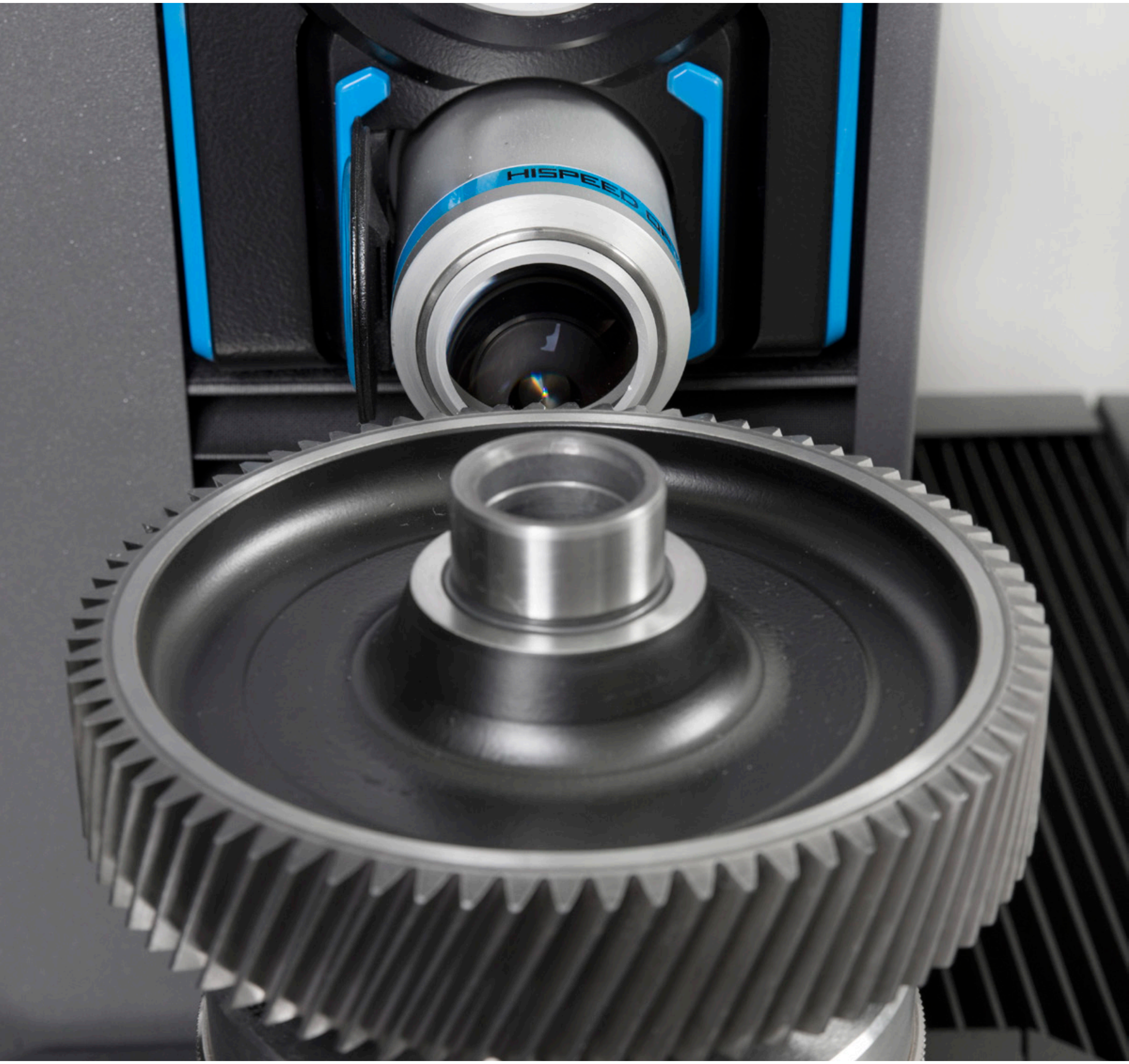
Optical Metrology for Evaluating Gear Noise

Klingelnberg looks at changing demands in automotive applications

Dipl.-Ing. Markus Finkeldey, Head of the Competence Center for Optical Metrology, Klingelnberg GmbH



Klingelnberg is keeping pace with changes in the industry and delivering the usual quality and flexibility that are required for higher gear throughput.

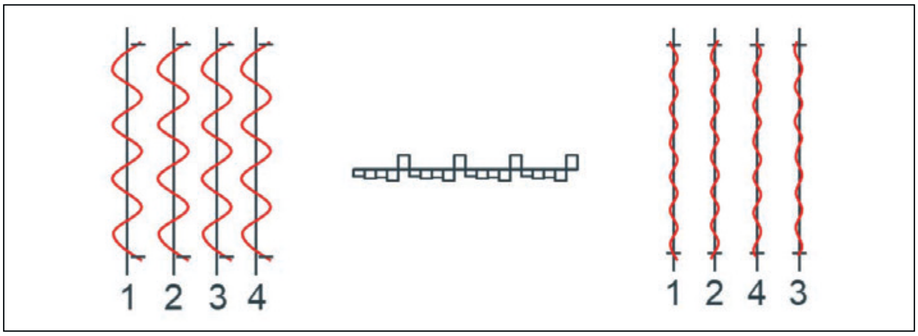


Figure 1—The three typical noise sources of a transmission caused by gears (from bottom to top): uniform profile deviations, uniform single pitch deviations, and nonuniform profile deviations distributed periodically over all teeth (here on four different teeth).

When electric drives are used in vehicles, the masking effect of an internal combustion engine disappears, allowing the noise behavior of the transmission to take center stage. At the same time, peak power and torque increase, engine speeds increase, and power must be transferred optimally in both directions due to the regenerative braking system. Conventional design parameters remain important, however: The build space is limited, durability must not be compromised, and the product must still be cost-efficient. Optical metrology as part of a hybrid measurement concept helps to overcome all these challenges.

In the automotive industry in particular, the demands placed on transmissions and thus also on gears have changed dramatically. When electric motors are used with increasing frequency, the design criteria and requirements for gear and transmission designs change. This applies to both hybrid drive concepts and pure-electric vehicles—in fact, the choice of energy source (battery or fuel cell, for example) hardly plays any role at all for the transmission. In addition to production machines, such developments call for even more precise, modern metrology.

The first question that is frequently asked is how accurate a measurement must be. A highly accurate measurement is often relatively slow—and thus expensive—putting it in direct conflict with modern gear measurement systems, with their fast cycle times on the shop floor and high-cost pressure. At the same time, today's evaluations, such as those used for noise analysis, require an extended measurement scope compared to conventional gear measurement. It is therefore important to know exactly what needs to be measured, and what the measuring equipment needs to be capable of doing. The capability of the measuring equipment is one of the factors that determines whether the end result is a capable process.

Capable Measuring Equipment Theory

To evaluate the capability of measuring equipment, two things are required: a target value in the form of a tolerance and a method to verify whether this tolerance can be reliably measured. The first reference for tolerances (cylindrical gears) is DIN ISO 1328, where formulas for geometry- and type-dependent tolerances for different quality classes can be found. Typical quality classes in the automotive sector range from Class 4 to Class 6 with corresponding values for numerous deviation types in the one- to two-digit-micrometer range. The method usually chosen is a capability analysis or measurement system analysis (Type 1 study), in which the repeatability (standard deviation or *Cg* value) and the systematic deviation (*Cgk* value) are determined on a certified artifact over a study range of at least 25 (typically 50) measurements. The *Cg* value for such an analysis is defined as follows:

$$Cg = \frac{(dt * T)}{(si * \sigma)}$$

where T is the drawing tolerance (as specified in DIN ISO 1328) and dt is a tolerance factor (typically 0.2, corresponding to 20 percent). *si* is a sigma interval factor that defines the permissible process variation via the number of standard deviations: Typically, this is 4 σ or 6 σ, ≈ 95 percent or ≈ 99 percent, respectively. *Cgk* is broadly equivalent to *Cg* but is extended to include an average deviation from a reference value. It is defined as follows:

$$Cgk = \frac{dt * T - 2 * |\overline{x} - x_m|}{si * \sigma}$$

where x is the mean value of the measurements and xm is the target value of the certified artifact. Such an artifact, sometimes called a master component A frequently selected target variable to describe a reliable process is *Cg* => 1.33 and *Cgk* => 1.33. The standard deviation (sigma, σ) used in both formulas is defined by:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2}$$

where n is the number of measurements, i an index, xi a measured value at point i i, and $\overline{x}$ is the mean value of all n measurements.

Practice of Capable Measuring Equipment

In the practice of gear measuring technology and quality control, gear designers like to modify the recommendations of DIN ISO 1328. In quality control as well, the target values for *Cg* and *Cgk* are often compared against concrete values, as are the sigma intervals and the tolerance factors. To define the demands on modern measuring equipment more precisely, it is helpful to take a look at the typical problem sources of gear noise caused by gears (see Figure 1).

Uniform Profile Deviations

Uniform profile deviations originate, for example, from the tool or are remnants of feed marks from the preliminary process. They are equally distributed on all teeth and are reflected in the tooth mesh frequencies as well as their multiples. Often, these amplitudes are in the 0.8 µm to 3 µm range. Theoretically, these defects can be detected by measuring a profile line of a tooth. In practice, three or four profile lines are often measured on different teeth. Thus, these defects can usually be determined with sufficient accuracy.

Uniform Single Pitch Deviations

These defects are responsible for low frequencies (3rd to 8th order), and the amplitudes are in the range of 0.4 µm to 3 µm. They originate, for example, from inaccuracies of the tool or processing machine, or from inadequate mounting of tools and blanks, or they are caused when machines are started up. A pitch measurement requires measuring all teeth on the pitch measuring circle at one or more depths. To correctly determine the amplitudes of the defect, it is necessary to correctly determine the axis position of the component in addition to ensuring that the measuring equipment is accurate.

Nonuniform Profile Deviations

These defects vary from tooth to tooth but occur periodically over the entire periphery. Their amplitudes are in the 0.02 µm to 0.8 µm range and are responsible for what's referred to as ghost frequencies, or ghost orders, in the evaluation. Causes for this type of deviation include the stability of the tool used in production as well as dynamic effects during production, such as vibrations, etc. In order to reliably detect nonuniform profile deviations and analyze their effects on gear noise, as many teeth as possible must be measured—and ideally all teeth. This task is usually very time-consuming with conventional tactile metrology.

The minimum requirements (3 µm amplitude at 20 percent and a 4-σ interval) of a piece of measuring equipment to reliably measure the described deviations can be determined by converting and plugging into formula 1. The limiting value of a standard deviation that can still be toleranced is obtained in this way ($\sigma \approx 112$ nm). Such a value can be achieved for modern tactile precision measuring centers, but the measurement reliability is minimal even when the amplitude is reduced by half to 1.5 µm ($\sigma \approx 56$ nm). The same threshold value must apply for fast, optical systems. However, due to the higher number of measurements within the same time frame, it

Figure 2—Hybrid metrology on a final drive for electromobility, gear quality 4 according to DIN ISO 1328, 82 teeth.

is recommended to increase the study size. In critical cases, Klingelnberg works with a minimum of 100 measurements to ensure that the results obtained remain stable over the duration of an entire shift (typically seven to eight hours).

Finding the Right Measuring Equipment for Every Challenge

Uniform deviations—both in profile and pitch measurements—can currently be determined quickly and with sufficient process reliability using hybrid precision measuring centers. The profile lines are measured using the tactile method and the pitch by means of optical sensors. Both systems achieve sufficient accuracies even under production conditions. Complete integration of optical metrology as a hybrid measuring concept in the precision measuring center means that the fast, contactless metrology benefits from flexible, tactile measurement of the workpiece axis, temperature compensation, and vibration isolation as an optional feature. Nonuniform profile defects currently require a comparatively high measurement effort. The required measurement precision in the form of a standard deviation of $\sigma << 100$ nm to reliably detect corresponding defect patterns can often only be achieved with tactile metrology and measurement strategies optimized for speed. Due to the nonuniformity and low amplitudes, deviations of this type are the greater challenge for gear measuring technology.

Klingelnberg Strategy

As shown in the example described here, for modern gear measuring tasks, a measuring system benefits from increased speeds—but this must not be at the expense of accuracy. The Klingelnberg optical system was developed and produced largely in-house and optimized for maximum accuracy right from the start. Optical pitch measurement has been achieving consistently reproducible results since the first delivery in 2021 and is thus the first step towards solving current challenges with modern metrology and conventional accuracy (see Figure 2).

Following the same approach, the next steps will solve the most time-consuming tasks at higher speed but with the measurement precision customers are accustomed to. Here, Klingelnberg is focusing on the challenges that the industry is currently facing, with an emphasis on integrated measuring concepts that can be further developed, particularly intelligent evaluation strategies.

