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MAY 2025

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Cylindrical Grinding
Mechanochemical Surface Finishing

TECHNICAL

Durability and Performance Rating Procedures for Plastic Gears

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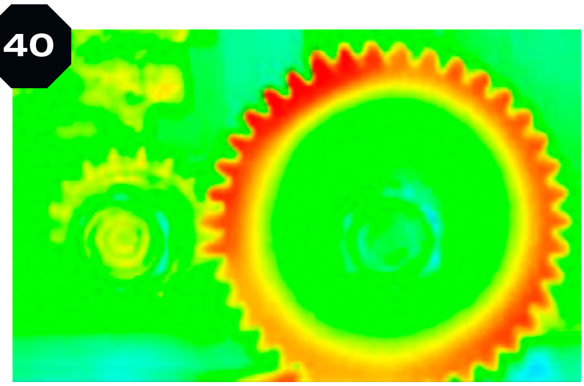

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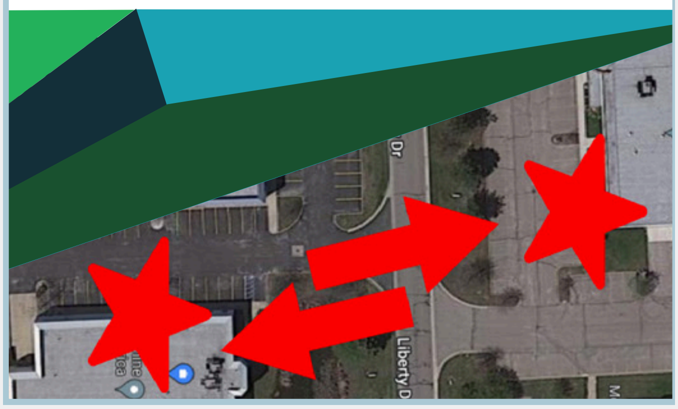

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Vol. 42. No. 3

GT EXTRAS

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GT REVOLUTIONS

LIFT Opens Advanced Metallic Production and Processing (AMPP) Center in Detroit

LIFT, the Department of Defense-supported national advanced materials manufacturing innovation institute, has officially opened its state-of-the-art Advanced Metallic Production and Processing (AMPP) Center in Detroit's historic Corktown district.

geartechnology.com/lift-opens-advanced-metallic-production-and-processing-ampp-center-in-detroit

GT VIDEOS

Grob Showcases Gear Ring Production with Power Skiving

The Grob G750T boasts efficient machining for gear rings by offering precise and efficient power skiving and seamless integration of milling and turning for maximum flexibility and productivity.

geartechnology.com/videos/grob-showcases-gear-ring-production-with-power-skiving

AS SEEN IN *PTE*

FVA–Workbench: The Foundation for Digital Twins

The digital transformation is fundamentally changing the industry, and digital twins play a central role. They enable real-time monitoring of physical systems, simulation of their behavior, and informed decision-making. A dissertation from the TU Darmstadt Institute for Product Development and Machine Elements (pmd) shows how the FVA-Workbench gearbox design software can be implemented as a platform for creating digital twins of industrial gearboxes.

powertransmission.com/fva-workbench-the-foundation-for-digital-twins

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Skiving of rings and shafts

Skiving³: machine, tool and process

Gear skiving machines LK 180/280 and LK 300/500

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Gear Technology

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- Skiving with conical and cylindrical skiving cutters
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Come Together

Come together, Right now, Over me

Even though the lyrics of the Beatles' classic "Come Together" are largely nonsense, it's hard to think of the chorus as anything but an anthem for cooperation and harmony. Basically, when things come together, this is the soundtrack.

So now that I've put the idea in your head, you probably can't help but hear it in the background as I tell you about some cool things happening in our industry.

[cue the baseline...]

♪♪♪♩

Every year, the members of the American Gear Manufacturers Association and American Bearing Manufacturers Association come together at the two organizations' combined annual meeting.

This year, the AGMA and ABMA *really* came together.

At the annual meeting in Austin, TX, the two groups voted to merge the associations under the umbrella of the newly formed Motion + Power Manufacturers Alliance.

This is a historic change. Each organization has more than a century of rich history. As someone who got to witness some of the behind-the-scenes discussions, I can assure you that it's a change the leaders of AGMA and ABMA didn't take lightly. It came after thousands of hours of discussions with members, multiple town hall meetings and very thoughtful deliberation by dedicated leaders on both sides.

Over the past decade or more, we've all witnessed consolidation of our industries, with the big getting bigger and the small getting absorbed or disappearing. We've also seen a convergence of roles within organizations, with one engineer responsible for gears, bearings and much more, a trend amplified by the push for more systems-based solutions as opposed to individual components.

Gears and bearings have always gone together, but this seems to make more sense now than it ever has before.

You can read about some of the thought process and reasoning behind the merger in the Voices article (p. 10) by Michael Cinquemani, the outgoing Chairman of the Board for AGMA, and Matt Frady, the outgoing Chairman of the Board for ABMA, who talk about building an organization that will last at least another 100 years.

What's clear from their message is that both associations are stronger than either would be alone. Members get more value, resources and opportunities, and the two industries gain a stronger, united voice.

What's also clear is that despite this joining of forces, the hard-earned reputation and recognition of the AGMA and ABMA names will remain. The pride of being an AGMA or ABMA member will continue.

Come together, yeah
Come together, yeah
Come together, yeah
Come together, yeah
Come together, yeah
Come together, yeah
Come together, yeah, oh
Come together, yeah
Come together, yeah

Randy Stott

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

AGMA and ABMA Unite to Form Motion + Power Manufacturers Alliance

Michael Cinquemani, AGMA Board Chair and CEO of Master Power Transmission and Matt Frady, ABMA Chair and General Manager, Dodge Industrial

MOTION + POWER MANUFACTURERS ALLIANCE™

American Gear Manufacturers Association®

ABMA® American Bearing Manufacturers Association

2025 is a historic year for the American Gear Manufacturers Association (AGMA), the American Bearing Manufacturers Association (ABMA), and their respective members.

On April 24, at the AGMA/ABMA Annual Meeting in Austin, the membership of each association voted to approve a merger between AGMA and ABMA, creating the Motion and Power Manufacturers Alliance (MPMA).

AGMA and ABMA will continue to keep their names in the marketplace as the 108-year-old AGMA brand and the 107-year-old ABMA brand have a significant history and value to their respective memberships.

The new MPMA entity will deliver increased value through standards creation under the AGMA and ABMA brands, more robust education and workforce development programs, a strong connection of the supply chain via face-to-face events and two industry publications, and advocacy at the Federal and Executive Branch levels.

The AGMA and ABMA have worked closely together on joint programming for the past 18 years, including AGMA managing ABMA since 2019. The Motion and Power Manufacturers Alliance brings together leading power transmission companies to add value to our ever-evolving community. This constitutes a dynamic evolution for two of the best-in-class associations working together for the greater good of its members and the industry at large.

The organizations will unite their committee structures to ensure both gearing and bearing issues and opportunities are explored, standards and programming will continue to be identified under the AGMA and ABMA names, and members will be encouraged to continue to identify as AGMA or ABMA members, as a part of MPMA.

AGMA's history is focused on standards and education, and business connections, while ABMA's value is focused on those issues as well as advocacy, brand protection and global markets, making the new Alliance an opportunity to grow value across both organizations under one umbrella. The industry is coming together as companies merge and acquire to form multi-faceted total system solutions providers, and having ABMA and AGMA come together under the MPMA makes sense to support the evolving market for the next 100 years.

The MPMA will have a united board of directors and continue to be governed by an executive committee including a chair, vice chair, treasurer, past chair and two at-large seats. AGMA Member Sara Zimmerman, Sumitomo, will serve as the chair in 2025–2026.

Combined, the MPMA will consist of more than 425 member companies representing the full spectrum of private and public companies, global and domestic business, open gear, enclosed gears and the full range of bearing solutions.

The merger represents a culmination of ABMA's and AGMA's long history of working together, including 18 years of joint Annual Meetings and nine years of AGMA's Power Transmission Alliance. For the past five years, AGMA has managed ABMA operations.

By creating the MPMA, the two associations have a stronger voice in the standards and advocacy community, enhanced education and training positions, and added value to its publications, the MPT Expo, and the online B2B community.

To best serve the respective members, the two associations are committed to looking to the future while continuing their main pillars of membership value: Standards, Education, Emerging Technology, and Industry Information.

"The bottom line is, we are here to serve you, and we are in this together," said Matt Croson, President of AGMA, and Jenny Blackford, President of ABMA, in a joint statement. "As we move the industry forward, we will honor what got us to over 100 years of existence while we will focus on what will allow us to thrive over the next 100 years. Simply put, the associations are stronger together as this merger unites the brightest and best minds throughout the gearing and bearing community."

motionpower.org

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AUSTIN, TX
April 24–26, 2025

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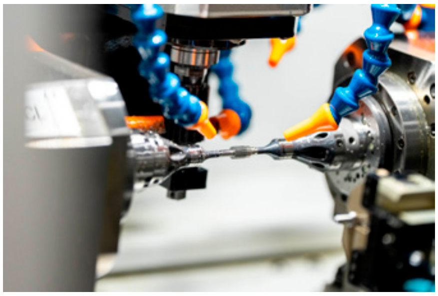
American Precision Gear

INSTALLS GEAR HOBBING MACHINE FROM HELIOS GEAR PRODUCTS



American Precision Gear (APG) has strengthened its manufacturing capabilities with the installation of the MZ 1000 D-Drive gear hobbing machine from Helios Gear Products. This investment not only improves throughput, but also elevates quality and precision machining capabilities, reinforcing APG's reputation as an industry leader in precision gear manufacturing.

Commitment to Quality and Innovation

At APG, quality is non-negotiable. "We spend more time inspecting parts than we do operating machines," explains Jarrod McClendon. "Every component is checked multiple times before leaving our facility. Customers rely on us for quality, and we take that responsibility very seriously."

The MZ 1000 D-Drive has been a game-changer, allowing APG to maintain its meticulous standards while significantly improving cycle times, operational efficiency, and overall productivity. Previously, a single gear could take four to five minutes to process manually. Now, with advanced automation and streamlined workholding, the same job can be completed in just seconds, often running lights out through the night.

Automation and Productivity Gains

The MZ 1000 D-Drive has significantly improved APG's ability to handle complex parts with extreme tolerances. "Some of our parts are so demanding—AGMA 12 and above, with near-zero tolerance on test radius—that they were incredibly challenging to produce at scale," explains Jarrod. "The MZ 1000 D-Drive completely transformed that. It holds tolerances down to a micron with remarkable consistency, making even our toughest jobs not only possible, but now the easiest jobs in the building."

Prior to this upgrade, APG relied on manual setups and extensive in-process inspections, leading to workflow bottlenecks. With the MZ 1000's synchronized headstocks and universal rail system, APG has streamlined operations, reduced setup times, and improved tool life by 200–300 percent. "What used to take weeks now takes days, and what took days now takes hours," says Tyler, a lead gear machinist at APG.

A Collaborative Approach to Success

APG credits its success to a culture of community and continuous improvement. "Our collaborative leadership and focus on quality in the machine shop sets the tone for the entire company," says Jarrod. "The machinists collaborate, cross-train, and focus on the little things that ensure quality and throughput. Our gear shop has followed their lead, and our partnership with Helios has only strengthened that."