Conclusion

With its optical metrology, Klingelnberg is keeping pace with changes in the industry and delivering the usual quality and flexibility that are required for higher gear throughput while also satisfying the requirements for state-of-the-art evaluation methods (Gear Deviation Analysis, GDA) and interfaces such as OPC UA (Unified Architecture Open Platform Communications). Hybrid metrology can be combined particularly effectively with the highspeed Höfler R 300 Cylindrical Gear Roll Testing Machine, a reliable combination for noise and quality control on the networked shop floor.

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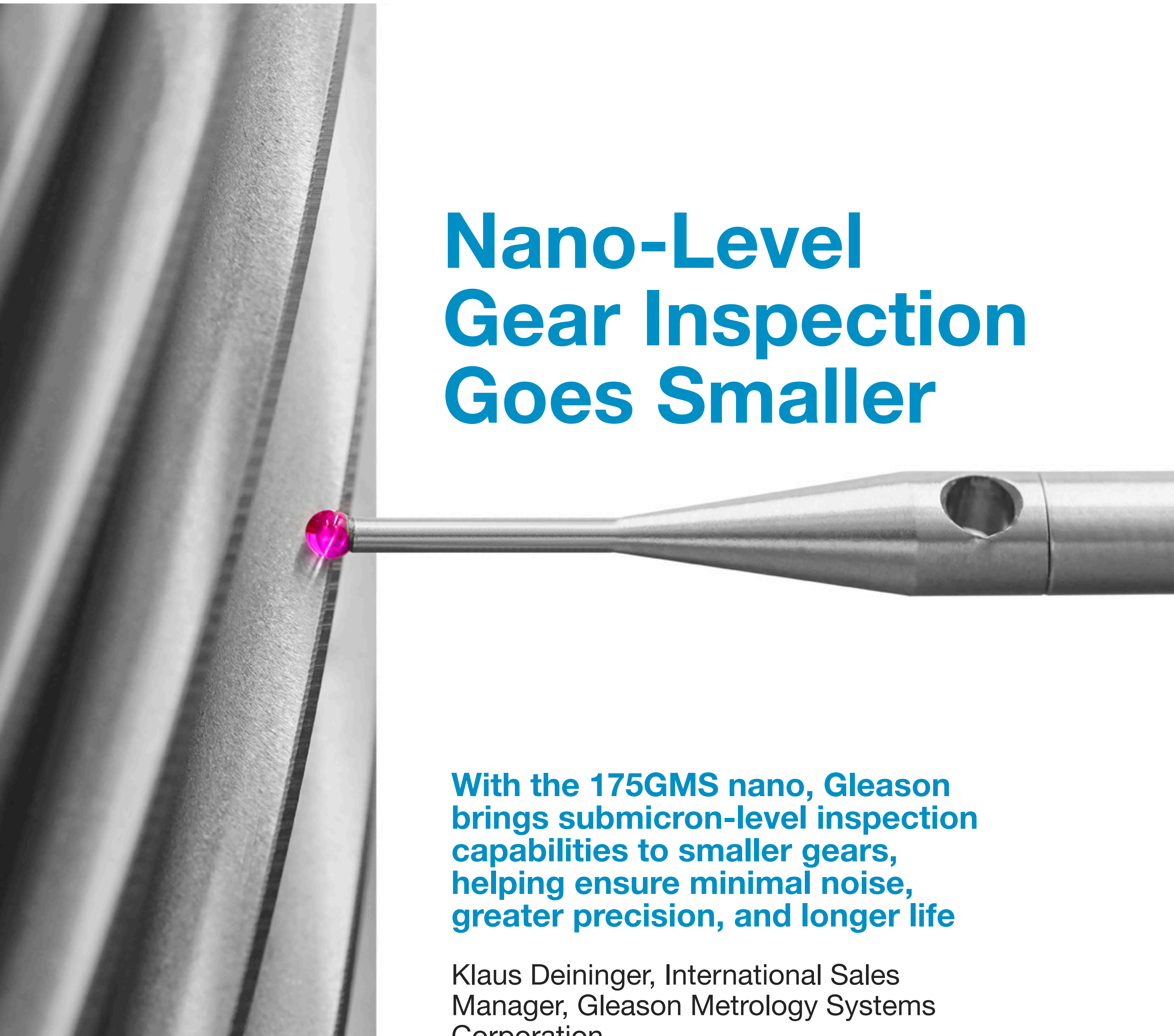


Nano-Level Gear Inspection Goes Smaller

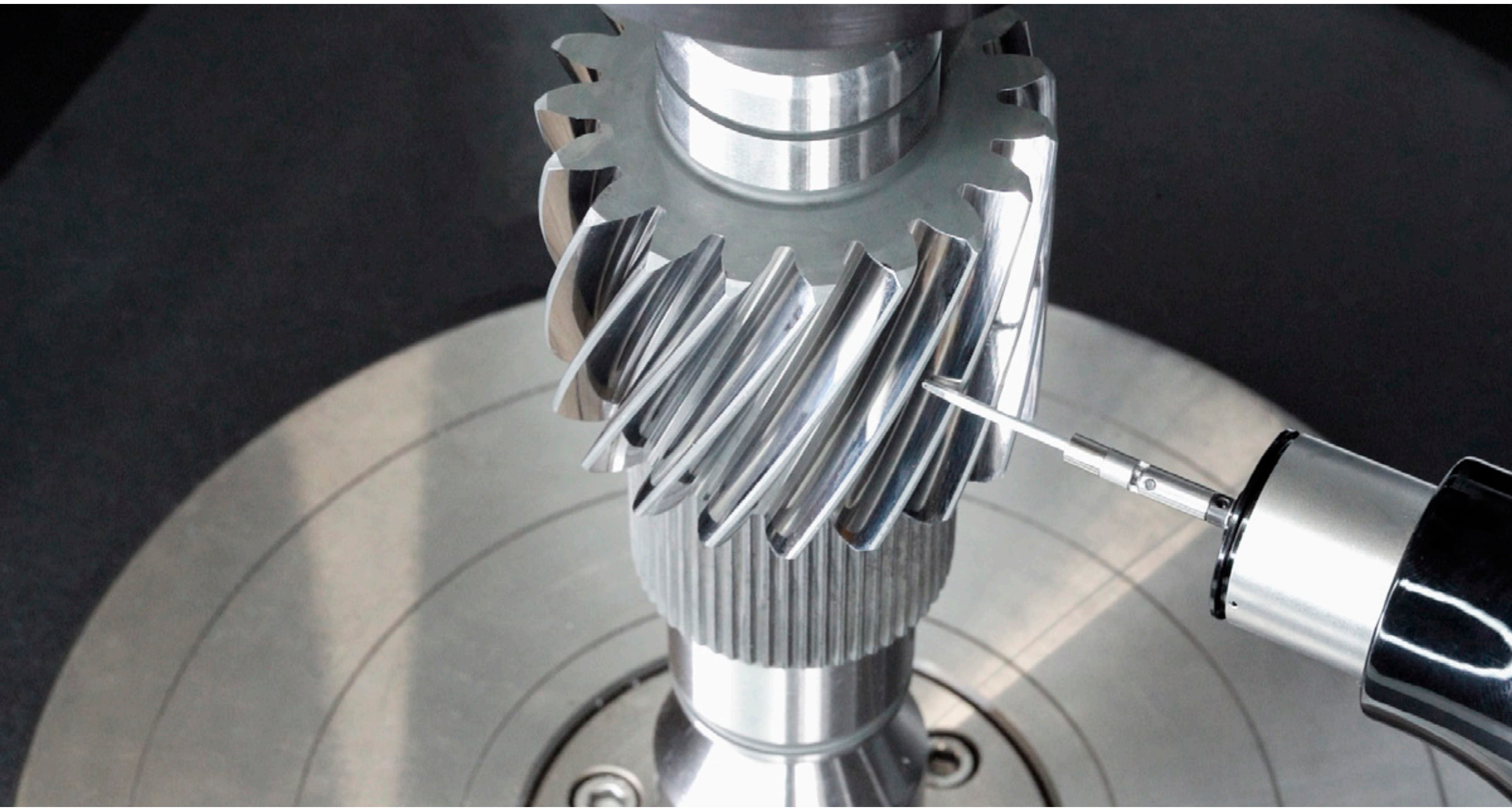
With the 175GMS nano, Gleason brings submicron-level inspection capabilities to smaller gears, helping ensure minimal noise, greater precision, and longer life

Klaus Deininger, International Sales Manager, Gleason Metrology Systems Corporation

Complete inspection of gear surface finishes at the submicron level became a reality with the introduction of Gleason's 300GMS nano, in 2022. The new system ushered in an exciting new era in gear inspection. For the first time, producers of EV transmission gears, and gears for other applications requiring very tight tolerances and low noise requirements, could quickly inspect surface finishes and perform extremely reliable noise analysis at submicron levels—benefits that were almost impossible to achieve just a few years ago.

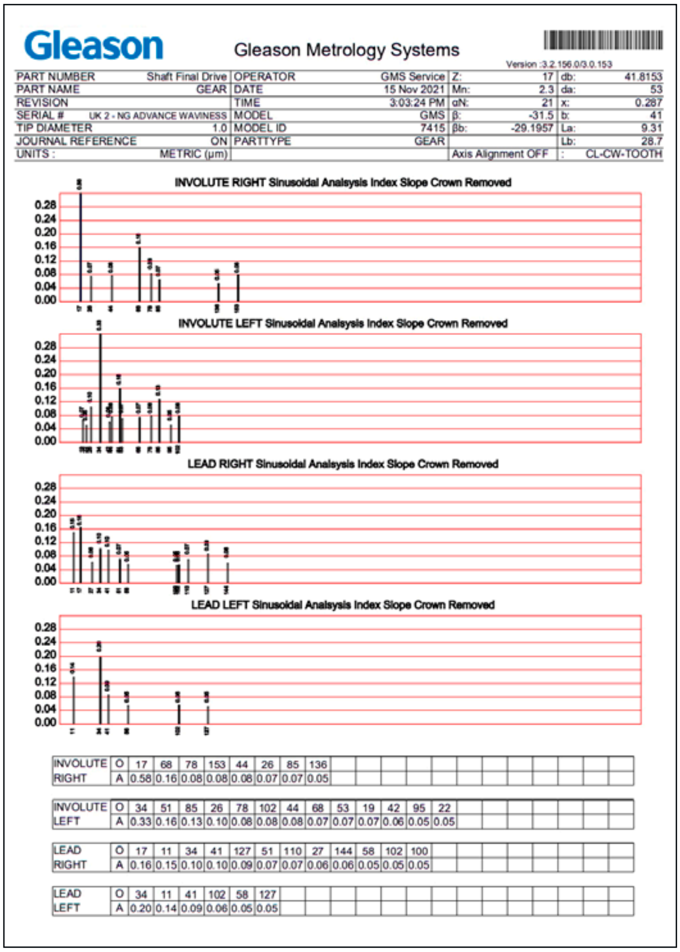
Now, based on the success of the 300GMS nano platform, Gleason has expanded its nano series with the introduction of the 175GMS nano gear metrology system. The 175GMS nano picks up where the very popular 175GMS leaves off. Like its predecessor, it's designed for the complete inspection of all types of gears as large as 175 mm in diameter and shaft-type gears up to 500 mm in length, with a module range of 0.4 (0.2 is optional) to 6.35 mm. But it also delivers the additional nano capabilities first offered with the 300GMS nano. Users can now measure, at submicron level, gear pitch, tooth size, profile, and lead at high speed along with surface finishes with a skidless probe seamlessly integrated into an automated probe changer. The latest *GAMA* software platform also performs noise analysis with the Advanced Waviness Analysis software tool. The 175GMS nano gear metrology system is equipped with a high-precision SP25 3D scanning probe head, a wide range of styli, and an advanced mathematical analysis that supports roughness evaluations to DIN, ISO, ANSI, and other standards. It also offers 3D measurement and GD&T analysis rivaling those of a CMM.

Based on the success of the 300GMS nano platform, Gleason has expanded its nano series with the introduction of the 175GMS nano gear metrology system, for all types of gears as large as 175 mm in diameter and shaft-type gears up to 500 mm in length, with a module range of 0.4 (0.2 is optional) to 6.35 mm.