Deburring, one of the most challenging aspects of fine-pitch gear manufacturing, has also contributed to their dedication to quality. "Our deburr team is detail-oriented and uncompromising," adds Jarrod. "Many of them are family or close friends, so they naturally help each other find solutions." With the MZ 1000 reducing required deburring needs by 80–90 percent, the deburring team can process more parts with the same meticulous attention to detail.

Beyond machining, APG's shipping and admin teams take ownership of final inspections, ensuring that every part meets stringent requirements before leaving the facility. "It can be monotonous job at times, but they make it fun and keep the company running smoothly, breathing life into the entire organization," Jarrod says.

A Trusted Partnership with Helios Gear Products & Monnier + Zahner

Helios Gear Products has been an invaluable partner in APG's journey. "They didn't just sell us a machine, they proved it would work for our needs," says Jarrod. "Their transparency and support were second to none. When we faced challenges, they sent engineers, connected us with other users, and even facilitated remote troubleshooting directly with Monnier + Zahner in Switzerland. That kind of support is rare, and so valuable to us."

Helios' expertise in precision gear manufacturing helped APG seamlessly integrate the MZ 1000 D-Drive, optimizing their process for high-accuracy, high-volume production. "This machine breathes life into our capacity," says Jarrod. "It allows APG to produce small, precision AGMA 12–13 quality parts in volume with absolute ease; something very few shops can do," adds Willie Taylor of Helios Gear Products.

Looking Ahead

With the MZ 1000 D-Drive fully operational, APG is poised for continued growth. "We want to keep investing in technology that makes the difficult jobs easier for our team," says Jarrod. "The goal is increased throughput with less effort, so our people can focus on collaboration, problem-solving, and maintaining our industry-leading quality."

Through a combination of advanced automation, skilled craftsmanship, and a strong partnership with Helios Gear Products and Monnier + Zahner, APG continues to set the standard in precision gear manufacturing.

heliosgearproducts.com

Vomat

OFFERS FILTRATION TECHNOLOGY FOR METALWORKING INDUSTRY

Choosing the right ultra-fine filtration system plays a key role in success in the metalworking industry. High-quality cooling lubricants and their efficient filtration are crucial for first-class product quality, cost-effectiveness and a smooth production process. The filter manufacturer Vomat from Treuen/Germany offers high-performance filter technologies for this purpose. Thanks to the flexible FA machine concepts, customized solutions can be implemented, e.g., with optional modules such as special cooling systems for temperature-optimized coolant filtration.

Ultra-fine lubricoolant filtration during tool grinding offers users clear advantages: The cleaner the grinding oil and the less frequently it needs to be replaced, the more lubricoolant costs are reduced. At the same time, tool costs and machine downtimes are reduced. Surface quality also improves, while the environment and resources are protected thanks to a positive energy balance and lower waste volumes. Steffen Strobel, sales manager at Vomat, explains: “The choice of suitable filtration and cooling has a direct impact on production costs. Our systems are therefore designed to help manufacturers make the most of these cost benefits.”

Vomat filters separate 100 percent of dirty and clean oil in a full-flow process. Clean oil in quality class NAS 7–8 (3–5 µm) is permanently available for the production process during the backflushing of the filter elements as required. This means that cooling lubricants can remain in the system significantly longer than with conventional filtration processes. Options such as internal, external or spindle cooling, disposal of recyclable materials, additional tanks and more enable an optimum complete system solution for filtration processes for individual applications.

“Tool manufacturers go to great lengths to produce high-performance cutting tools. This is because the production conditions now have a major influence on the final quality of the tool. This ranges from temperature-stabilized production conditions and state-of-the-art, fully automated hardware and software for grinding to automated testing and measuring concepts. The temperature-optimized ultra-fine filtration of the cooling lubricant is a key piece in the mosaic for achieving consistently reproducible premium quality in large-scale production,” Strobel said.

In continuous operation, the cooling lubricant is continuously cooled during ultra-fine filtration. Vomat offers various solutions for this. For the FA 120–240 series, the condenser is mounted in the cover of the filter system or optionally as an external condenser, which is mounted on the outside wall of the building with an internal/external switchover function. The control accuracy is ± 0.2 K at an ambient temperature of 15–35°C with a cooling capacity of 9–40 kW. In addition, the cooling of the axis drives can be connected to the filter system as a modular unit. Strobel emphasizes: "The precise temperature setting gives the tool grinder the necessary security that there are only minimal temperature fluctuations, even in the micro range. This enables it to produce consistently high quality within the required tolerance ranges."

Vomat also offers external cooling units with condensers that achieve a cooling capacity between 9 and 60 kW. Another option is customizable cold water cooling with an external water circuit. If required, modular units for cooling axis drives, spindles and motors can be connected to the filter system.

"Our systems are designed as solutions for individual applications, modular systems and central systems. Thanks to their advantages, they represent an efficient alternative to conventional filter systems in the metalworking industry," said Strobel. "If the tool manufacturer uses state-of-the-art grinding technology, our filtration technology with its high control accuracy gives them the security of producing consistently high tool quality in a reliable process."

oelheld.com

KUKA

OFFERS MATERIAL HANDLING SOLUTIONS AT PROMAT 2025

KUKA Robotics unveiled the latest heavyweight addition to its line of autonomous mobile robots (AMRs), the KMP 3000P, at Promat 2025 in Chicago. KUKA showcased a live cell demonstration to meet manufacturing workforce challenges for improved production. This cell showcased the capabilities of KUKA's new KMP 3000P AMR that transported heavy rolls to a KR QUANTEC for handling and placement.

With the capacity to transport loads up to three tons in any direction, including diagonally, the KMP 3000P's omnidirectional drive ensures maximum flexibility in the tightest of spaces in intralogistics. Four integrated 3D cameras and two laser scanners enable a 360-degree view, allowing the platform to recognize obstacles and drive around effortlessly. This increases efficiency and safety in a variety of working environments while eliminating the need for in-floor guide systems. Equipped with an inductive charging system, the KMP 3000P charges wirelessly both centrally in a station and/or at various locations within the area through inductive charging pads attached to a facility's floor.

The transported material was handled by an AIRSKIN equipped KR QUANTEC high payload robot that enables the robot to safely operate significantly faster than a cobot in a fenceless environment without compromising its reach, payload and reliability. The KR QUANTEC series consists of all-purpose, six-axis robots with the versatility to reliably handle a variety of production applications. The series' streamlined design is also very adaptable to cost-effective cell planning.

kuka.com

Schunk

HIGHLIGHTS GRIPPING AND AUTOMATION TECH AT HANNOVER MESSE

Schunk follows a comprehensive, collaborative technology strategy to enable flexible, future-oriented automation in any environment and at any level of digitalization—today and in the future.

In the Schunk Control Center, users always have full transparency over their process steps. Here, the latest mechatronic Schunk grippers can be digitally commissioned, monitored, and adjusted as needed. The family includes the EZU centric gripper, EGU parallel gripper, and EKG electric gripper for small components. These grippers offer a wide range of communication interfaces, PLC function blocks, and plugins for various robot manufacturers. Additionally, the Control Center provides extended configuration options and regular software updates, enabling users to unlock the grippers' full potential. This forward-looking platform is set to be gradually expanded to all Schunk products.

More productivity at every level of automation. The new mechatronic gripper generation is fully networkable, offers smart functions, and can be seamlessly integrated into digital plant simulation.

When developing its digital building blocks, Schunk follows an open, user-centric approach. To this end, the company provides open-source software for its new grippers on open platforms such as GitHub and ROS, making it accessible for further development and expanding the range of applications. Significant potential lies not only in industrial robotics, but also in cobots and humanoid robotics, which can be used in various environments. To collaboratively unlock these diverse and complex application areas, Schunk offers its proprietary humanoid SVH 5-finger gripping hand as open-source software and as a digital twin.

The digital factory of the future will be planned and optimized virtually before it takes shape in the real world. Particularly complex systems can be designed and simulated more efficiently in the industrial metaverse, reducing time and effort. To support this, Schunk provides CAD data for all its 13,000 components, gradually refining them into highly realistic digital twins. The latest mechatronic grippers are already available as advanced digital twins, replicating not only communication interfaces but also the physical behavior of the grippers during movement.

Schunk demonstrates what a virtual industrial process could look like at Hanover, using the example of a complete automation cell for battery cell handling in the e-Mobility sector. Developed together with technology partner ISG, the system allows simulation in the ISG Virtuos tool. From there, models can be directly exported to the NVIDIA Omniverse, where Schunk provides not only its component libraries, but also complete assemblies and custom automation solutions to create virtual industrial worlds. Additionally, the AI software for the 2D Grasping Kit, awarded the HERMES award 2024 for handling unsorted parts, is already being trained and further developed in the metaverse.

At Hannover Messe, Schunk demonstrated how a consistent technology strategy across all levels can drive productivity and efficiency. “At Schunk, our customers are at the heart of all our innovations. We enhance physical components with digital solutions to meet customer needs and support efficient automation at every level—compatible with any ecosystem,” said Timo Gessmann, CTO, Schunk.

Exhibitors came together in the project “battery use-case “to demonstrate how automated battery production and sustainable recycling processes can become a reality through collaborative partnerships. Schunk, together with FANUC, presented automated process steps for handling prismatic battery cells during unloading and feeding into a welding system.

schunk.com

Mazak

EXPANDS NEO MACHINE TOOL SERIES

Mazak continues to expand its NEO Series of machines with the new Integrex j-200 and j-200S NEO models. The horizontal multitasking machines feature single and twin-turning spindle versions with milling spindles to significantly shorten cycle times and provide single-setup part processing. As part of the NEO Series, the machines combine advanced technology and outstanding value with high-performance productivity.

Integrex j-200 and j-200S NEO advanced technology encompasses enhancements that include higher-torque integral spindle technology for maximum material removal, specifications for faster spindle rpm, positioning accuracy and higher torque ratings along with expanded tool magazine capacities and longer tool lengths. Added heat displacement compensation equipment provides stable machining accuracy, increased operating efficiency and reduced power consumption.

High-performance specifications for the new Integrex j-Series NEOs offer shops increased spindle torque ratings of 20 hp/240 ft-lbs (15 kW/326 Nm) for main spindles, 20 hp/123 ft-lbs (15 kW/167 Nm) for second spindles and 25 hp/42 ft-lbs (18.5 kW/57.3 Nm) for B-axis milling spindles that provide 0.0001-degree indexing positioning. Tool magazines now accommodate up to 72-tools and allow for maximum tool lengths up to 9.8 in. (250 mm).

For heat compensation, Mazak's AI Thermal Shield on the new machines suppresses changes in the cutting-edge position based on spindle speed and temperature of the machine. The function stabilizes continuous machining accuracy through meticulous machine control, considering temperature changes, machine position, coolant on/off and other factors. New AI algorithm calculations improve the accuracy of compensation, and with accumulated and learned data from subsequent measurements, thermal displacement compensation is optimized for each machining environment for stable machining accuracy.

Paired with the Integrex j-Series NEO machines, Mazak's Smooth Coolant System boosts both energy and labor efficiency. The system reduces coolant cleaning frequency for less required maintenance, while integrated inverter controls for multiple coolant system pumps optimize operational efficiency. This results in power consumption reductions up to 20 percent and less CO^2 emissions. Along with the coolant system, high-capacity coolant tanks enable continuous operation for long periods of time as with fully automated machine operation.

Featuring Mazak's Mazatrol SmoothG control, the machines excel at high-speed and high-accuracy machining, offering both G-code and conversational programming platforms. The control provides unsurpassed ease of operation with its 19-in. touch screen and 3D model-based graphical user interface for intuitive operation like that of smartphones and tablets.

For seamless automation to help shops overcome skilled labor shortages while keeping pace with increasing production demands, Mazak offers its Ez Loader for the new Integrex j-200/j-200S NEO machines. The Ez Loader redistributable automation system incorporates a stand-alone, plug-and-play automation system that uses multiple pallets, an easy to use programmable pendent, compact floor space and all necessary equipment for a flexible hassle-free machine integration and lights-out production.

mazak.com/us-en/

Tips for Optimizing Your Cylindrical Grinding Processes

Unlocking next-level precision and efficiency on the shop floor

Jeff Holtzapple, Business Development Manager, EMAG LLC

Choosing an appropriate grinding wheel is fundamental to achieving optimal performance in cylindrical grinding. A good practice is to consult a trusted expert from an abrasives supplier when the answers seem to point in every direction.

Cylindrical grinding is an essential machining process in precision manufacturing, ensuring that components meet stringent tolerances with superior surface finishes. Optimizing this process involves a strategic approach to wheel selection, process automation, in-process measurement and machine maintenance. This article explores key technical factors that influence the efficiency and accuracy of cylindrical grinding operations.

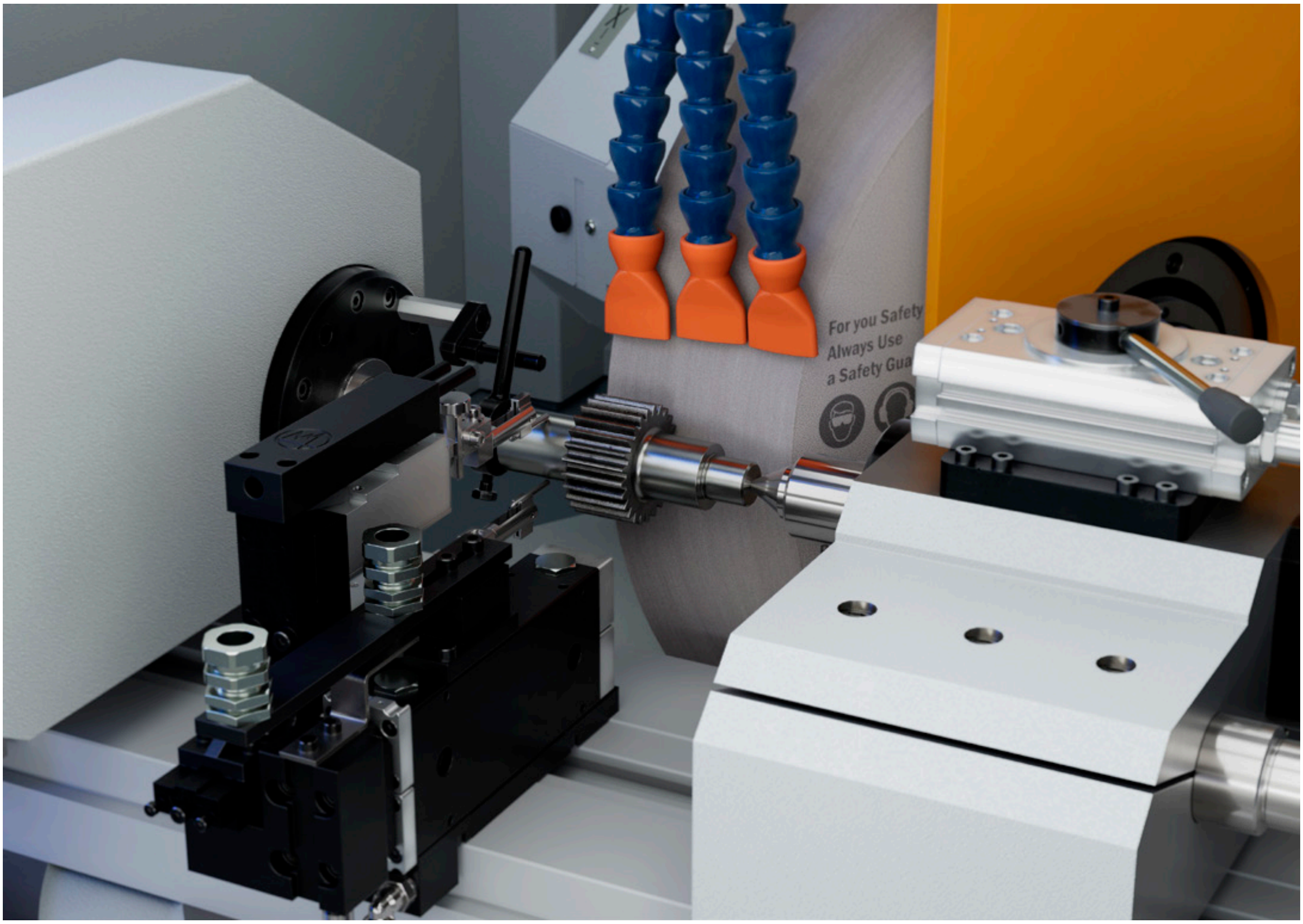
Grinding Wheel Selection and Optimization

Selecting the appropriate grinding wheel is a fundamental aspect of achieving optimal performance in cylindrical grinding. There are several parameters to consider, and at times, the guiding principles can seem contradictory. A good practice is to consult a trusted expert from an abrasives supplier when the answers seem to point in every direction. Below is some general information on where to start.

- **Material Compatibility:** The grinding wheel composition should be matched to the workpiece material. Start with the type of material, ferrous or non-ferrous, and then determine the hardness of the material. Aluminum oxide wheels are generally suited for steel or ferrous materials, while silicon carbide is preferred for non-ferrous metals and ceramics. Another grinding wheel category is superabrasives. These can generally be used on any part-material composition and are considered when other types of wheels are not performing well. As in all machining operations, tooling costs are calculated into the overall price-per-part and profitability.

- **Abrasive Grit and Bonding:** The choice of abrasive grit size impacts surface finish and material removal rates. Coarser grits facilitate aggressive stock removal, whereas finer grits enhance surface quality. The bonding material, or grade of the wheel, must also be selected based on the required wheel durability and heat resistance. Grindability describes how easy or difficult a material is to grind. When dealing with a material with a high-grindability, try starting with a course, durable grit and harder grade. For low-grindability applications, smaller grits with softer grades are a good starting point.

- **Operating Parameters:** The speed of the grinding wheel and workpiece feed rate must be precisely controlled to optimize cutting forces, such as grinding pressure, prevent thermal damage and minimize tool wear. Part tolerance, finish requirements and part geometry or form will also likely factor into wheel selection. Finding the correct combination of composition, grit size, toughness and grade hardness for the part application will strike an optimal balance between cutting cycle times, machine performance and part results.



In-process measurement control enables the grinding machine to measure the grinding process and to adjust accordingly, improving the precision and accuracy since deviations can be detected and corrected in real time.

Integrating Manual and CNC Techniques

While CNC grinding provides high precision and repeatability, manual techniques remain valuable for specific applications. The selection of grinding methodology should be based on production requirements:

- **CNC Grinding for High-Volume, Complex Geometries:** Automated CNC systems ensure consistent tolerance and efficiency in many production environments. One area gaining traction at all levels of production grinding is loading/unloading automation. The ability to consistently load parts the same way every time eliminates variables and potentially frees talented personnel to focus on other areas of the production process where they are needed. Although highly engineered custom automation can benefit process optimization and profitability, finding the right supplier while maintaining your project budget can be challenging. Today, machine tool OEMs and distributors offer flexible off-the-shelf part-automation, which can help enhance the process without breaking your budget.

- **Manual Grinding for Specialized Applications:** Certain low-volume or highly customized components benefit from the skill and adaptability of manual operators. An example where manual grinders are frequently used are in tool-room environments. Manufacturing facilities often require in-house support for rework, part repairs and tooling, which, although limited in quantity, require similar stringent tolerances and quality as the production processes they support.

- **Hybrid Approach:** In some cases, a combination of CNC and manual grinding techniques can achieve both efficiency and fine-tuned precision.

In-Process Measurement and Quality Control

To maintain consistency and precision in cylindrical grinding, real-time measurement systems should be integrated into the workflow:

- **Probing and Sensing Technologies:** Advanced optical and tactile probes enable in-situ measurement, reducing the likelihood of dimensional errors. In-process measuring systems contact the part during the grinding. Once the desired diameter is reached, the program disengages the wheel and the process continues.

- **Force Monitoring Systems:** Continuous monitoring of grinding forces helps in detecting anomalies such as tool wear or excessive heat generation. Production parts often arrive to the grinding process with too much or too little grinding stock. The grinder's built-in ability to monitor these differences, called "GAP and Collision Control," improves cycle times and avoids damage to equipment and scrapped workpieces.

- **Statistical Process Control (SPC):** Implementing SPC methodologies allows for real-time data collection and analysis, facilitating proactive process optimization.

Machine Maintenance Strategies for Performance Optimization

Proper maintenance is critical to sustaining optimal machine performance and extending equipment lifespan. Planning the maintenance for your grinder, conventionally called preventative maintenance, allows facilities to schedule the downtime of equipment and helps to avoid unexpected equipment failures during important production operations. The maintenance guidelines provided by equipment manufacturers should be followed carefully and include some of the following:

- **Routine Cleaning and Lubrication:** Regular removal of debris and adequate lubrication of moving components prevent premature machine wear and mechanical inefficiencies. Whether your equipment utilizes a manual or automatic lubrication system, ensure the oils or grease are being applied to their intended components, even if they are in hard-to-see locations.
- **Grinding Wheel Dressing and Balancing:** Periodic wheel dressing maintains abrasive sharpness, while balancing ensures vibration-free operation and improved accuracy. A properly dressed and balanced wheel protects the machine's spindle bearings.
- **Coolant System Management:** The effective use of coolant controls heat buildup, enhances surface finish and reduces wheel degradation. Whether the application calls for an oil or water-soluble coolant, proper filtration can help optimize the machining process and keep pumps and hoses clean and free from grinding swarf.

Maximizing efficiency in cylindrical grinding requires a combination of strategic wheel selection, process automation, real-time quality monitoring and diligent maintenance. By implementing these technical best practices, manufacturers can achieve superior precision, reduce downtime and enhance overall productivity in their grinding operations.