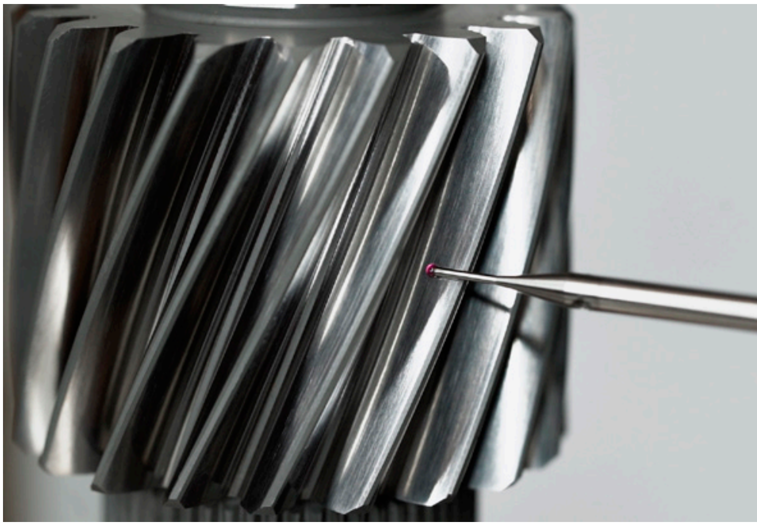
Users can now measure, at submicron level, gear pitch, tooth size, profile, and lead at high speed along with surface finishes with a skidless probe that is seamlessly integrated into the automated probe changer.

Like all the metrology systems in the Gleason GMS series, the 175GMS nano seamlessly integrates into any user's manufacturing ecosystem through Gleason's latest *GAMA 3.2* application with its best user-friendly interface supporting a dozen plus international languages. Fully compatible with Windows, it effortlessly integrates into server environments, opening avenues for enhanced SPC data evaluation and remote maintenance services via Gleason Connect, among others.



175GMS nano can quickly inspect surface finishes and perform extremely reliable noise analysis at sub-micron levels, using the latest GAMA *software platform and* Advanced Waviness Analysis *software tool.*

Through Gleason's "Closed Loop" feature, users can take the connectivity of manufacturing and inspection to the next level. The 175GMS nano communicates inspection results directly to Gleason production machines, enabling automatic correction of machine settings. From power skiving to threaded wheel gear grinding, this synergy opens new horizons for quality production. Additionally, inspection results like topography measurements and order spectrum from *Advanced Waviness Analysis* software can be forwarded to *KISSsoft* design software. In *KISSsoft,* the designer can then see the differences between the design and the actual produced gear and evaluate variables such as the differences in contact patterns in the final application under various load conditions. Noise behavior can then be predicted even before testing on a single flank tester or end-of-line tester at the final installation. This technology advantage, known by Gleason as "Smart Loop," holds the key to elevating gear designs faster and more seamlessly to a much higher level, for peak performance.



The 175GMS nano Gear Metrology System is equipped with a high-precision SP25 3D scanning probe head, a wide range of styli, and an advanced mathematical analysis that supports roughness evaluations to DIN, ISO, ANSI, and other standards.

The 175GMS nano is optionally equipped with the patented Advanced Operator Pendant (AOP) enabling operators to record video and voice messages and to monitor environmental conditions. It may also be used to support remote maintenance via video telephony, and it can read bar and QR code information directly into the machine, for further use in inspection protocols or to select the appropriate inspection cycle.

As gear industries advance, so too does the need for unparalleled precision. The 175GMS nano gear metrology system heralds the advent of a new era, where nano-level inspection is no longer the exception, but the rule. The Gleason 175GMS nano is just the latest example of how Gleason continues to redefine the boundaries of what's possible, setting the stage for the future of gear quality and performance.

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Crossroads of Creativity and Manufacturing

Mary Ellen Doran, AGMA Director, Emerging Technology

I fly out west to Los Angeles later this month. It will mark the fourth time AGMA will provide a curated tour on the RAPID+TCT show floor. Each year brings more clarity on developed technologies, I am always looking for one or two tweaks that move the needle on the next possibility for additive manufacturing to impact traditional manufacturing processes. Are we looking for mass-produced 3D metal gears? The short answer is: no. But we are always watching indicators that may change that answer.

Additive manufacturing affords options outside the capabilities of traditional subtractive manufacturing. We are constantly monitoring this space. If the right material with the right science to rival gear is created, that would be important to note. If two materials can be printed together where they could not be traditionally machined together to create better gears, this would be an important step. (Especially, if it could be made cheaply.) And if that material could be printed in a nontraditional form that elevates what a gear can do now, then we will see disruption in the gear industry.

On this trip, we plan to show attendees useful information in three specific areas for gear manufacturers today: materials, cutting tools, and tooling. The tour will take our group to 15–17 exhibitors for a short presentation and then the opportunity for direct interaction, where we can ask our burning questions. Do you print hobs? How can we utilize 3D printing for tooling? And what is the latest in materials development? And then a little bit of time is saved to see the new and visionary.

Past AGMA RAPID tours have afforded our members audiences with leaders in the field, like Jonah Myberg, CTO for Desktop Metal. Last year, we had a great discussion with Mark Norfolk, President & CEO of Fabrisonic, learning about low-temperature ultrasonic additive manufacturing, his company's novel technique, which is definitely "cool." These discussions have led to deeper dives for the wider AGMA audience; in Desktop's case, a presentation at an AGMA SNL event, and in several other cases, we have brought RAPID exhibitors into the AGMA Emerging Tech webinar series.

2023 AGMA webinars from 3DEO, Fortify, Lumafield, and Mantle3D are still available on-demand, for free, on the AGMA website. We stay in touch with all these companies so if you have any questions after you watch the webinars, just let me know and I will put you in direct contact. I hope to find new players, a technique, or a technology to bring to the 2025 webinar series.

AGMA RAPID tour of Fabrisonic booth in 2023.

This year seems to have an extra layer of anticipation for me. I think it is for two reasons. First, is that the show is in California. Recent RAPID shows were held in more traditional manufacturing cities like Detroit or Chicago. Having the show on the West Coast will bring additional 3D printing companies based there as seen by the more than 400 exhibitors. It will give AGMA West Coast members an easier trip to attend an AGMA event. And there could be a slightly larger aerospace presence. And second, specifically having the show in Los Angeles allows for a bigger presence of the film industry and its unique use of this technology.

The influence of the more creative industry with different objectives and end uses side by side with manufacturing applications always provides new insights. I was just at the Boston Robotics Summit where the buzz of "the possible" was almost palpable. There was something great about the juxtaposition of keynotes by Amazon Robotics leadership and a live demo of the new *Star Wars* robots by Disney creators. While the two have very different objectives we can all learn from the widely varied applications of science. How does Amazon use AI to create new robotic projects compared to Disney? What are the lessons we can learn by looking at two distinctly different applications? I think the influence of Hollywood applications in the 3D space will provide that same experience at RAPID. I look forward to the show.

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New Committee Restructuring—Version 2!

Todd Praneis, AGMA Vice President, Technical Division

In 2023, the Technical Division Executive Committee (TDEC) worked on a technical committee restructuring that replaced the standing, topic-specific committees with working groups, which would focus only on an active project and fold when the project was completed. Due to feedback received on the change, the TDEC took a step back and re-evaluated the restructuring. This led to a new committee-based structure that takes the good parts of project working groups and merges them with the good parts of technical committees. The committees are consolidated and include sub-working groups to perform the work on information sheets and standards.

Current	New	
3a-Nomenclature	NEW: Accuracy and Nomenclature	
3b-Fine Pitch		3a-Nomenclature
3c-Plastics		4b-Gear Accuracy
3d-Powdered Metal		3b-Fine Pitch
3f-Spline	3f-Spline	
4a-Cutting Tools	4a-Cutting Tools	
4b-Gear Accuracy	4d-Sound and Vibration	
4d-Sound and Vibration	5c-Metallurgy and Materials	
5a-Helical Gear Rating		3c-Plastics
5b-Bevel Gearing		3d-Powdered Metal
5c-Metallurgy and Materials	5a-Cylindrical Gear Rating	
5d-Lubrication	5b-Bevel Gearing	
6a-Wormgearing	5d-Lubrication	
6b-Encl. Drives	6a-Wormgearing	
6d-Epicyclic	NEW: Gear Applications	
6e-Flexible Coupling		6b-Encl. Drives
7a-Helical Marine		6d-Epicyclic
7b-High Speed		7a-Helical Marine
7c-Aerospace		7e-Mill Gearing
7e-Mill Gearing		7f-Vehicle
	6e-Flexible Coupling	
7f-Vehicle	7b-High Speed	
7h-Wind Turbine Gear	7c-Aerospace	
	7h-Wind Turbine Gear	
22 committees	**14 committees**	

As shown, we are keeping our committee structure and consolidating from 22 committees to 14. The indented committees will be rolled up into the upper-level committees shown. The yellow-highlighted committees are shadow committees for the International Standards Organization (ISO).

The consistency of having a subject-matter-based committee will provide members with a stable and familiar "home" to share historical knowledge. Committees will be responsible for monitoring the sub-working groups and responding to ISO ballot requests. They will be continual groups that will not fade in and out.

The sub-working groups will be made up of interested technical parties from across the AGMA technical community, including the parent committee, and will consist of a group of active participants interested in the project at hand. Once a project is completed, the working group will disband. Keeping a working group structure allows for broader engagement, quicker responses to new topics, and quicker publication of documents.

If you have any questions or are interested in learning more about the important work of the committees, email *tech@agma.org* with any questions.

Nonlinear Analysis of Gear-Fatigue-Damage Under Variable Load

Daniel Vietze, M.Sc., Dr.-Ing. Josef Pellkofer, and Prof. Dr.-Ing. Karsten Stahl

Until the end of the 19th century, the dimensioning of mechanical structures and parts was based solely on static strength. If this characteristic value of any material or structure is exceeded even once, a failure is very likely. Therefore, engineers designed parts in a way that the static strength is sufficiently higher than the highest load expected in the service. In 1875, an Austrian train derailed between the cities of Linz and Salzburg due to a wheel breakage. Fortunately, no fatalities had to be reported, but the investigation of the accident was challenging. (Ref. 1). The failure could not be explained with any known theory. In this context, Wöhler (Ref. 2) discovered the correlation between reduced strength and dynamic loads and thereby created the fundamentals for fatigue life analysis.

Fatigue life analysis is the umbrella term for summarizing the theories and methods for calculating the service life of components under dynamic and in most cases variable load. Damage accumulation hypotheses (DAHs) are one major part of fatigue life analysis. If variable loads occur during operation, a DAH is required to calculate the service life or to dimension the load-carrying capacity of any component or structure accordingly. The oldest and still most widely used approach to damage accumulation is the linear one. This approach dates back to the first half of the 20th century and was developed and published by Palmgren (Ref. 3) and Miner (Ref. 4). Due to neglecting the sequence of variable loads and assuming a linear growth of the damage, this approach is mathematically simple and easy to apply for nearly any use case. Today, the linear approach is also the most common for calculating the service life of gears under variable load. International standards like ISO 6336-6 (Ref. 5) or ANSI/AGMA 2101-D04 (Ref. 6) recommend the use of this approach for the calculation of gears.

Although the linear approach to damage accumulation is commonly used and the results enable a reliable dimensioning of gears, research has shown that the sequence of loads can lead to a significant change in the service life of gears (Refs. 7–9). Because of this shortcoming of the linear approach to damage accumulation the nonlinear approach exists. The nonlinear approach can consider the load sequence when calculating the damage but comes with the tradeoff of increased complexity.

This paper presents a comparison of the linear and nonlinear approaches for damage accumulation of tooth root breakage damage of gears. In the beginning, the theoretical fundamentals of damage accumulation are presented compactly. To compare the suitability of the methods an extensive set of experimental data is presented at first. The data is evaluated with both the linear and the nonlinear approach and the results are compared. For the linear approach, the method according to Miner (Ref. 4) and Palmgren (Ref. 3) is applied. For the nonlinear approach, the method developed by Subramanyan (Ref. 10) is used. The objective of this evaluation is to assess if the more complex method yields a potential benefit for a more accurate service life prediction of gears.

Theory of Damage Accumulation

Load Carrying Capacity and the S/N Curve

Gears can fail due to different failure modes. For the fatigue life analysis of gears, pitting and tooth root breakage are of particular importance. Damage modes like scuffing, which can occur after a few load cycles under critical conditions, cannot be analyzed with the methods of fatigue life analysis. To describe the load carrying capacity of gears under different loads, the S/N curve (also known as Wöhler curve) is common. The S/N curve includes information on how many load cycles of a certain load level can be withstood by the gear. Figure 1 shows a schematic S/N curve.

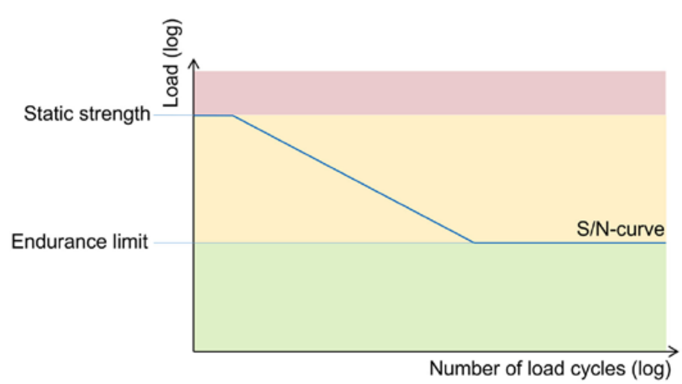


Figure 1—Schematic S/N curve (Ref. 11).