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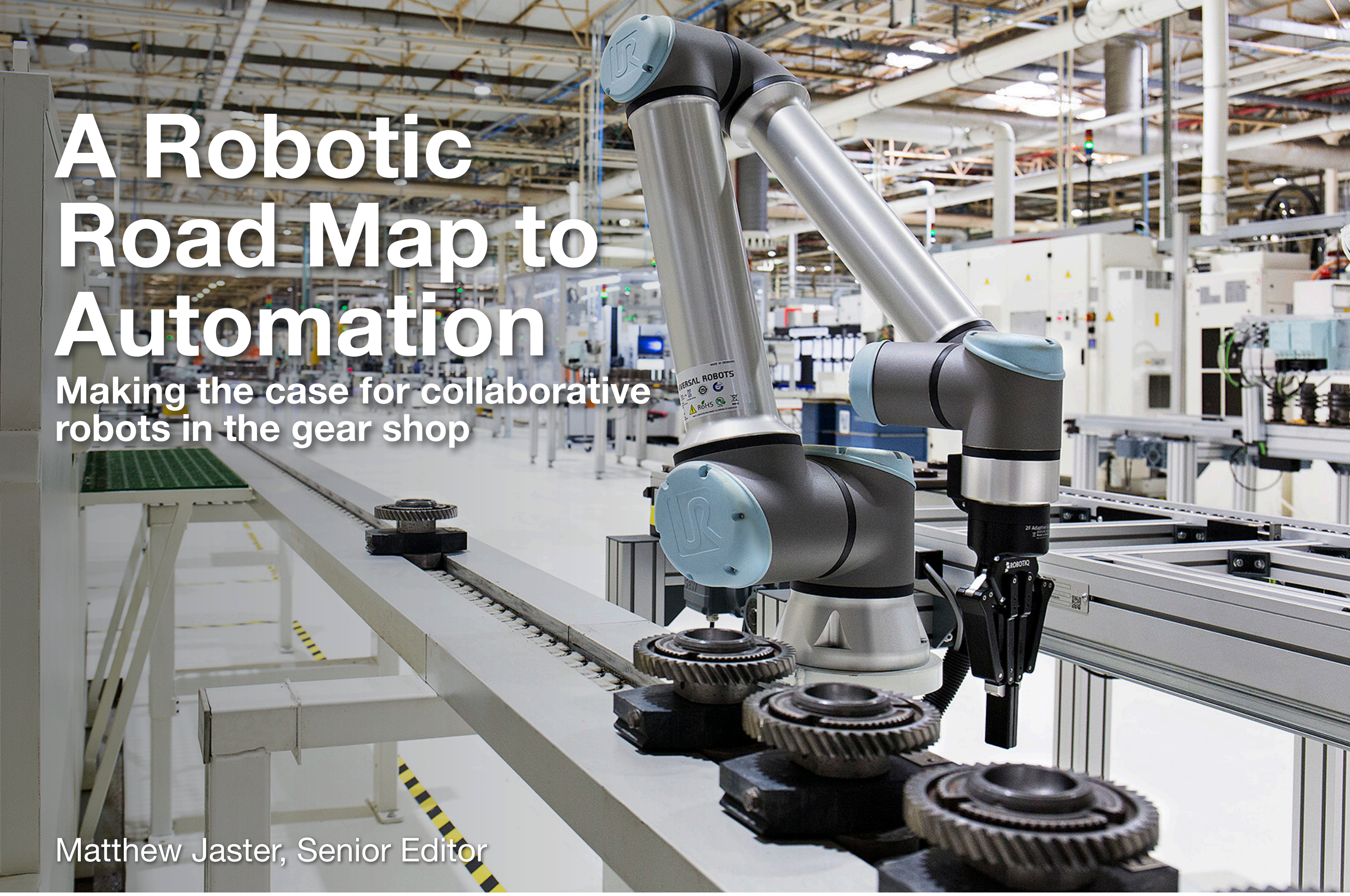
A Robotic Road Map to Automation

Making the case for collaborative robots in the gear shop

Matthew Jaster, Senior Editor



Our annual State-of-the-Gear-Industry survey in January included the question, “What role will emerging technologies play in your organization in the coming years?” Notably, many respondents plan to implement shop floor automation and cobots into their gear shops. The game plan and timetable, however, varies on a case-by-case basis. To assist in the development of an automation program, we’ve interviewed experts from ABB, Universal Robots and KUKA Robotics to provide insightful and timely feedback on how to start this journey in gear manufacturing.

First Steps

Chris Savoia, UR+ global program director, said the first step for successful automation is identifying pain points on the shop floor—set time aside for a line walk, which is an on-site assessment where key stakeholders observe and analyze manufacturing processes to identify automation opportunities and improve efficiency. Line walks usually involve external experts; many experts will do one for free.

“Before the line walk, clearly define your objectives, like improving precision, enhancing flexibility or boosting productivity. Note how collaborative robots can play a crucial role here due to their small footprint, making them ideal for gear shops with limited floor space,” Savoia said.

When ready, Savoia suggests you gather a diverse team with expertise in production, maintenance and quality control. Perform a physical walkthrough of the production line, observing each step closely. It’s important to map all manual processes down to the smallest detail. For example, do not omit how an operator may perform a short inspection after picking a part up. Make sure to draw a top-down diagram of the work cell layout and use it to start imaging how a robot would physically fit into the space. Pay special attention to bottlenecks, repetitive tasks and areas where precision is critical.

“Cobots are particularly beneficial in these scenarios because they are easy to program, allowing for quick deployment and flexibility in handling different tasks,” Savoia added.

It is vital to engage directly with front line operators to understand their daily tasks and challenges. These insights are invaluable for identifying automation opportunities. Equally important is to collect and analyze data on key performance indicators (KPIs) such as cycle times, quality metrics and productivity rates. This data can identify areas where automation will have the most impact. Cobots, with their built-in safety features like collision detection and force-limited operation, can work alongside human operators without extensive safety barriers, enhancing both safety and efficiency.

“It’s important to understand that collaborative robots can be used in ways that traditional robots can be used. Every day, collaborative robots are getting more payload and more speed, while maintaining their safety systems and ease-of-use,” Savoia said.

Corey Ryan, director of medical robotics at KUKA, says shops should first consider what the cobot’s role will be and what it will be doing.

"In most gear shop operations, the cobot will act primarily as a machine tender, loading and unloading workpieces into the machine to eliminate the need for an operator to tend the machine all day. Most cobots are not robust enough to hold or manipulate the workpiece during heavy machining, however, some applications might allow the robot to transfer the part to a light secondary operation such as buffing, polishing or deburring," Ryan said.

Andie Zhang, global collaborative robot product manager, ABB Robotics, believes a good first step would be to identify repetitive, labor-intensive, or precision-critical tasks that a robot could improve and ensure that it is feasible for the robot to integrate with conveyors and processing equipment.

"Another key step would be to determine whether a collaborative robot or a traditional 6-axis robot are more feasible for the application to be automated. Cobots are ideally suited for applications that require an operator to frequently interact with the robot—like in the case of high mix, low volume production runs," Zhang said.

The reduced time it takes for an operator to enter the collaborative robot cell, whether behind a fence or not, makes changeovers far quicker and less disruptive. Also, for tasks that require a lot of path programming, a cobot solution can be a good fit due to simplified programming methods.

Though cobot reach and payload capacities have grown and are expected to continue to, there are still limiting factors that would eliminate a cobot from consideration.

"Traditional industrial robots are better suited for very complex operations or processes requiring high speeds to achieve the necessary throughput and handling heavy objects," Zhang added.

Benefits to Gear Shops

In addition to price, a cobot's primary benefit to small and medium-sized shops is its ease of programming and simple interface.

"Someone without robotic expertise can perform a basic setup and go in and change code. To redeploy a cobot, you can just change a couple of touch points so the cobot can do everything as before with a new starting point. That would be more difficult with an industrial robot," said Ryan.

An industrial robot has more features that provide more opportunity, and shops should also consider the extra speed and throughput an industrial robot provides.

"In many cases, an industrial robot with an area scanner, light curtain or other safety-rated stop mode might be better. When humans are not in the area, an industrial robot can run at ten times the speed of a cobot, but the complexity of deployment makes it tougher. It's a trade-off—industrial robots offer more options and productivity but require a deeper knowledge of the system to set up properly," Ryan added.

Cobots offer many of the advantages of traditional industrial robots along with easier use, more intuitive programming and, most notably, greater flexibility.

"Smaller, lighter and inherently more portable than industrial robots, cobots are easy to install and move freely around a factory whenever and wherever they're needed. They're designed with agility and ease of use firmly in mind, capable of being programmed and operated without requiring specialist robotic or software knowledge," Zhang said.

When you automate with an industrial robot, you must automate 100 percent of the task, but with collaborative robots you can automate only the difficult or dangerous tasks for a human operator and the human can do the rest.

"Another type of flexibility comes with a cobot's capacity to be reconfigured, either for changes that come along for their assigned job, or for repurposing for an entirely new task. In some instances, lighter weight cobots are mounted on mobile carts that can be easily moved between different workstations to perform different functions. This reconfigurability, i.e., the ability to be quickly and easily re-programmed to meet changing market requirements, makes manufacturers more efficient and significantly nimbler," Zhang said.

In gear manufacturing, cobots can be implemented most effectively by focusing on tasks that benefit from consistency and precision. Machine tending is a prime example, according to Savoia.

"They excel at loading and unloading CNC machines, allowing for continuous operation and freeing up workers for more complex tasks. Quality inspection is another area where cobots shine. Equipped with vision systems, they can perform consistent, tireless inspections, ensuring high quality standards. Packaging and palletizing are also great applications for cobots in gear shops. They can handle the repetitive work of preparing finished products for shipping, reducing strain on human workers. Assembly operations, particularly for smaller gears or components, can also be effectively automated," he said.

The key is to identify tasks that are repetitive while allowing your skilled workers to focus on more complex, value-added activities that require human expertise and decision-making.

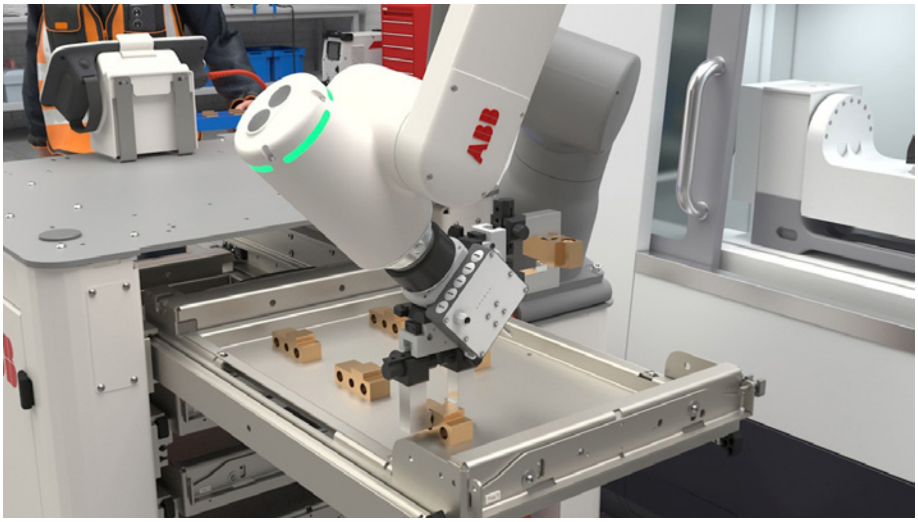


ABB focuses on cobot solutions providing quick installation and operational efficiency.

A Cobot Checklist

What should a gear manufacturer look for when shopping for collaborative or industrial robot solutions?

"A track record of successful cobot installations in the gear manufacturing industry and the type of cobots in their portfolio that are compatible with the specific automated tasks. This includes ensuring the OEM has automation equipment that withstands the rigors of a gear manufacturing environment," Zhang said. "A service and support network for the full lifespan of the robot installation, from system design, through installation, commissioning and ongoing service. Many robot OEMs have a roster of system integrators with specific expertise in applications like gear manufacturing. In many instances the availability of a system integrator is a key consideration."

Finally, Zhang said to consider user-friendly programming interfaces such as teach pendants, graphical programming and offline programming options. "This allows even non-specialists to quickly automate their applications by manipulating simple graphical command blocks rather than writing complex programming code," Zhang added.

When choosing a cobot manufacturer, Savoia at UR said several factors should be considered. "First and foremost is quality. Second, safety features and certifications are paramount.

With its integrated torque sensors, the KUKA LBR iiwa enables the automation of delicate assembly tasks for force-controlled joining operations and process monitoring.

Lastly, look at the manufacturer's customer support and training resources. It's important to think about safety from the moment you start—not at the end," Savoia said. "Moreover, the workflow and movement patterns of human workers around the cobot need to be carefully considered. Even though our cobots have built-in safety features like force limiting, the overall layout of the workspace and the nature of human-robot collaboration in your specific application can introduce risks that need to be addressed.

Another critical factor is the integration with other machinery. "In gear manufacturing, cobots often work in conjunction with CNC machines, conveyor systems or other automated equipment. It's important to tie safety systems together. For example, make sure all e-stop buttons work to shut down all equipment in the work cell," Savoia said.

If you're only deploying cobots for one or two applications, then simplicity of programming and operations are the prime considerations.

"However, if the cobots are being integrated into a more complex system using larger industrial robots for heavy lifting, transporting and packaging, shops will need a full solutions provider such as KUKA or another supplier with a full robotic portfolio," Ryan said. "You should not deal with more than one robot provider in a single shop if it can be avoided. As for risk assessments, in addition to the cobot's travel, speed and potential impact force, its tooling must be a prime concern. Tooling should be neither sharp nor pointed, there should be no pinch point or hotspots, and the system should be examined holistically for safe human/machine interaction.

Trending Topics in Collaborative Robots

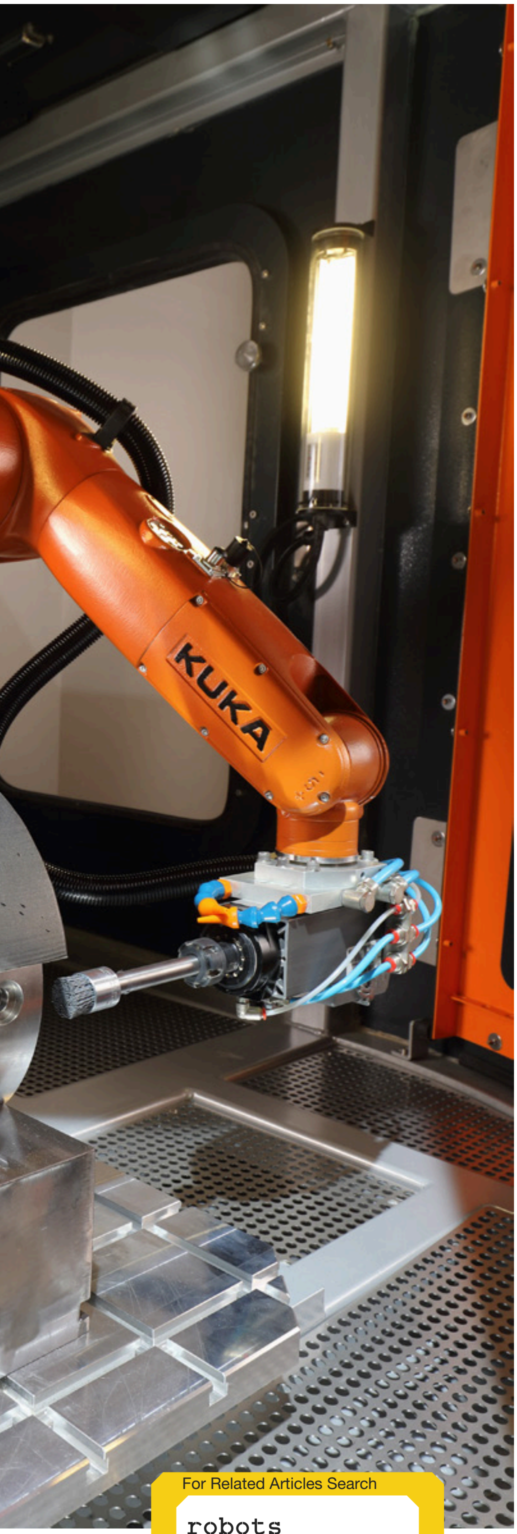
The collaborative robot market has seen significant evolution in recent years, according to all our subject experts.

"In 2025, we're seeing more intuitive programming interfaces that make it easier than ever for non-experts to program cobots. One of our key innovations in this area is our new programming platform, PolyScope X. PolyScope X is specifically designed to enhance flexibility in high-mix, low-volume production environments, which are common in gear manufacturing. This platform allows machine shop operators to achieve changeover times of less than ten minutes, far below what was previously possible. This means

The KUKA KR Agilus is used to deburr a gear housing.

gear shops can run more batches in a day and operate in a more strategic and flexible way, adapting quickly to diverse orders," Savoia said.

The quality of cobots has drastically improved with a variety of available options at different price points in recent years.



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"The introduction of block programming, rather than writing code textually, is a very big part of what makes cobots useful to shops. Advances in force control technology have made them even more deployable, but perceptions have also changed. Initially, people would not accept a robot being able to operate without a fence, but now attitudes have changed 100 percent on that," Ryan said.

Zhang said the advent of collaborative robots provided an innovative robotic option that could work safely alongside humans but was suitable for only the lightest duties; restricted to working in relatively clean production environments such as light assembly, material handling and product testing."

"Over the last few years cobots have become faster, stronger, easier to program, and better able to withstand the rigors of industrial settings. As a result, cobots are now a viable alternative to standard industrial robots for many applications. The trend is going from small part, lighter payload processing, to heavier part applications like CNC machine tending, where the smaller footprint and greater flexibility of cobots is a major benefit."

The Future: Innovation and Accessibility

Looking ahead, our subject experts see an exciting future for cobots in the gear manufacturing industry.

"We'll likely see even greater AI integration, leading to more autonomous operation. Our cobots will be able to make more complex decisions independently, adapting to new tasks with minimal human input. This is an extension of the work we're already doing with our UR AI Accelerator and our collaboration with NVIDIA on physical AI capabilities," Savoia said.

"I anticipate significant advancements in human-robot collaboration. Improved sensing technologies and more natural interfaces will allow our cobots to work alongside humans even more seamlessly. They'll be better at interpreting human gestures and intentions, making collaboration more intuitive.

This focus on human-scale automation, however, will likely place some limits on how much further we increase our cobots' payload capacity. While we've successfully expanded our range, we don't anticipate dramatically increasing payloads far beyond the 30 kg mark of the UR30. Our philosophy is centered on creating robots that can work safely alongside humans without the need for safety guarding, and significantly larger payloads could compromise this core principle," he added.

Instead of pushing for larger payloads, UR is focusing on enhancing the intelligence and versatility of cobots within the human-scale range. This might include improvements in precision, speed, and the ability to handle more complex tasks within the existing payload limits.

"I also foresee an expansion into new industries and applications. As our cobots become more versatile and easier to use, we'll see them adopted in sectors beyond traditional manufacturing," Savoia said. "In the gear industry specifically, this might mean cobots taking on more specialized tasks in gear design, prototyping, or even in areas like customer service and logistics."

Zhang said the payloads and working ranges (i.e. arm reach) of collaborative robots will continue to get bigger and longer, allowing them to handle a greater variety of applications. They will also get tougher, allowing them to be installed in the most challenging environments. Some pundits predict that in ten years, virtually all industrial robots will be collaborative.

"Despite all the recent advancements in cobots, one area that has lagged is accuracy. Cobots were just not as accurate or precise as traditional industrial robots. This has begun to change," Zhang said.

"Looking forward, I think competition is going to be the biggest change in the cobot space over the next few years. Shops can't get enough people to work, and they are looking at all sorts of ways to use cobots—food production, farming, etc.—and these cobot applications will continue to grow into the future," Ryan said.

Keeping the Boats Afloat

Marine Industrial Gears (MIG) is always on call, ready to repair transmissions on everything from river boats up the Mississippi, to oil tankers on the high seas.

Nick Deaville, Regional Sales Manager, Gleason Corporation

With so much at stake, MIG relies on a new Gleason Profile Grinder to speed the return of big gears to peak performance.

Cliff Hill saw an opportunity to do it better. With a career that began in 1979 servicing Lufkin and Falk gearboxes for marine applications, he'd had his share of frustrating parts shortages, technology issues, difficulties in getting quotes and ever-increasing pricing. There had to be a better way. So, in 2003, Cliff Hill founded Marine Industrial Gears (MIG). 11 years later, his son Clifton Hill joined the company. Today, Marine Industrial Gears is indeed doing it better, from its workshop on the Mississippi River just west of New Orleans, in Harvey, Louisiana, and a second repair facility strategically located in Paducah, Kentucky, a waterway hub where the Mississippi and Missouri rivers converge. From these two facilities MIG can cover much of the eastern United States, the Gulf of America/Mexico and, when the need arises, go anywhere in the world where a surface ship needs repair. This includes gearboxes of every make and model—Falk, Lufkin, Reintjes, Western, Twin Disc Gears and Haley—many of which have had to endure the harshest conditions that exist out on the open seas.

All Hands On Deck!

All of these projects have at least one thing in common: marine gearboxes leave no room for failure. Taking a ship out of service for an extended period can cost the owner a fortune, let alone the enormous price tag associated with replacing the gearbox. Repairing and returning a gearbox to reliable service must be done quickly and efficiently. It's what MIG excels at. With no time to waste, MIG takes an all-hands-on-deck approach to repair. Most machining can be done in-house, rather than waste precious time outsourcing. This includes line boring of reduction gears, crankshafts, struts, stern tubes, and rudder stocks; drilling and reaming of engine and gearbox foundations after alignment; even machining and fabricating of foundation bolts, bearing sleeves, and shafts in the required high quality. And now, with the recent acquisition of a Gleason P1600/2000G Profile Grinding Machine, add finish grinding to the MIG toolkit.

The MIG Crew "on board", installing a new transmission gear on high seas.

The recent acquisition of a Gleason P1600/2000G Profile Grinding Machine, add finish grinding to the MIG toolkit.

Marine Industrial Gears Services at a Glance

Global service to the marine and industrial transmission industry, with facilities in New Orleans, LA, and Paducah, KY. 24/7 Field Service. Line boring of reduction gears, crank shafts, engines, struts, stern tubes, and rudder stocks. Alignment, drilling and reaming of engine and gearbox foundations. Full-service machine shop with turning and milling capabilities. Gear profile grinding up to AGMA class A. Rework and manufacturing of foundation bolts, bearing sleeves, seal components, thrust bearing spacers and shafts. Stock of clutches, bearing assemblies, rotating seals, airshafts, bearings, etc.

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Inside MIG's new gear profile grinding machine.

Final alignment touches to a reworked marine transmission.