Failure of machine elements is always fraught with scattering. Because of this, an S/N curve represents a certain probability of failure (Ref. 12). A failure probability of 1 percent, 50 percent or 99 percent is the most common but other values such as 10 percent or 90 percent are also used. To specify a S/N curve for a material or a machine element, a complex and extensive test procedure, often called the Wöhler-test, has to be conducted (Ref. 13).

The load in Figure 1 is divided into three ranges:

- Loads higher than the static strength (red zone)
- Loads between the endurance limit and the static strength (yellow zone)
- Loads below the endurance limit (green zone)

Loads exceeding the static strength have to be avoided entirely because they will most likely cause an immediate failure of the gear. A load below the endurance limit is considered nondamaging up to a certain amount of load cycles. For gears, this threshold of load cycles is usually chosen between 6 and 100 million load cycles and should exceed the expected service life of the gear. A load between the endurance limit and the static strength can be withstood by the gear for a certain amount of load cycles. To calculate the number of allowable load cycles, the Basquin equation (Ref. 14) is applied:

$$N = C\ L^{-k} \tag{1}$$

where

N is the number of allowable load cycles
C is the constant describing the position of the S/N curve
L is the load corresponding to the number of allowable load cycles
k is the slope of the S/N curve

For use cases with a nonvariable load, the S/N curve can be used directly to calculate the expected service life according to Equation 1. For cases of variable load, a DAH is required.

Damage Accumulation Hypotheses

Calculating the combined damage of a sequence of variable loads is one of the most important aspects of fatigue life analysis. Therefore, a lot of different DAHs have been published over time (Ref. 12). The objective of all of these hypotheses is to represent the process of damage growth as realistically as possible, while still remaining as generally valid as possible. Important to mention is the fact that the damage is represented by a damage sum D, which is usually considered to be zero for a new component and starts increasing from the beginning of the service life. In the theory of fatigue life analysis, a component is considered damaged to a certain degree as soon as the first damaging load is applied, even if there is no detectable damage, like a crack. DAHs can be categorized into linear and nonlinear hypotheses.

Linear Damage Accumulation Hypotheses

In general, linear DAH traces back to the theory according to Palmgren (Ref. 3) and Miner (Ref. 4) and is based on the following assumptions:

- Every load cycle of a certain load level causes the same amount of damage.
- The amount of damage caused by any load cycle does not depend on the previous damage already caused to the component.

These assumptions basically lead to an entire neglect of the load sequence. Therefore, it is possible to use a load spectrum instead of the actual load sequence, which in many cases is the only feasible way because the load sequence is not known during the design process. On the other hand, in many cases, the load spectrum can be estimated with a certain amount of reliability. To generate a load spectrum, the occurring range of load is divided up into a certain amount of load levels, and the occurring load cycles are categorized accordingly (Ref. 5). For gears, every tooth of a gear is exposed to one load cycle for every revolution of the gear. Due to this characteristic, it is possible to transfer a load sequence into a load spectrum without the use of complex methods such as the Rainflow-counting algorithm. Figure 2 shows a schematic load sequence and the corresponding load spectrum. Additionally, the load sequence of one single tooth is plotted.

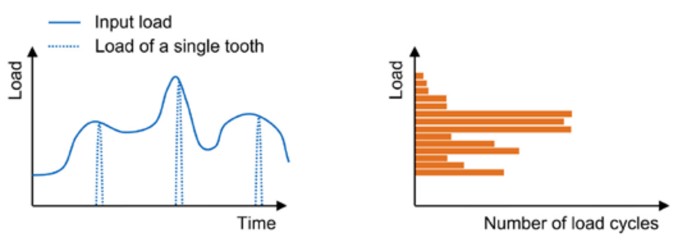


Figure 2—Schematic load sequence (left-hand side) and load spectrum (right-hand side).

The damage sum D caused by a load spectrum according to Palmgren (Ref. 3) and Miner (Ref. 4) is calculated as the sum of damage caused on every single load level:

$$D = \sum_i d_i \tag{2}$$

with

$$d_i = n_i * \frac{1}{N_i} \tag{3}$$

where

D is the damage sum
d_i is the partial damage of the load level i
n_i is the number of load cycles on the load level i
N_i is the number of allowable load cycles on the load level i according to Equation 1

In its original form, the DAH according to Palmgren (Ref. 3) and Miner (Ref. 4) (also referred to as "Original Miner") does not consider any load levels lower than the endurance limit. Therefore, it is assumed that all load cycles of the corresponding load levels do not cause any damage. Especially high loads can result in a decreasing endurance limit throughout the service life (Ref. 9). This effect can result in an underestimated damage sum, not representing the actual state of damage and overestimating the service life. To include this into the DAH, two variations of "Original Miner" were developed:

- **Elementary Miner:** This DAH ignores the endurance limit and calculates the number of allowable load cycles according to Equation 1 for every load level.
- **Miner-Haibach:** The DAH "Elementary Miner" attributes load levels below the endurance limit with a high contribution

to the total damage. This often leads to a very conservative damage estimation. Therefore, Haibach (Ref. 12) developed a DAH based on the Miner hypotheses, but with a reduced slope of $2k$-1 for loads below the endurance limit.

Figure 3 shows the number of tolerable load cycles as assumed by the three presented DAHs based on the theory according to Palmgren (Ref. 3) and Miner (Ref. 4).

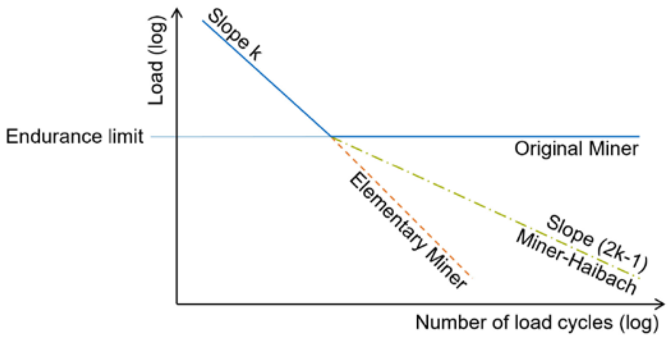


Figure 3—Number of tolerable load cycles as assumed by the DAHs based on Palmgren and Miner (Ref. 11).

Nonlinear Damage Accumulation Hypotheses

Nonlinear DAHs are designed to take the load sequence into account. Therefore, they cannot use load spectra as input. Instead, the actual load sequence is required to apply these methods. Over the last 70 years, many nonlinear DAHs have been published. A comprehensive summary of nonlinear DAHs was published by Fatemi and Yang (Ref. 15) and extended by Hectors and De Waele (Ref. 16).

The objective of this paper is to review the use of nonlinear DAHs for gear fatigue. Currently, nonlinear DAHs are not commonly used for gears and there are no reliable publications about the suitability of nonlinear DAHs for gear fatigue. Therefore, this paper starts investigating the use of nonlinear DAHs for gears and compares the results with the linear approach according to Palmgren (Ref. 3) and Miner (Ref. 4). As mentioned, there are a lot of nonlinear DAHs and all of them differ more or less. One of the oldest and most widely referred methods is the DAH according to Subramanyan (Ref. 10).

The theory according to Subramanyan (Ref. 10) is based on the S/N curve as input to describe the load-carrying capacity. The calculation of the damage sum must be done sequentially for every group of load cycles at the same load level. The method does not require a separate calculation for every load cycle, instead, a new calculation step is only required if the load changes. This leads to a method that usually does not consume much computing power and is possible by hand. The DAH according to Subramanyan (Ref. 10) only requires the load sequence in addition to the input required for the method according to Palmgren (Ref. 3) and Miner (Ref. 4). This is not the case for many other nonlinear DAHs. Usually, nonlinear DAHs require additional information describing the behavior of the material and component under variable load (Ref. 16). To include this factor in the calculation, usually at least one additional coefficient is required. In most cases, this value cannot be derived directly and is not published within the theory therefore additional effort is necessary. Unfortunately, in many cases, a sufficient description of the procedure to determine this input value is not included in the publication. Therefore, this paper utilizes the DAH according to Subramanyan (Ref. 10) because it uses the same input as the linear approach and only requires the load sequence. Therefore, the two DAH approaches are the best comparable ones. Additionally, the DAH according to Subramanyan (Ref. 10) is the basis for other nonlinear DAHs such as the one according to Rege and Pavlou (Ref. 17), which is an example of an approach requiring additional input.

The damage sum D caused by the number of load cycles n to an undamaged component is calculated according to Subramanyan (Ref. 10) as follows:

$$D = \frac{\ln N_D - \ln N}{\ln N_D - \ln n} \tag{4}$$

where
D is the damage sum
N_D is the number of load cycles at the knee point of the S/N curve
N is the number of allowable load cycles on the load level according to Equation 1
n is the number of load cycles of the current sequence

The calculation according to Equation 4 can only be applied directly for the first sequence of loads. To calculate the damage sum D_{next} after the next amount of load cycles n_{next}, the current damage sum $D_{initial}$ has to be transferred from the past load level $L_{initial}$ to the upcoming load level L_{next} first. This is done by calculating the number of transfer load cycles $n_{transfer}$ according to Equation 5.

$$n_{transfer} = e^{\left(\ln N_D - \frac{\ln N_D - \ln N_{next}}{D_{initial}}\right)} \tag{5}$$

where
$n_{transfer}$ is the equivalent number of load cycles transferred to the next load level
N_D is the number of load cycles at the knee point of the S/N curve
N_{next} is the number of allowable load cycles on the next load level according to Equation 1
$D_{initial}$ is the initial damage sum

To apply Equation 4 to calculate the damage sum D_{next}, the next amount of load cycles n_{next} has to be added to the number of transfer load cycles $n_{transfer}$. The resulting number of load cycles n can be inserted into the calculation and yields Equation 6.

$$D_{next} = \frac{\ln N_D - \ln N_{next}}{\ln N_D - \ln(n_{next} + n_{transfer})} \tag{6}$$

where
D_{next} is the damage sum after the next amount of load cycles
N_D is the number of load cycles at the knee point of the S/N-curve
N_{next} is the number of allowable load cycles on the next load level according to Equation 1
n_{next} is the next amount of load cycles
$n_{transfer}$ is the equivalent number of load cycles transferred to the next load level

This sequence of calculation steps has to be repeated for every set of load cycles.

Influence of the Load Sequence on the Service Life of Gears

Whether the load sequence has influence on the service life of gears cannot be answered with a simple yes or no. At the moment, international standards (Refs. 5, 6) do not recommend taking the load sequence into account when calculating the expected service life of gears under variable load. As mentioned before, both ISO 6336-6:2019 (Ref. 5) and ANSI/AGMA 2101-D04 (Ref. 6) do not include a nonlinear method for damage accumulation. But it is important to point out that the standards do not make any statement about a possible load sequence influence. Usually it is uncommon to include considerations about the load sequence into the design process because the load sequence is unknown in advance. For the sake of completeness, it is mentioned, that there are cases where the load sequence is known at least to a certain degree. For example, in aviation, there are considerations regarding the load sequence within one single flight (Ref. 12). On the other hand, in cases of calculating or estimating the remaining service life of gears or other machine elements, the load sequence can potentially be included into the process and therefore may result in a more accurate result. A concept for such a method is presented by the authors in (Ref. 11).

There are several publications about the influence of the load sequence on the service life. Unfortunately, most of these publications do not focus on gears, instead tensile specimens are typically used. A potential impact of the load sequence on the service life can be linked partially to the residual stresses within the machine element (Ref. 12). Gears are usually heat-treated and, in many cases, shot-blasted. Both processes result in residual stress and therefore results obtained with specimens without a similar treatment cannot be transferred to gears. The process of gear failure and the related growth of damage are usually analyzed separately for every damage mechanism. For the damage mechanisms of pitting and tooth root breakage, an interaction is very unlikely, especially at the beginning of the damage development. Therefore, the damage mechanisms are considered independent of each other in international standards (Refs. 18–20) and in most of the research, including in this paper. For experimental investigations on gears, it is common to use a gear design, which usually only fails due to one specified failure mode. A brief overview of publications about the influence of the load sequence on gears is presented below. This paper focuses on the damage mechanism of tooth root breakage. Because of its scope, only publications and results regarding this failure mode are summarized. This summary and the whole paper are limited to gears manufactured out of gear-typical steel, such as 18CrNiMo7-6 or 16MnCr5. Because materials such as aluminum, carbon, or plastic may show a different behavior regarding damage growth and failure, these materials are not included.