Geared Up for Grinding

While MIG's focus up until recently had been the servicing of marine transmissions, including alignments, line boring, milling and other jobs, Cliff Hill saw an opportunity to gain control of inventory, shorten delivery and serve his customers better by adding medium and large gear production to MIG's repertoire. Consequently, MIG sought a machine to cover their typical gear service range: gears 48–50 in. (1,210–1,270 mm) in diameter, 24 in. (600 mm) face widths, herringbone-type shafts with double helical gears and other industrial gears of similar size and more.

While Cliff was researching grinding options, a customer and friend recommended Gleason. "He said, 'Go to Gleason and ask for their 2-meter grinder'," Cliff recalls. "So we narrowed our search down to the ideal machine: a Gleason P1600/2000G Profile Grinding Machine. This machine fits ideally the scope of the workload." Indeed, MIG's new Gleason Gear Grinder features cutting-edge technology to rough- and finish-grind any cylindrical external gear up to 79 in. (2,000 mm), to the highest AGMA quality class. The P1600/2000G enables MIG to grind all main transmission elements such as bull gears, pinions or idler gears for all makes and models of marine and industrial gearboxes. Now, gears with minor surface damage can be kiss-ground (light surface grind) in-house with lightning-fast turnaround on all gear elements to minimize downtime.

The new grinding machine also delivers a very important capability that wasn't possible with other grinders in this size range: rough grinding gears from a solid gear blank, and thus eliminating all of the costs and time associated with, for example, the typical gear hobbing operation. This includes the prohibitively long wait time for delivery of the hob needed to cut a particular gear. While "grind from solid" makes sense in theory, its practical application is not easy to achieve, since very aggressive metal removal rates are required in the roughing stage, thus producing significant volumes of swarf and the need for exceptional thermal stability. According to Cliff, the Gleason machine excels in both areas.

"In addition to relying on the machine's capabilities, as a newcomer to gear grinding, we have leaned heavily on Gleason for all of their resources and knowhow," Cliff says. "They gave us the confidence early on to handle the technology and machine operation. It's opened the door to a robust gear grinding business over and above just gears for our usual marine applications."

What's Downstream?

With all these resources at hand, MIG is looking upriver and across the Gulf for more industrial gearbox business. This includes mills for sugar cane and industrial drives found in grain elevators, not to mention the South American market, with huge demand for repair and replacement of aging transmissions. As MIG seeks to expand further into the gear business, "It will always be Gleason," says Cliff. "Marine Industrial Gears is a no-BS, hands-on shop with honest pricing and efficient service. This is why we chose Gleason as a partner—we talk the same language."

gleason.com

Mechanochemical Surface Finishing for High-Speed Gears for EV Transmissions

Meeting the noise and efficiency demands of the electric drivetrain era

Boris Zhmud, Tribonex AB; Boris Brodmann, Optosurf GmbH; and Morteza Najjari, Xtrapid Innovations, LLC.

Powertrain electrification has been a growing trend in the automotive industry. Electric motors used in battery electric vehicles (BEVs) operate at high speeds ranging from 3,000 to 16,000 rpm, with high-performance motors reaching over 20,000 rpm. For instance, Tesla's carbon-sleeved motor used in Tesla Model S Plaid may reach 24,000 rpm at the top speed of 330 km/h. There are experimental designs of interior permanent magnet synchronous motors (IPMSM) reaching 100,000 rpm. The combined inverter/motor efficiency of a typical BEV equipped with a single-speed reduction gearbox reaches a maximum close to the maximum motor speed. Small high-revving motors achieve higher power density and are also lighter and cheaper to manufacture. However, a single-speed gearbox cannot ensure optimum efficiency and driving comfort at different speeds and loads. Hence, quite a few multi-speed gearboxes have hit the market over recent years. Even though the use of a multi-speed gearbox tends to increase the engineering complexity and manufacturing cost of an EV, it is well justified for premium passenger cars, off-road vehicles, and commercial vehicles due to improvements in the driving range, dynamic performance, and gradability (Ref. 1).

Higher speeds of electric motors bring new challenges with lubrication, heat management, and noise. Gear meshing is the primary source of an intrusive whining noise that irritates most drivers. This noise is usually linked to a transmission error and geometric imperfections of the gears. For example, profile angle deviation ($f_{H\alpha}$) and tooth trace angle deviation ($f_{H\beta}$) have been shown to have a significant impact on the noise level through the gearing process (Ref. 2).

Gear microgeometry also has a significant impact on the contact pressure and temperature distribution for meshed gear flanks. Certain modifications, such as crown, taper, and tip relief, have particularly large effects on gear tribology (Ref. 3). Suboptimal microgeometry is associated with an increased risk of scuffing, which is particularly common in transmission gears operating under long-duty cycle hours (Ref. 4).

Gear design usually includes specific optimizations to address issues such as efficiency, noise, and service life. However, it is not always possible to improve all characteristics simultaneously. Perfect gears exist only in theory. In practice, gear manufacturers must always strike a balance between quality and price, which varies a lot from application to application. Gears used in EV transmissions have significant differences in design and, in general, tighter tolerances compared to gears used in traditional stepped and dual-clutch transmissions for ICE-powered cars.

The adequate accuracy for gears used in electric vehicles is around ISO 1328 Grade 6, but high-speed gears rated for speeds over 20,000 rpm may have even higher quality requirements. The contact mechanics in the gear-tooth contact are sensitive to shape deviations at different wavelengths: form, waviness, roughness and microstructure. To optimize the load capacity and the NVH behavior, lead modifications are introduced (Ref. 5). Unfortunately, many traditional gear-cutting techniques, such as generating grinding, profile grinding, gear hobbing, shaving and honing, are plagued by twist errors. To address this problem, special process control or tool geometry adjustment methods have been developed to minimize twist errors in the manufacturing of gears (Ref. 6). To improve transmission efficiency, higher surface quality on tooth flanks is required. This leads to a wider use of advanced surface finishing technologies such as fine grinding or polish grinding (Ref. 7). For instance, with conventional generating grinding, it is challenging to go below R_a 0.5 μm, but when using a combined polish-grinding process, one can reach R_a around 0.1 μm. Mass-finishing processes such as accelerated surface finishing (ASF) and isotropic superfinishing (ISF) allow even smoother surfaces, with R_a down to 0.01 μm. Recently developed mechanochemical surface finishing methods, such as Triboconditioning CG process developed by Tribonex AB, can be used as the final finishing operation bringing about a triad of effects: (i) surface roughness profile optimization, (ii) compressive stress buildup, and (iii) tribofilm priming, which greatly improves the tribological and NVH behavior of gears (Refs. 8,9). Triboconditioning CG treatment can be carried out using standard mass-finishing equipment, such as vibratory tub finishers, centrifugal barrel finishers, and stream- and drag-finishers (see Figures 1–3). The major difference is the use of special chemically reactive process fluids and media types.

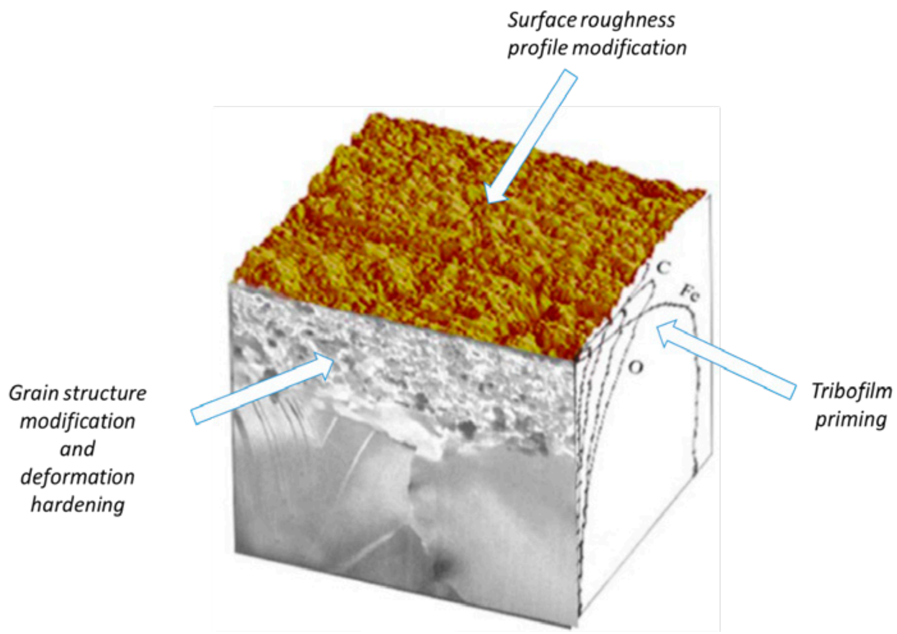

Figure 1—The surface effects brought about by the Triboconditioning CG process.

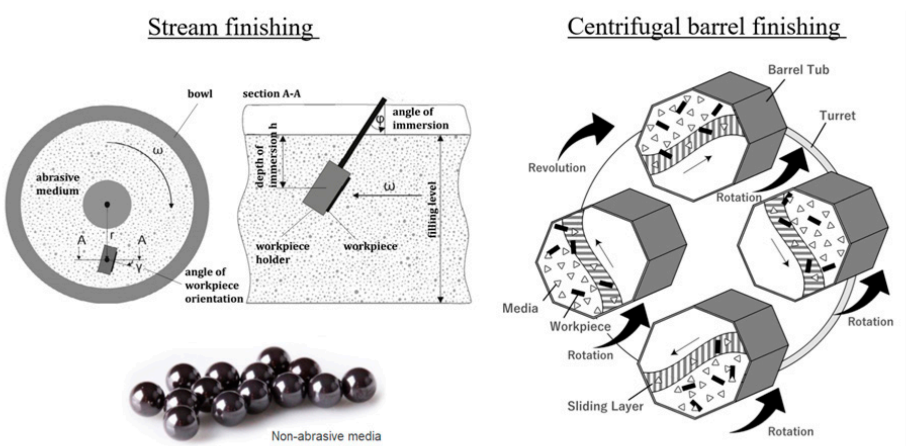

Figure 2—Examples of common mass-finishing platforms suitable for running the Triboconditioning CG process.

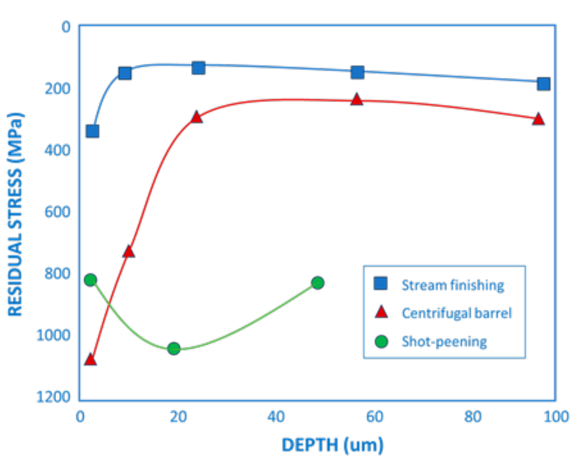

Figure 3—Typical residual stress depth profiles generated by different techniques.