Within his research, Suchandt (Refs. 21, 22) investigated the existence of an endurance limit for gears regarding tooth root breakage. For the case of nonvariable load, gears usually have, like mentioned before, a pronounced endurance limit. This may not be the case for variable load scenarios, because pre-damaged gears may have a reduced endurance limit due to the already occurred loads above the original endurance limit. The investigations focused on gears with an initial crack in the tooth root. These gears were then used to determine an endurance limit. Suchandt's (Refs. 21, 22) investigations showed that the endurance limit decreased by 40 percent compared to the original one for the pre-damaged gears. Therefore, he concluded that it is possible to consider loads below 50 percent of the original endurance limit as nondamaging throughout the whole service life. This finding points out why the neglect of the load sequence can pose a potential issue. Stahl (Ref. 9) also showed in his research that different load sequences have an impact on the service life of gears regarding tooth root breakage. He showed that random load sequences result in a decreased service life compared to an ordered block sequence. In his experimental investigations, a significant reduction of the service life occurred for load sequences with shorter subsections compared to load sequences with relatively longer subsections. He also investigated the influence of an overload on the service life. An overload had more impact on reducing the service life, if applied early compared to one applied later in the load sequence.

Theoretical Comparison of Palmgren/Miner and Subramanyan

Damage Levels and Limitations

Like the DAH according to Palmgren (Ref. 3) and Miner (Ref. 4), the DAH according to Subramanyan (Ref. 10) does not require any additional inputs besides the S/N curve and the load sequence. This makes both approaches suitable for a direct comparison. At the beginning, a graphic comparison of the trend of different damage sums within the S/N diagram will be conducted.

In both theories, the S/N curve describes the moment of predicted failure and, therefore is equivalent to a damage sum of one. Figure 4 shows different damage sums and their locations as functions within the S/N diagram for the DAH according to Palmgren (Ref. 3) and Miner (Ref. 4). Due to the linearity of the theory, all the damage levels are parallel to each other. All the presented damage lines and S/N curves are linked to a probability of failure of 50 percent. In this context, it is important to mention that the standard deviation of the failure of gears due to tooth root breakage depends on the load. This was shown and described by Stahl (Ref. 23).

Figure 5 shows the same damage sums and their locations as

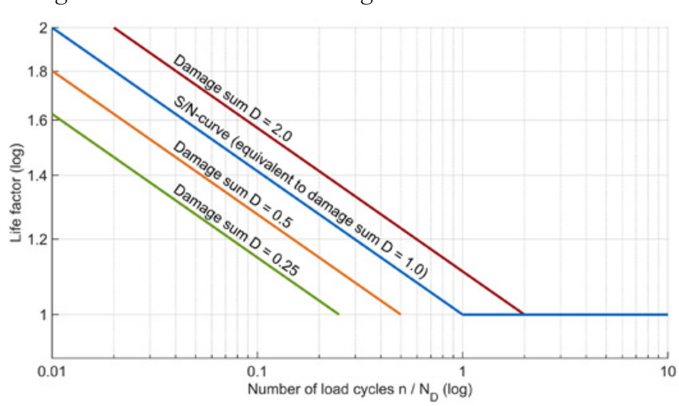


Figure 4—Different damage levels according to Palmgren/Miner in the S/N diagram.

function within the S/N diagram for the DAH according to Subramanyan (Ref. 10).

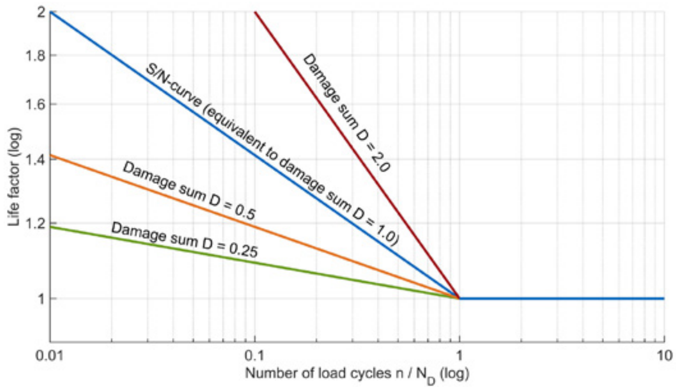


Figure 5—Different damage levels according to Subramanyan in the S/N diagram.

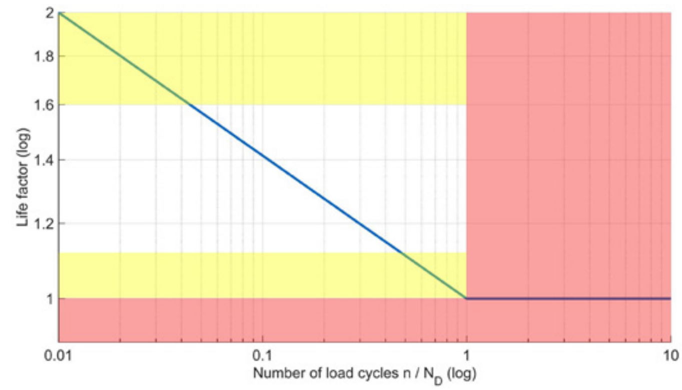


Figure 6—S/N diagram with limitations of the DAH according to Subramanyan (Ref. 10).

The damage levels for the DAH according to Subramanyan (Ref. 10) are not parallel within the S/N diagram. This is due to the nonlinear approach and therefore the sequence of loads has an impact on the resulting damage sum.

The DAH according to Subramanyan (Ref. 10) has some major limitations:

- Loads lower than the endurance limit cannot be integrated into the calculation. Therefore, these loads must be excluded similar to the DAH "Original Miner." Since all damage levels have their origin in the knee point of the S/N curve, it is not possible to integrate loads lower than the endurance limit similar to the DAHs "Elementary Miner" and "Miner-Haibach."
- As presented in Figure 5, all damage levels originate at the knee point of the S/N curve and become steeper as damage increases. Due to this fact, it is not possible to have a number of load cycles n larger than the number of load cycles at the knee point of the S/N curve N_D. This would cause the damage sum to become negative and is therefore illogical. This issue can be retraced when looking at Equation 4. Especially when the scattering of the service life of input data is quite high, this can cause an issue.
- According to the original publication (Ref. 10), the method is not suitable for loads slightly above the endurance limit and for very high loads. This is due to the course of the damage lines. Unfortunately, there is no reliable statement about the range of loads, which should be avoided when calculating with this DAH.

Due to the mentioned limitations of the DAH according to Subramanyan (Ref. 10) the range of load and number of load cycles the DAH can be applied for is limited. Figure 6 shows the usable areas within the S/N diagram in white. The red areas within the figure are not mathematically valid and the yellow area represents the issue with loads slightly above the endurance limit and with high loads. Because there are no concrete limits for the load given in the literature, the limits were set at a life factor of 1.1 and 1.6 by the authors for this paper. The upper limit was chosen in a way that the corresponding load is sufficiently below the typical range of the static strength of the gear. This is to ensure that the load still results in a service life and does not lead to immediate failure. The lower limit is chosen at 1.1 to ensure a minimal distance to the endurance limit while maintaining a wide load range to apply the DAH according to Subramanyan (Ref. 10).

Impact of the Nonlinear Calculation

The nonlinear approach changes the results of the damage accumulation and therefore a different damage sum can be expected when comparing it to the linear approach according to Palmgren (Ref. 3) and Miner (Ref. 4). Table 1 shows a comparison of the resulting damage sum according to the DAH "Original Miner" and the DAH "Subramanyan" for three different load sequences. All these load sequences are designed to result in the same damage sum according to the linear approach. The difference between the three sequences is the intensity of the load mixing. This comparison is not designed to determine which of the theories is better suited for gears. Rather, the objective is to show the differences resulting from the various formulae.

The results presented in Table 1 (located at the top of page 44) show two trends:

- The DAH according to Subramanyan (Ref. 10) results in much higher damage sums compared to the DAH according to Miner (Ref. 4). The increase is between 106 percent and 118 percent.
- According to the DAH "Subramanyan" a load sequence is increasingly damaging with increasing load mixing. The difference in this case is up to 5.5 percent.

The influence of the different intensities of load mixing is within a realistic range. The general differences in the resulting damage sums are very high and unexpected. To understand the impact of the calculation, Figure 7 compares the development of the damage sum with an increasing number of runs of the load sequence with high load mixing, as presented in Table 1.

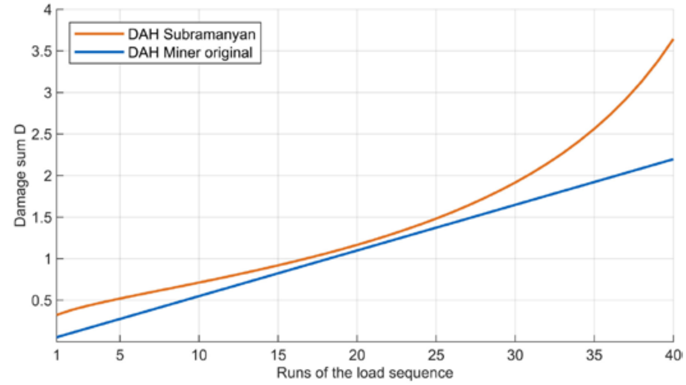


Figure 7—Comparison of the damage development.

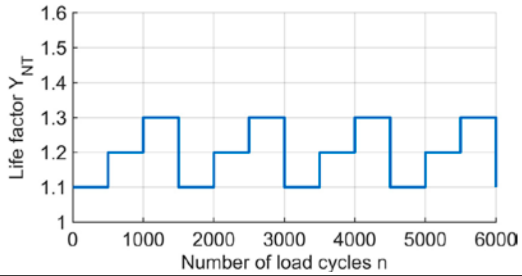
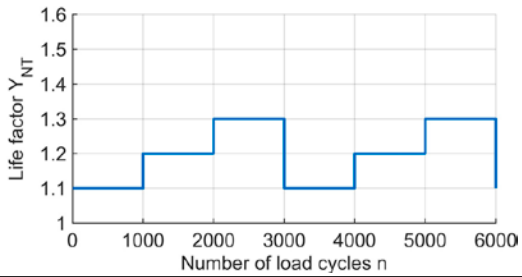
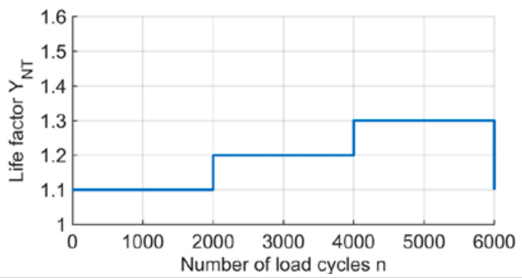
Load sequence	Damage sum according to DAH “Original Miner”	Damage sum according to DAH “Subramanyan”
High load mixing		
	0.2197	0.4791
Moderate load mixing		
	0.2197	0.4699
Low load mixing		
	0.2197	0.4530

Table 1—Comparison of the damage sum according to different DAHs – Influence of load mixing.

The results presented in Figure 7 show that the difference in the damage sum between the two DAHs first decreases with increasing runs of the load sequence and then increases again for damage sums greater than about 1.3. In the range around a damage sum of 1, the two DAHs are quite close. Therefore, it can be assumed that both DAHs can be expected to predict failure with a reasonable difference. Based on this theoretical comparison, it is not possible to determine which of the two is more suitable for gear fatigue. Therefore, a comparison with the experimental data is necessary.

Experimental Study

Setup and S/N Curve

To compare the suitability of different DAHs for the prediction of the service life of gears under variable load, a dataset of fatigue tests with variable load sequences is required. For the tests, a pulsator test rig was used at the FZG. This test rig enables a time-efficient test procedure that allows an extensive data set to be realized. Figure 8 shows the test rig used. For the tests, a special gear design was applied, which is optimized for this kind of test and has already been used in several research projects at the FZG. Information about the gear is presented in Table 2.

Figure 8—Test rig.

Gear	Spur Gear
Normal Modual	5 mm
Number of teeth	24
Face width	20 mm
Machining	Milling and grinding
Material	Steel 18CrNiMo7-6
Heat treatment	Case-hardened

Table 2—Gear data and picture of tested gear with four datapoints.

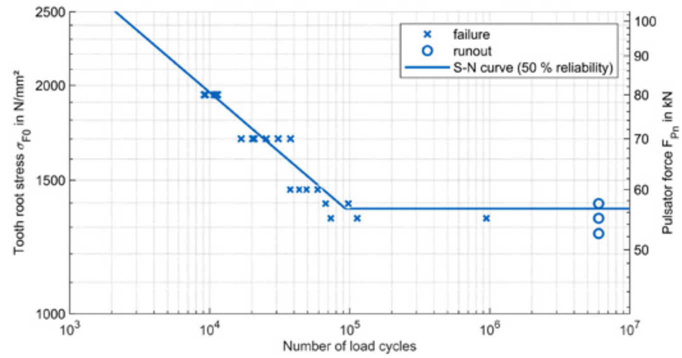


Figure 9—S/N curve of the tested gear.