As mentioned, the Triboconditioning CG treatment modifies the surface roughness profile of gears by removing surface peaks and rendering the surface increasingly negatively skewed (Refs. 8,9). This is evidenced by changes in the roughness parameters such as R_a, R_z, R_{pk}, R_k, and R_{sk} measured using conventional surface metrology tools such as stylus and white-light profilometry. Unfortunately, the said tools only allow measurements of amplitude roughness. As far as the tribological performance of gears is concerned, having additional information about gradient roughness is expedient (Ref. 10). This can be done by scattered light analysis using an Optosurf OS500 scattered light system. The scattered light method is based on a mirror facet model of the surface (also known as the Kirchhoff or tangent plane approximation) and, hence, is best suited for the analysis of sufficiently smooth and highly reflective surfaces. When the incident light beam hits the surface, the individual light rays are reflected at the microfacets in directions determined by the individual facet's orientation. As a result, the reflected specular beam broadens. This phenomenon is known as diffuse scattering. The backscattered light is transmitted to a focal plane utilizing Fourier optics. The detected intensity distribution corresponds to the frequency distribution of the scattering angles, as explained in Figure 4.

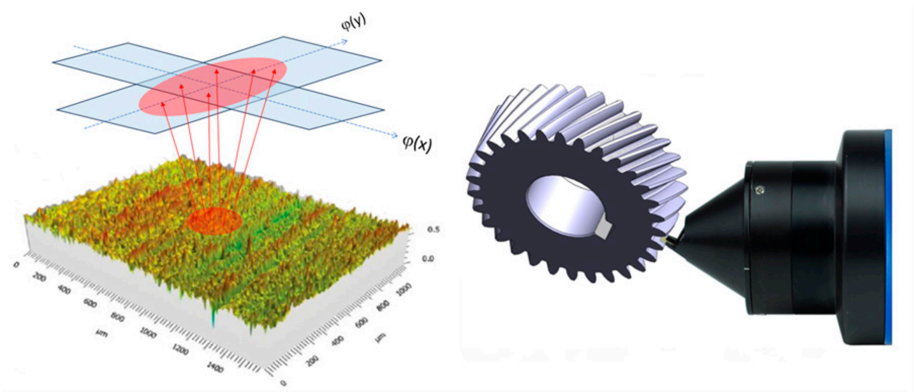

Figure 4—The principle of gradient roughness characterization using scattered light analysis.

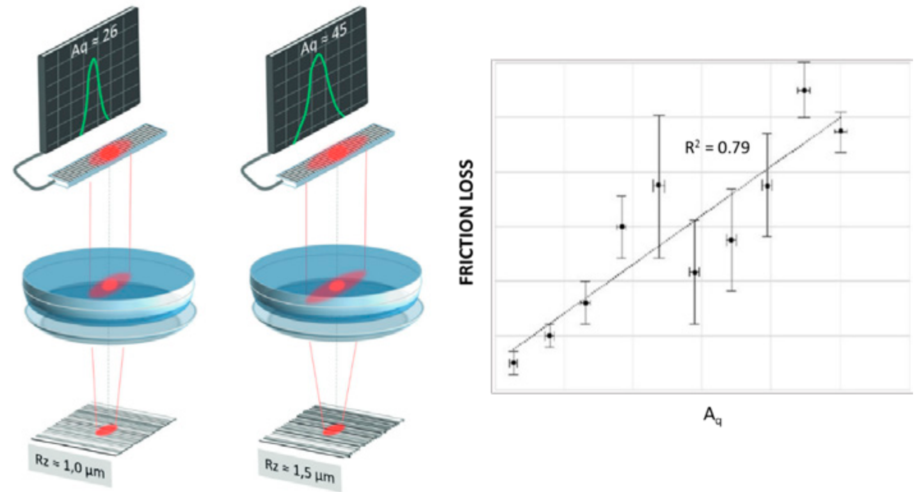

Figure 5—Correlation between the A_q parameter and friction losses (Ref. 10).

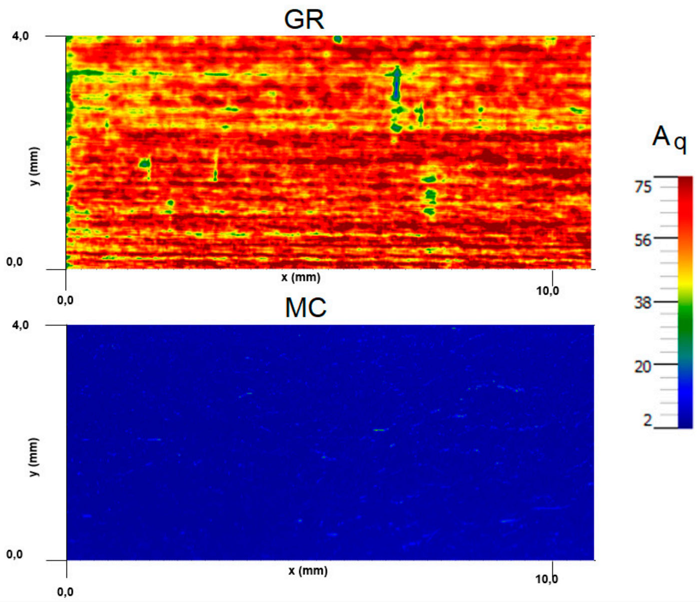

Figure 6—A_q maps for tooth flanks for conventionally ground (GR, the top) and mechanochemically finished (MC, the bottom) gears obtained using the Optosurf technique.

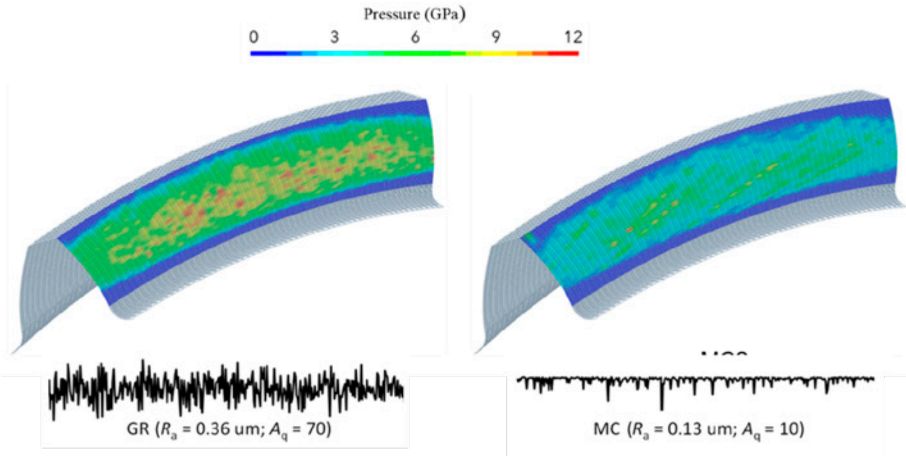

Figure 7—The effect of gear surface finish on the calculated contact stress map for meshed gears (Ref. 9).

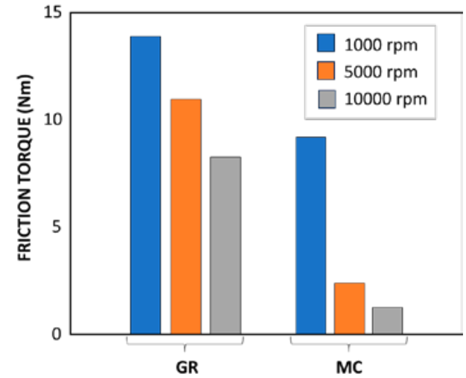

Figure 8—Calculated friction torque for a pair of helical gears shown in Figure 7. The gears are assumed to be lubricated by Dextron VI ATF fluid at 60°C.

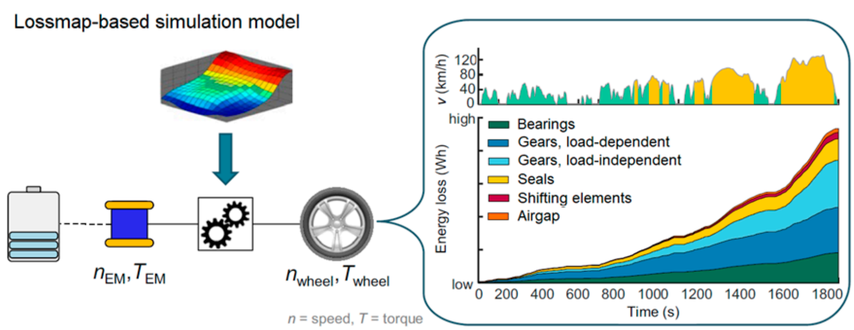

Figure 9—The principle of loss map-based simulations (Ref. 13).

Editors' note: *The Worldwide Harmonised Light vehicles Test Procedure (WLTP) is a global driving cycle standard for determining the levels of pollutants, CO2 emission standards and fuel consumption of automobiles.

The variance of the angular distribution (A_q) of scattered light relates to the scattering angle (φ) as

$$A_q = k\sum_{i=1}^{n}(\varphi_i - \overline{\varphi})^2 p(\varphi_i)$$

where k is a normalization factor, $p(\varphi)$ is the normalized intensity distribution, n is the total number of angle classes, and the bar denotes the average value. Hence, A_q can be determined directly from the scattered light measurements.

There is a reasonably good correlation between the A_q parameter and the magnitude of friction losses in the boundary and mixed lubrication regimes, making scattered light measurements highly valuable for gear surface finish quality control (see Figures 5 and 6).

The influence of gear microgeometry on various dynamic aspects of gear performance, such as noise generation, contact patterns, contact shocks, and torque variations, can be simulated using various loaded tooth contact analysis (LTCA) models (Ref. 11). LTCA can be further integrated with thermal elastohydrodynamic (TEHD) simulations to study the effects of surface finish and lubricant characteristics on gear tribology at the component level, and CFD simulations to accommodate the macroscopic effects of lubricant flow and heat transfer at the system level (Ref. 12). Figures 7 and 8 show an example of how the surface finish characteristics affect the contact stress map and friction torque for a helical gear pair (Ref. 9).

The main transmission losses in a vehicle include losses in gears, bearings, seals, and other components. The losses associated with gears and bearings can be further divided into load-dependent friction losses and load-independent viscous losses. A number of robust loss map-based simulation models have been developed that allow calculation of losses for individual transmission components for different transmission designs and speed-torque combinations (Ref. 13). To evaluate the efficiency of electric powertrains, the modular simulation model is often used (see Figure 9). The effects of different surface finishes on load-dependent gear friction can be determined using thermal elastohydrodynamic simulations (see Figure 7) or appropriate component rig tests, such as the FZG efficiency tests (Ref. 9). Then, by using loss map-based simulations, the impact of different surface finishes on total transmission losses can be predicted (see Figure 9).