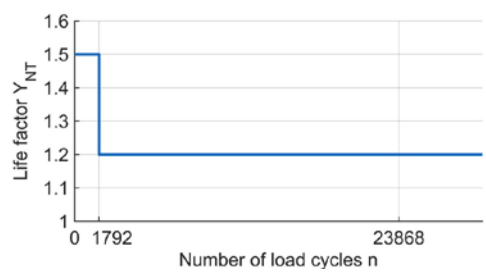
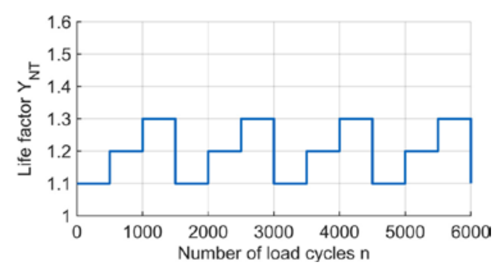
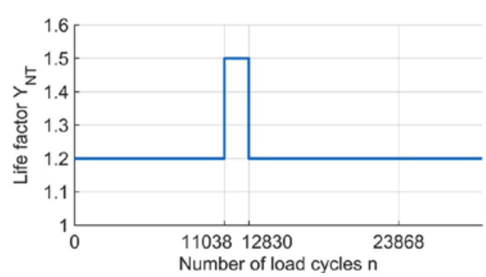
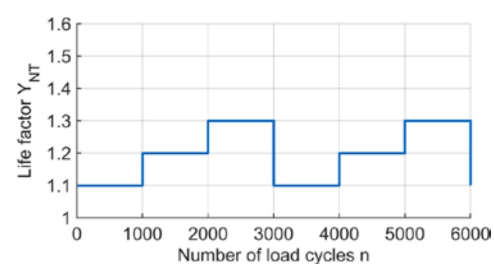
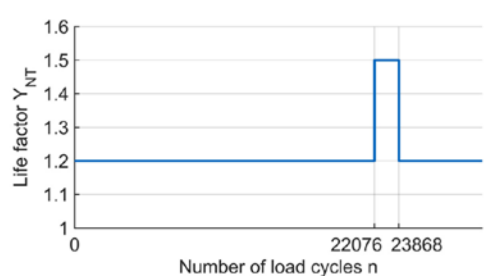
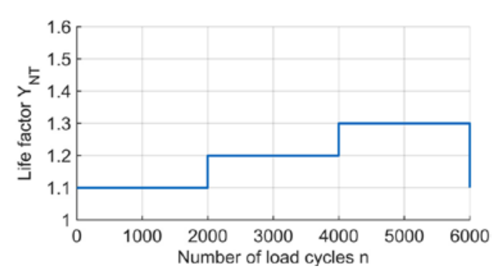
Influence of overload timing	Influence of load mixing
Early life overload	**High load mixing**
	
Midlife overload	**Moderate load mixing**
	
Late life overload	**Low load mixing**
	

Table 3—Applied load sequences.

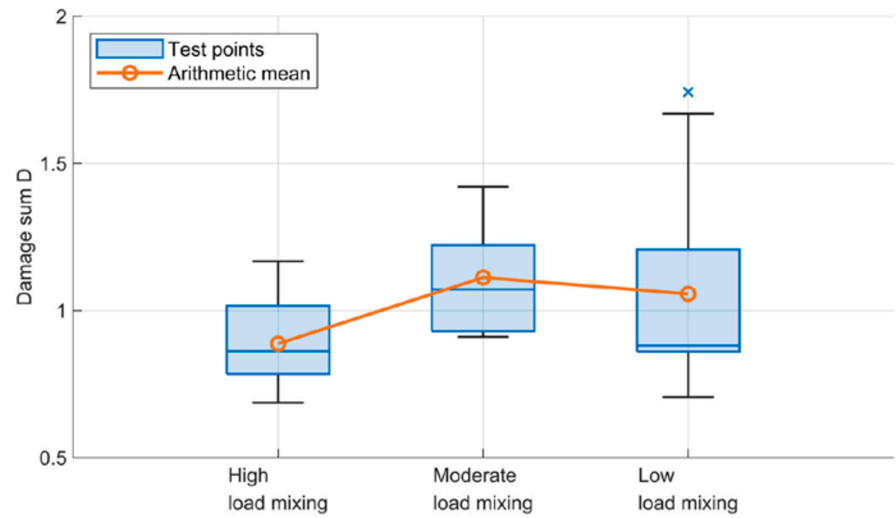
To enable a calculation according to the DAHs "Original Miner" and "Subramanyan" a S/N curve is required. The S/N curve was determined following the procedure described by Tobie (Ref. 13) and is shown in Figure 9. The limit of load cycles, at which a test was declared a runout, was set at six million.

Tooth Root Breakage Tests with Variable Load

To compare different DAHs for their suitability for the fatigue of gears, a dataset with service life information under variable load is required. For this test series, the same test rig and the same gears as presented in the section "Setup and S/N Curve" were used. Two different types of variable loads were investigated with three assorted characteristics. The six different load sequences are presented in Table 3.

The load sequences regarding the influence of the load mixing are like the ones used in the section "Theoretical Comparison of Palmgren/Miner and Subramanyan" for the theoretical comparison. For the tests, the sequence is repeated until the gear fails due to a breakage of one tooth. The test was conducted ten times for each of the three load sequences.

Results according to DAH "Original Miner"



Results according to DAH "Subramanyan"

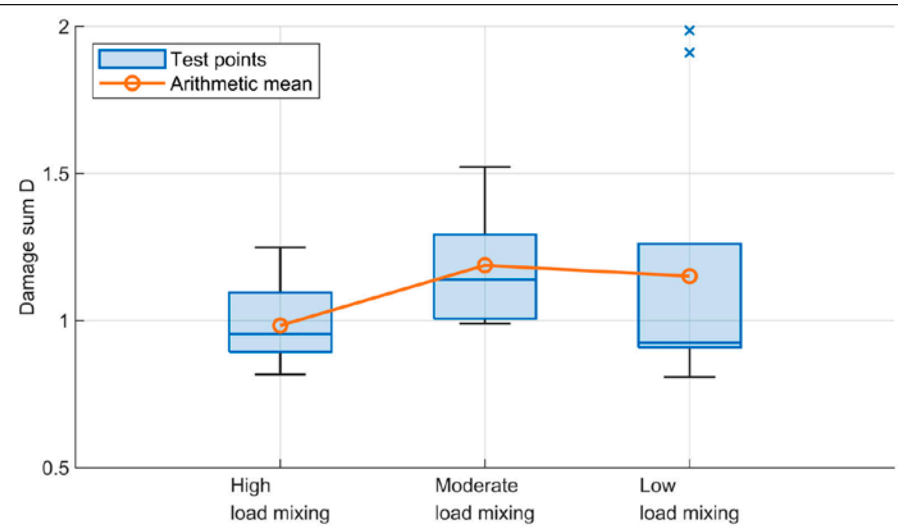


Table 4—Results of the test series regarding the load mixing.

To test the influence of the timing of a high load or overload, three different load sequences were designed. Reference for the sequences is the damage sum according to the DAH "Original Miner." The length of the high load is chosen in a way to account for a damage sum of 0.25. The position within the sequence is chosen as follows:

- Early-life overload: The load sequence starts with the overload.
- Midlife overload: The overload is positioned in a way that it is in the middle of the theoretical service life according to the Miner hypotheses (Ref. 4), which would end at a damage sum of one.
- Late-life overload: The overload is positioned in a way that it is at the end of the theoretical service life according to the Miner hypotheses (Ref. 4), which would end at a damage sum of one.

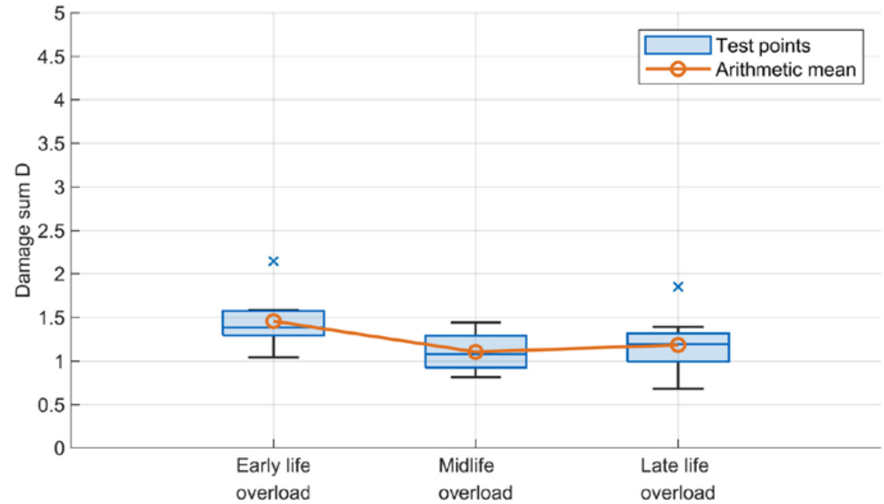
If a gear has not failed at the end of the sequence, the test ends with a constant load until the gear fails. The sequence is not repeated and therefore the overload only occurs once. As for the influence of the load mixing, the test was conducted ten times for each of the three load sequences.

Results and Comparison

In this section, the results of the experimental investigations are presented and analyzed according to the DAHs "Original Miner" and "Subramanyan." Because all of the loads applied in the test are higher than the endurance limit of the gears, the DAH "Original Miner" is equivalent to the DAHs "Elementary Miner" and "Miner-Haibach." For the comparison, the recorded load sequence of every test run was converted to the damage sum corresponding to the moment of failure, using the methods presented within sections "Linear Damage Accumulation Hypotheses" and "Nonlinear Damage Accumulation Hypotheses" and the S/N curve shown in Figure 9.

The comparison of the two DAHs is based on their suitability to account for the differences in service life caused by the load sequence. The impact of the load sequence on the service life can be derived from the results according to the DAH "Original Miner" because this DAH is linear and does not take the load sequence into account. In the next step, these results are compared to a similar evaluation of the data according to the DAH

Results according to DAH "Original Miner"



Results according to DAH "Subramanyan"

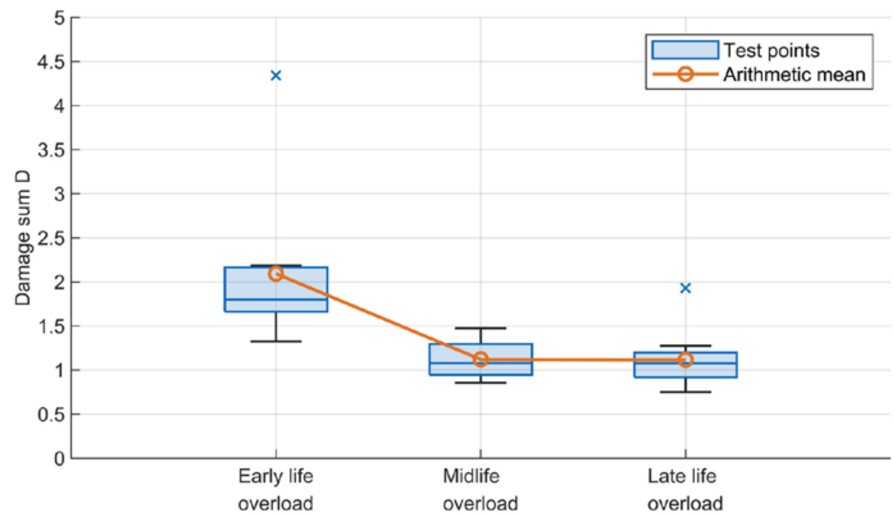


Table 5—Results of the test series regarding the overload timing.

"Subramanyan." If the deviations between the results for the three different load sequences are smaller than the ones according to the DAH "Original Miner," the nonlinear approach can account for the influence of the load sequence to a certain degree and is, therefore, more suitable for gears. On the other hand, if the deviations increase or are comparable, the approach is less suitable for gears or equally suitable but more complex.

Influence of Load Mixing

The results of the test series investigating the influence of the load mixing are presented in Table 4. The data is analyzed with the DAHs "Original Miner" and "Subramanyan" and is displayed as boxplots.

The results indicate that load mixing influences the service life of gears. When looking at the damage sum according to "Original Miner" the service life of gears is significantly decreased in the case of high load mixing. Moderate and low load mixing results in similar mean values, but the scattering of test points is significantly higher with low load mixing. These observations correspond to the results according to Stahl (Ref. 9). A high number of load changes results in a significant reduction of the service life.

When comparing both DAHs, the results show similar trends. In general, the DAH according to Subramanyan (Ref. 10) results in higher damage sums than the DAH "Original Miner". The scattering of the damage sums within the data points of one load sequence differs for both DAHs. This can be explained by the nonlinear growth of the damage sum when applying the DAH "Subramanyan" (compare Figure 7). These observations are consistent with the theoretical comparison in the section "Theoretical Comparison of Palmgren/Miner and Subramanyan." The deviations between the calculated service life of the three load sequences are very similar, especially for a qualitative comparison. For this reason, the DAH "Subramanyan" does not provide any added value over the DAH "Original Miner" in this case.

Influence of Overload Timing

The results of the test series investigating the influence of the overload timing are presented in Table 5. The data is analyzed with the DAHs "Original Miner" and "Subramanyan" and displayed as boxplots.

The results of the overload timing test series also indicate there is an influence of the load sequence on the service life of the gears. The load sequence starting with the overload results in much higher damage sums at failure compared to the other two load sequences. This is the case for both used DAHs. The average damage sum according to the DAH "Original Miner" for the early overload is 32 percent higher compared to the midlife overload and 23 percent higher compared to the late-life overload. These results show a reversed trend to the observations according to Stahl (Ref. 9). Stahl (Ref. 9) showed in his research that an overload results in a higher reduction of the service life if applied early compared to an occurrence later in the load sequence.

Comparing the results of both DAHs the same trend for increased damage sums for the DAH "Subramanyan" can be observed. The DAH according to Subramanyan (Ref. 10) also calculates higher damage sums for early life overload. The deviation of the average damage sum for the early overload compared to the other two load sequences is 87 percent in both cases. These results show that the DAH according to "Subramanyan" can account for the differences in service life between midlife and late-life overload better than the DAH according to Miner. However, the deviation between the early life overload and the other two load sequences is greatly increased, therefore the DAH performs worse with this difference. This can be explained by the theory behind the DAH according to Subramanyan (Ref. 10). The formulae of the hypothesis are designed in a way that load sequences starting with a high load and ending with a low load result in an increased damage sum compared to sequences starting with low load and ending with high load (Refs. 10, 15, 16). Expressed in a different way, load sequences starting with a high load and ending with a low load result in a decreased service life compared to sequences starting with low load and ending with high load. This assumption contradicts the presented results for the different overload sequences. For this particular case, the results show that a high load decreases the service life least if the high load is applied right at the beginning of the service life. Therefore, the use of the DAH according to Subramanyan (Ref. 10) does not result in a decreased difference in the resulting damage sums; instead, it increases the difference even more. In conclusion, the DAH according to Subramanyan (Ref. 10) results in a decreased accuracy compared to the DAH according to Palmgren (Ref. 3) and Miner (Ref. 4).

Conclusion and Outlook

Conclusion

The presented experimental results indicate that the load sequence influences the service life of gears regarding the failure mode tooth root breakage. The two series of tests regarding load mixing and overload timing showed differences in average service life:

High load mixing resulted in a significant decrease in the service life compared to moderate and low load mixing. Moderate and low load mixing resulted in comparable average service lives, but the scattering was significantly increased in the case of low load mixing.

A significant influence on the service life of gears could be observed regarding the timing of a high load or an overload. In the presented test series, the case of an early life overload resulted in a significantly higher service life compared to the mid and end-life overload.

These trends correlate only partially with previous research according to Stahl (Ref. 9). The results for the influence of the load mixing show good accordance. The results for the influence of the overload timing contradict each other. At the moment, there is no conclusive explanation for this and it has to be addressed further in upcoming research.

The shown differences in service life caused by different load sequences cannot be accounted for with linear DAHs and therefore the nonlinear DAH according to Subramanyan (Ref. 10) was applied in this paper to investigate if it yields any potential benefit. For the presented data, Subramanyan's nonlinear DAH (Ref. 10) showed no increased accuracy compared to the approach according to Palmgren (Ref. 3) and Miner (Ref. 4). For the influence of load mixing and overload timing, both approaches nearly showed the same trends. Therefore, no improvement of the service life calculation is to be expected by using the more complex nonlinear DAH according to Subramanyan (Ref. 10) for this particular case. At the same time, the DAH according to Subramanyan (Ref. 10) has more limitations compared to the linear approach according to Palmgren (Ref. 3) and Miner (Ref. 4). This results in a decreased general validity of the nonlinear DAH. Therefore, the results of this paper lead to the conclusion that the general recommendation to apply a linear approach to damage accumulation is valid for the presented data and there is no motivation to apply the more complex approach according to Subramanyan (Ref. 10).

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Outlook

In this paper, a first analysis of the data using only one nonlinear DAH was presented. As stated, no advantage of the use of this approach could be derived from this. The DAH according to Subramanyan (Ref. 10) is only one of many nonlinear DAHs published today. Therefore, the next step will be the investigation of more nonlinear DAH in a similar manner. At first, the DAHs will be analyzed theoretically to determine their suitability for the use case of gears. A systematic comparison of the DAH is planned to determine the most promising methods. In the upcoming steps, the presented experimental data will be assessed with the chosen nonlinear approaches. This does not require any additional experimental investigations because the presented dataset now exists. The objective of further research is to investigate promising and widely published DAH approaches to establish their suitability for gears. Additionally, the influence of the load sequence on the service life of gears has to be investigated further. As presented contradictions with other research appeared and have to be clarified. In the end, it may be possible to detect a DAH, which enables a more accurate service life prediction compared to the nearly 100-year-old approach according to Palmgren (Ref. 3) and Miner (Ref. 4).

Funding

The presented results are based on the research project STA 1198/19-1; supported by the German Research Foundation e.V. (DFG). The authors would like to thank for the sponsorship and support received from the DFG.

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NGC Gears

ENHANCES GEARBOX MANUFACTURING WITH ENDOFLEX FROM UPC-MARATHON

NGC Gears has completed the installation of two additional EndoFlex generators from UPC-Marathon, a Nitrex company, at its new facility in Jinhu, China location. This acquisition brings the total of generator sets to five since 2022, collectively generating an impressive 800 m^3/h (22,252 ft^3/h) capacity of endothermic gas supplied to carburizing and hardening furnaces used for processing various gear components. The latest installations in February and March of 2024 support the heat-treating operations of the company's wind energy gearbox production.

NGC's decision to expand capacity is in response to the growing demand for wind power solutions in China and globally. Recent statistics indicate a robust growth trajectory for wind energy, with the country leading the world in both installed capacity and the manufacture of wind power equipment. The new endothermic gas generating systems will significantly enhance the company's production capabilities, enabling NGC to meet increasing market needs with greater efficiency and reliability.

EndoFlex offers several benefits, including precise control of production media to the carburizing and hardening environments, leading to higher-quality gear production with improved longevity and performance. The result is improved carburizing and hardening processes, higher-quality hardened gears, reduced operating costs, and increased efficiency. The EndoFlex mixes ratios more accurately and efficiently, ensuring a constant furnace atmosphere and consistent gas quality. This leads to immediate cost savings through reduced electricity and gas consumption and minimized waste.

Johnny Xu, General Manager at UPC-Marathon China, shared, "The latest EndoFlex investments align with NGC's development of low-consumption, high-efficiency gearbox products for large-scale onshore and offshore wind turbines. Our collaboration with NGC is focused on advancing excellence in the wind power sector, and we are thrilled to see the tangible benefits our EndoFlex units bring to NGC. This partnership highlights the strength of our products and reinforces our commitment to providing quality, local solutions to meet the demands of modern manufacturing for a greener future. We look forward to continuing our work with NGC and delivering the superior endogas quality needed for their high-standard production processes.

ngcgears.com

AGMA

WINS FIRST PLACE IN TRADE SHOW AWARD FOR MPT EXPO

The American Gear Manufacturers Association (AGMA) was presented with the Trade Show Executive's Fastest 50 Grand Award in the "Fastest-Growing Show by Percentage Growth in Total Attendance in 2023" category on May 9 at the Fastest 50 Awards & Summit in Las Vegas.

The award was given for the AGMA's 2023 Motion + Power Technology Expo (MPT Expo), which was one of only 23 shows ranked in three of Trade Show Executive's award categories:

- Ranked #1 by total attendance.
- Ranked #18 by the number of exhibitors.
- Ranked #33 by net square feet.

AGMA's Jenny Blackford, Chief Operating Officer, and Leah Lewis, Director, Meetings & Events, accepted the award on behalf of AGMA.

"Many wonderful people at AGMA, staff and members, worked tirelessly to make the 2023 MPT Expo a success. It's fulfilling to have that dedication recognized by Trade Show Executive's Fastest 50," said Leah Lewis, director, meetings and events, AGMA. "The growth of MPT Expo highlights how the gear industry and wider power transmission industry thrive on in-person connections, and we're proud that MPT Expo is the place where the industry comes to do business."

MPT Expo, formerly Gear Expo, was one of the only trade shows that happened in 2021 in the United States. The award recognizes the growth between then and the 2023 show.

"We are very proud to be a show that kept its doors open in 2021 and I think that made all the difference for MPT Expo last year," continued Jenny Blackford, COO, AGMA. "Our membership and the gear industry never stopped working during the pandemic and this award reflects the resiliency they demonstrate—we are happy to be the association that supports them."

The 2025 MPT Expo will return to Detroit on October 21–23, 2025.

agma.org

Continental Diamond Tool

ENTERS STRATEGIC PARTNERSHIP WITH KREBS & RIEDEL

Continental Diamond Tool Corporation (CDT) announces its partnership with Krebs & Riedel, a global leader in the abrasives industry. This collaboration positions CDT as the exclusive North American source for Krebs & Riedel abrasive products within the USA, Canada, and Mexico.

Erik Van Meter, Senior Product Manager of Conventional Abrasives at Continental Diamond Tool and Krebs & Riedel's official representative, expresses enthusiasm about the new partnership, stating, "We are thrilled about the high-quality products Krebs & Riedel will bring to the table. They are a well-respected name in conventional grinding wheels and have products for many industrial grinding markets which include automotive, aerospace, gear and medical."

The collaboration between CDT and Krebs & Riedel signifies a partnership deeply rooted in a shared commitment to excellence. For more than half a century, Continental Diamond Tool Corporation has consistently delivered technically superior precision grinding products across a variety of industries. As a thriving second-generation family business, CDT's commitment to innovation and quality is reflected in its state-of-the-art North American manufacturing facility, which is undergoing a sizable expansion to cater to new product development and meet diverse customer needs. With this and a growing subsidiary in the United Kingdom, it has solidified its status as a premier worldwide manufacturer of custom superabrasive grinding wheels and diamond dressing tools.

Similarly, Krebs & Riedel is a family-owned enterprise headquartered in Bad Karlshafen, Germany, since 1885. It has a proud century-long legacy in providing quality abrasive products globally. With over 30 distributors and subsidiaries, K&R's dedication to customer satisfaction aligns seamlessly with CDT's founding principles. This partnership promises cutting-edge solutions and unwavering commitment to superior products and customer service in the abrasive products landscape. In this strategic move, CDT and Krebs & Riedel are poised to tackle the most critical tooling requirements of a growing market of customers.

"This partnership marks an exciting chapter for Continental Diamond Tool Corporation as we join forces with Krebs & Riedel to expand our product offerings in North America," said Nick Viggiano, President of CDT. "We are proud to align with Krebs & Riedel's esteemed reputation and look forward to delivering exceptional abrasive products and unparalleled service to our customers across the continent and beyond."

"With CDT we have found the partner who complements our high-performance products with superior service. From the first meeting we felt the same level of professionality and passion for grinding. I am convinced that our customers in North America will feel the same," said Florian Riedel, Managing Director of Krebs & Riedel.

cdtusa.net/products

Eaton

RECEIVES RECOGNITION FOR ITS 4-SPEED ELECTRIFIED VEHICLE TRANSMISSION

Eaton's heavy-duty 4-speed electrified vehicle (EV) transmission was named a 2024 *Automotive News* PACEpilot Innovation to Watch at an awards ceremony on April 29. The recognition acknowledges post-pilot, pre-commercial innovations in the automotive and future mobility space.

Eaton's EV transmission provides superior performance on grades and acceleration for electric commercial vehicles while offering more flexible gear ratios compared to competitive technologies. The compact 4-speed transmission for heavy-duty applications is designed to improve system efficiency, enabling longer vehicle range and battery life.

"We are honored to be chosen by the PACEpilot judges to receive this prestigious award," said Scott Adams, senior vice president, Global Products, Eaton's Mobility Group. "Our heavy-duty EV transmission is an innovation that is receiving interest from manufacturers around the world who would like to improve the performance of their electrified commercial vehicles."

The 4th annual PACEpilot program was presented by *Automotive News*. The competition was open to suppliers and startups that invented products, software/IT systems or processes and idea incubators that have the capacity to transform the automotive industry. The *Automotive News* PACEpilot program is leading the way in distinguishing global emerging innovators.

Eaton earned an *Automotive News* PACEpilot recognition following an extensive review by an independent panel of judges including a comprehensive written application and a virtual pitch session.

eaton.com

Jergens

APPOINTS NATIONAL SALES MANAGER FOR WORKHOLDING SOLUTIONS GROUP

Jergens announces that Omar Andino will take the lead as the WSG national sales manager. Andino, who has been with the company since October of 2018, will leverage his wide range of manufacturing and engineering experience in his new position to continue the sales growth of the many workholding products.

"Omar has been a valuable member of the Jergens team for five years now", said Matt Schron, Jergens vice president, and general manager. "His demeanor is very approachable and conversational, with application and fixture design background that gives us another advantage as he and his team continue to support our customers, distributors and sales rep's", continued Schron.

Previously, Omar had been on the Jergens Custom Design and Build team, and an application engineer. Prior to joining Jergens, he had been in the plastic injection molding industry, in material handling, a tool maker, designer, and shift supervisor for companies including Meritec and Cosmo Corp. He has spent his career in and around tooling, process improvement, automation, and workholding, all with an eye for improving efficiency.

Omar Andino

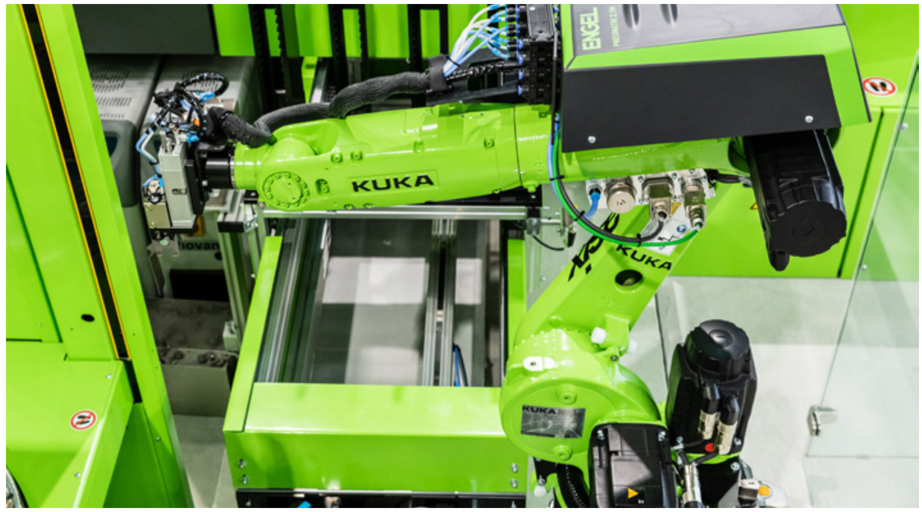
"I'm a learn as you go kind of guy, and I really enjoy understanding how things work," said Andino. "Jergens has given me the opportunity to take on as much as I want, which is how I built up my AE (application engineer) skills and took on my first solo custom design and build project after 2-1/2 months", he continued.

That same sense of design and construction is also part of Omar's private life as he enjoys wrenching on motorcycles and cars, as well as household renovations and woodworking. Omar holds an Engineering Technical Certificate from Lakeland Community College. He and his wife Kelly live in Painesville, OH, and enjoy their blended family of seven children.

jergensinc.com

KUKA Robotics

ANNOUNCES INJECTION ENGEL AS A SYSTEM PARTNER



Continuing a global relationship that spans more than 20 years, eight-year KUKA Strategic Partner ENGEL, a leader in plastic injection molding machines, technologies, and turnkey solutions, has become a KUKA Robotics System Partner. In its new relationship with KUKA, ENGEL will not only continue to incorporate KUKA robots as standard components in its injection molding solutions but also integrate and retrofit KUKA robotic products into existing plastic injection molding machines and systems.

ENGEL has used hundreds of KUKA robots for upstream and downstream automation of its injection molding machines and cells since establishing its North American presence. The company relies primarily on KUKA's all-purpose, high-payload QUANTEC, high-powered, low-payload CYBERTEC and versatile medium-payload IONTEC robots, all of which provide 6-axis operation and flexibility to customers for virtually any market segment.

"We want to emphasize that being a preferred partner is more than just a label for us," said Vanessa Malena, President Americas at ENGEL. "KUKA and ENGEL stand for premium quality products, and our customers will benefit from this longstanding partnership of integrating hundreds of KUKA robots in injection molding cells. Companies that want to increase the automation of their injection molding production, even if they may have little or no experience with robots, will be able to rely on a team of experts from two market leaders who will set them up for success."

ENGEL's integration solutions provide manufacturers who are looking to expand their operations or who have not yet automated their processes a feature-rich system that is easy to use and operate. By using the same controller for the machine and added automation, shops can increase efficiency and productivity with no robotic programming experience.

"The ability to fully integrate KUKA robots into the ENGEL machine controller has more advantages than optimal communication between injection molding machine and automation," said ENGEL Vice President of Automation Stefan Aberl. "It is easier and more convenient for operators to work with one controller, and the integration also allows remote access for troubleshooting of complete production cells via just one access device."

To commemorate its new relationship with KUKA, ENGEL is offering a special automation integration promotion for new and existing customers from May 1, 2024, to April 30, 2025, that includes an additional 12-month warranty that brings the total warranty period to 24 months, free simulations to determine reach, cycle time and feasibility and a 20 percent discount on maintenance training.

kuka.com

JUNE 16–19

PowderMet 2024

The leading technical conference on powder metallurgy and particulate materials in the Americas, PowderMet 2024 (Pittsburgh, PA) is a hub for technology transfer for professionals from every part of the industry, including buyers and specifiers of metal powders, tooling and compacting presses, sintering furnaces, furnace belts, powder handling and blending equipment, quality-control and automation equipment, particle-size and powder-characterization equipment, consulting and research services, and much, much more. The show is co-located with AMPM 2024 focusing on metal additive manufacturing. AMPM 2024 will feature worldwide industry experts presenting the latest technology developments in this fast-growing field.

geartechnology.com/events/5069-powdermet-2024

JUNE 25–27

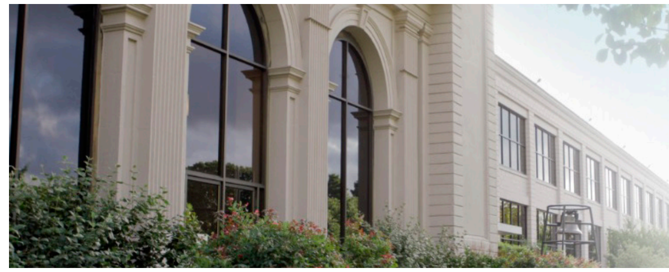
RAPID + TCT 2024

For more than 30 years, RAPID + TCT has defined the crucial role of additive manufacturing and industrial 3D printing by empowering the establishment of an industry that continues to conceive, test, improve and manufacture new products at a faster, more cost-efficient pace. RAPID + TCT provides everything you need to know about the latest 3D technologies, all under one roof. At the RAPID + TCT conference, over 100 industry leaders go beyond the hype to bring you real-world solutions to advance your manufacturing processes. New this year are the Hollywood Showcase, an exploration of the role of AM in movie magic, and The Discovery Zone, a launchpad for newcoming exhibitors with groundbreaking ideas.

geartechnology.com/events/5094-rapid-tct-2024

JULY 16–18

WZL Gear Conference USA



The 10th WZL Gear Conference - USA is being hosted by Gleason Corporation in Rochester NY and will provide the opportunity for North American companies to connect with WZL and learn about current research activities. For more than 50 years the annual WZL Gear Conference in Aachen, Germany, has been fostering technical collaboration and communication among the members of the WZL Gear Research Circle. The two-day conference is devoted exclusively to the presentation of the latest research in gear design, manufacturing, and testing. Additionally, the software resources of the WZL Gear Research Circle are available for examination, including solutions for ger design and manufacturing process development. Participants of the conference are encouraged to tour the WZL laboratory with its shop floor and test rigs. Within this environment associations are formed and the exchange of knowledge among the members of the technical community is promoted. With up to 300 participants from Europe and overseas, the WZL Gear Conference is one of the largest annual events dedicated to gear technology in Europe.

geartechnology.com/events/5095-wzl-gear-conference-usa

SEPTEMBER 9–14

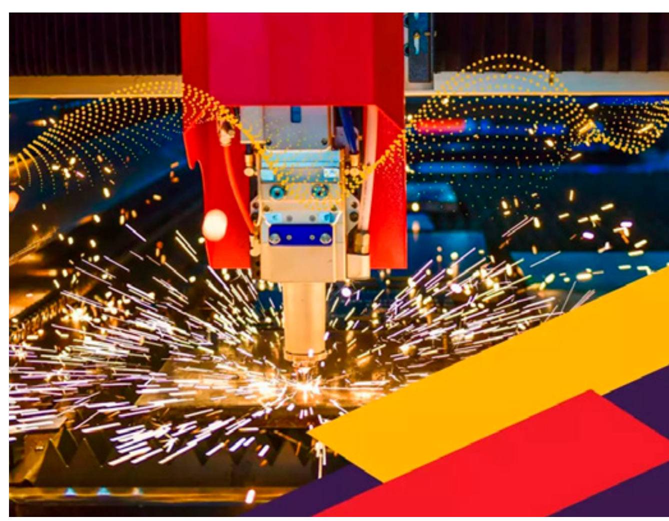
IMTS 2024

The International Manufacturing Technology Show (IMTS) is the largest manufacturing technology show in the Western Hemisphere. The IMTS conference brings the industry together to discuss new opportunities and network with the manufacturing community. Highlights include the Smartforce Student Summit, Exhibitor Workshops, the Emerging Technology Center and more. Pavilions include additive, gear generation, machining, tooling, quality, automation, software, and more. Explore even more exhibits at the Automation Sector featuring advanced motion systems, vision and imaging, data analytics, systems integration, artificial intelligence, and cloud and edge computing.

geartechnology.com/events/4989-imts-2024

OCTOBER 15–17

Fabtech 2024



Fabtech provides a 'one-stop-shop' for metal forming, fabricating, welding, and finishing trade show. Attendees can meet with 1,300+ suppliers, discover innovative solutions, and find the tools to improve productivity and increase profits. There is no better opportunity to network, share knowledge and explore the latest technology. Gain insights into industry trends that will help you prepare for what's ahead, all here in one place. The Fabtech Conference combines 60-90 minutes sessions and workshops covering the latest in advanced fabrication technology, workforce, and management topics.

geartechnology.com/events/5075-fabtech-2024

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Immersive Engineering

Siemens and Sony collaborate on spatial content creation system

Matthew Jaster, Senior Editor

Engineers Assemble. If you're a product engineer in charge of designing the latest and greatest manufacturing creations, it's officially "Tony Stark" time. If Philip K. Dick is more your speed over the Marvel Cinematic Universe, than how about "Tom Cruise" time in *Minority Report*? Siemens and Sony recently introduced a solution that combines the *Siemens Xcelerator* portfolio with Sony's new XR head-mounted display (HMD), SRH-S1—designed using Siemens' own *NX* software—insert chicken vs. egg debate here.

Simply put, all those flashy, tech-savvy computer dashboards from science fiction films are no longer science fiction. I've seen quite a bit of this in early 2024—just when you think product engineering couldn't get more intuitive along comes Sony's XR technology.

"Sony succeeded in implementing *NX* in the fastest schedule in the world and we were able to improve our design process productivity by 25 percent," said Seiya Amatatsu, head of Sony's XR Technology Development Division at Siemens Realize Live event in Las Vegas. "Although significant advancements have been made with *NX*, I wanted to achieve further evolution with a product that brings innovations allowing direct editing in an immersive environment. I believed that could be realized with Siemens and as a result, the XR head-mounted display was developed that could bring innovative products to market more rapidly."

Sony's XR head-mounted display is a fundamental part of the forthcoming *NX Immersive Designer*, an integrated solution that combines Siemens' *NX*, exclusively with Sony's breakthrough XR technology to deliver immersive design and collaborative product engineering capabilities.

"Our head-mounted display and dedicated controllers lets you create more intuitively in a fully immersive environment, allowing you to move freely between the virtual and real worlds—collaborating and creating with colleagues around the world in real time—and it will enable more innovation," explained Hirohito Kondo, deputy general manager, XR Business Development Division, Product Management Department of Sony.

"We're not just viewing designs. This is about doing meaningful hands-on engineering. That is why the image quality is so important—as well as the precision of the controls and even the comfort of the headset—because together, it lets you collaborate more, engineer better, and innovate faster. It lets you do real, meaningful engineering—and without ever having to build a physical prototype," Kondo added.

Based on discussions at Realize 2024, it appears the user can create multiple virtual monitors and design/manipulate objects with intuitive hand controllers. It's basically supercharging an engineer's ability to create high quality, realistic renderings in a virtual space. Just another tool for the industrial metaverse and what the future of manufacturing can look like.

Siemens' *NX Immersive Designer* is expected to launch at the end of 2024. To register your interest in Siemens' *NX Immersive Designer* and learn more about how it is going to change the landscape of immersive visualization and collaboration, visit:

plm.sw.siemens.com/en-US/nx/products/nx-immersive-designer/

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