The average electric car consumes around 200 Wh/km to complete the WLTP* cycle (23 km). The average energy loss in the transmission is around 10 Wh/km, of which load-dependent gear losses are around 50 percent. Hence, while no significant range extension is expected from using

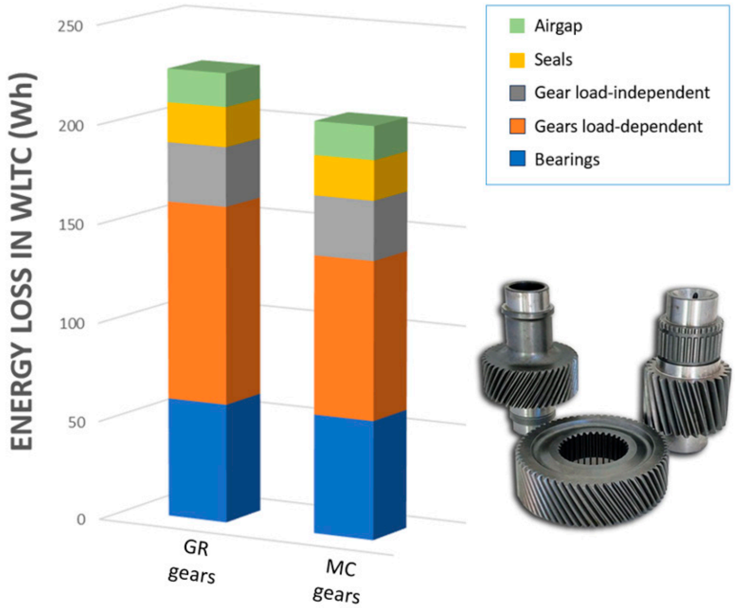

Figure 10—The effect of gear surface finishes on the total transmission energy loss in the WLTP cycle.

mechanochemically finished gears, the reduction in gear friction helps reduce transmission fluid temperature, thus extending the longevity of the fluid and seals. Besides that, mechanochemically finished gears are less prone to wear and micropitting (Refs. 8,9).

These results show that mechanochemical surface finishing is a promising technology for enhancing the tribological performance of EV transmission gears. It should be noted that a reduction in the surface roughness does not automatically lead to a reduction in the friction torque, as there is an intimate interplay between the gear microgeometry and the surface roughness, and with mass-finishing techniques, it is virtually impossible to modify the surface roughness without incurring some subtle modifications to the microgeometry. In some situations, a rougher surface may be more forgiving of geometric imperfections as it undergoes faster run-in wear, allowing easier tooth profile self-adaptation. From a practical viewpoint, one should strive to manufacture gears either as close as possible to their run-in condition or in a condition that responds well to the running-in. Hence, surface and microgeometry optimizations must always go hand in hand. This is a complex, multidimensional task that requires robust CAE tools, manufacturing and quality control methods, and extensive testing.

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AGMA 3D Printing Committee Wraps Up Fifth Guided Tour at RAPID + TCT 2025

Mary Ellen Doran, AGMA Vice President, Emerging Technology

The AGMA 3D Printing Committee completed its fifth annual guided tour of the RAPID + TCT show floor April 8–10 in Detroit, offering members a curated look at some of the most exciting innovations in additive manufacturing. With over 400 exhibitors on display, narrowing the field to just fifteen standout companies was no small task. Nonetheless, the 2025 tour successfully highlighted a diverse mix of material suppliers, machine manufacturers, industry vendors, and breakthrough technologies shaping the future of manufacturing.

This year's tour featured a strong AGMA connection, showcasing companies and individuals with past and present ties to our organization. Several AGMA member companies were included, such as Nidec, Seco/Vacuum, and ANCA—each providing insights into how additive technologies are being integrated into gear manufacturing processes.

We also reconnected with Igor Ortiz and Piera Alvarez from Etxetar, who were exhibiting at the show. Igor previously presented at AGMA's Emerging Technology webinar in February, where he discussed how their team used directed energy deposition (DED) to repair gear teeth on a ring gear—an innovative application of additive technology in gear repair. At RAPID, attendees had the opportunity to view actual DED samples from that project and gain a deeper understanding of the process.

A notable stop on the tour was the University of Waterloo's booth. AGMA previously visited their Multi-Scale Additive Manufacturing (MSAM) Lab on campus in 2024, and it was exciting to catch up on the latest research and developments emerging from their program. This is one of the largest additive labs in North America. Their work continues to push the boundaries of metal additive manufacturing, with promising implications for gear and power transmission applications.

We also included a few major industry players. Nikon updated us on the latest offerings from their additive work. They have a lab in California for companies to conduct secure research. Colibrium Additive (formerly GE Additive) displayed a hob printed from tool steel that reached 70 Rockwell hardness. This represented only the second instance we've seen of a 3D-printed hob, marking another step forward in tool manufacturing via additive methods.

We met some promising new entrants as well. Freemelt develops advanced 3D printers using electron beam powder bed fusion (E-PBF) and is working on complex tungsten geometries for defense applications. Fictiv is reimagining supply chain logistics by pre-qualifying manufacturers and building comprehensive sourcing solutions for their customers. ToffeeX stood out for its physics-driven generative design software, particularly its unique approach to managing thermal properties. We hope to learn more about their capabilities and potentially invite them for a future webinar.

One stop, Pantheon Design—a polymer machine maker out of Vancouver—showed some savvy. The CEO, also an engineer, redesigned the gearbox for a personal electric skateboard to contain herringbone gears, printed in 45 minutes on their machine, to reduce friction and noise. He has clocked more than 3,000 miles on the hills of San Francisco with no wear in sight. They are printing and testing a variety of products; they had an e-bike on hand, pushing the limits of their technology.

The tour also included several innovative material suppliers. The materials landscape grows more competitive each year. We visited 6K, Globus Metal Powders, and spoke with Metal Powder Works, who will be our invited guest at next week's committee meeting. Each company brings a distinct approach to material development: Metal Powder Works mechanically mills powders without heat and focuses on softer metals, while 6K applies a proprietary 6,000-degree process to create highly spherical particles.

Overall, the 2025 RAPID + TCT tour provided AGMA members with invaluable exposure to the rapidly evolving world of 3D printing, reinforcing the importance of staying connected to the emerging technologies that may shape the future of the gear industry.

The committee is sponsoring a 3D presentation from Dodge discussing their use of 3D printing for prototyping at the upcoming AGMA Strategic Networking & Leadership Event, June 4–6 in Greenville, SC.

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New Standardization Projects

Todd Praneis, AGMA Vice President, Technical Division

The AGMA Technical Division Committees have been working on improvements and additions to our standardization efforts. We have three new projects to announce and are looking for technical experts from our membership to join the effort.

Our Metallurgy and Materials committee is kicking off a project to revise ANSI/AGMA 2004-C08, Gear Materials, Heat Treatment and Processing Manual, to bring the latest information into the document. Work on AGMA 923-C22, Metallurgical Specifications for Steel and Cast-Iron Gearing, will be used to help in the revision process, as well as using comments from the three reaffirmations of the document.

The recently reactivated Cutting Tools committee has initiated a project to update ANSI/AGMA 1104-A09 Tolerance Specification for Shaper Cutters to do a general update and add AAA tolerance definitions. They are also looking to add information on applying the tolerances to skiving cutters.

Finally, the Wind Turbine committee is starting a project, AGMA 950-Axx, with a temporary title of Wind Turbine Main Gearbox Condition Assessment based on Visual Inspection. This will be a definition and guidance document to support in-situ inspection of wind turbine main gearboxes to help with consistent nomenclature and techniques for evaluation.

These new projects, along with our existing nine projects listed below, show great dedication from our technical community to continuously improving our knowledge and information for our industry.

Current open standardization projects:

- AGMA 948-AXX, Electrified Vehicle Drivetrains. Working Draft stage.
- AGMA 949-AXX, Guidelines for Repair of Industrial Gearboxes. Working Draft stage.
- AGMA 1010-GXX, Appearance of Gear Teeth – Terminology of Wear and Failure. Working Draft stage.
- AGMA 908-CXX, Geometry Factors for Determining the Pitting Resistance and Bending Strength of Spur, Helical and Herringbone Gear Teeth. Working Draft stage.
- AGMA 936-AXX, Calculated Bending Load Capacity and Pitting Resistance of Powder Metallurgy, PM, External Spur and Helical Gears. Working Draft stage.
- AGMA 6011-KXX, Specification for High-Speed Helical Gear Units. Second General Ballot stage.
- AGMA 9000-EXX, Flexible Couplings - Potential Unbalance and Mass Elastic Properties. Committee Comment stage
- AGMA 919-2-AXX, Condition Monitoring and Diagnostics of Gear Units and Open Gears: Part II – Applications and Advanced Analyses. Working Draft stage.
- AGMA 926-DXX, Recommended Practice for Carburized Aerospace Gearing. Working Draft stage.

Should you be interested in any of these projects, please don't hesitate to contact *tech@agma.org* to find out more.

Durability and Performance Rating Procedures for Plastic Gears

Dr. Damijan Zorko, Rok Kalister and Dr. Borut Černe

High-performance plastic gears are increasingly replacing metal gears in several applications due to the many advantages they exhibit. The main ones are lower weight, no need for lubrication, cheaper mass production, significantly better noise, vibration and harshness (NVH) behavior and chemical/corrosion resistance. Most plastic gears are produced by injection molding, which enables great design flexibility, e.g., joining several machine elements into one molded part, while gear geometry modifications like enlarged root rounding or altered profile shapes are also possible (Ref. 1).

Plastic gears have been used since the 1960s, when they were initially used for simple motion transmission applications. Over the years, with the development of new, improved plastic materials, technology started to make its way into power transmission applications. Until recently, plastic gear drives were employed for applications with power up to 1 kW; however, lately, there have been attempts to use high-performance plastics in gear drives exceeding the 10-kW mark.

Along with ever-increasing customer requirements, the NVH behavior of polymer gears is also gaining importance. One of the early studies of the acoustic performance of polymer gears was carried out by Hoskins et al. (Ref. 2), in which the researchers examined the influence of diverse materials used in polymer gears and different operational circumstances on the spectrum of sound frequencies. Parameters such as the texture of the surface, wear, and temperature, stemming from the interaction between tooth surfaces, were recognized as the factors affecting the intensity of sound energy. Trobentar et al. (Ref. 3) compared the acoustic behavior of polymer gears with different tooth profiles, i.e., involute and S-gears. The tooth profile of the S-gears had a convex addendum and concave dedendum, which resulted in a progressively curved (in the shape of the letter S) path of contact. The authors found that S-gears exhibit lower noise than involute gears, which can be attributed to the more favorable contact conditions. Polanec et al. (Ref. 4) studied the noise of coated POM polymer gears. Three physical vapor deposition (PVD) coatings were investigated, i.e., aluminum, chromium, and chromium nitrite. The study revealed that uncoated polymer gears exhibited the lowest sound pressure level, and hence no positive impact of the coating on the reduced noise could be confirmed. Furthermore, the coating started to peel off during operation, causing increased friction and meshing disturbances, which resulted in an increased sound-pressure level.

The broader adoption of polymer gears could be facilitated if standardized design methodologies were established and pertinent material information became accessible. Presently, there is a lack of a global norm that would formalize the calculations, design principles, and recommendations specific to polymer gears. Certain national standards on this topic do exist, for instance, BS 6168:1987 (Ref. 5), as well as the Japanese standard JIS B 1759:2013 (Ref. 6). The latter draws from ISO 6336:2006 (Ref. 7) with some adaptations detailed in Moriwaki et al.'s study (Ref. 8). Additionally, guidelines from diverse engineering associations are at one's disposal. VDI 2376:2014 (Ref. 9), a successor to VDI 2545 (Ref. 10), was published in 2014, stands as the most comprehensive and commonly employed framework for polymer gear design. It encompasses evaluation techniques for the most recurrent failure modes in polymer gears. Fundamental material data for substances like POM and PA 66 are also encompassed. AGMA (Refs. 11,12) has also issued design guidelines, though these focus solely on potential materials and gear configurations, neglecting design models and essential material data crucial for polymer gear design. Tavčar et al. (Ref. 13) introduced a holistic design optimization for polymer gears that encompasses all plausible failure modes. Efforts have also been made to incorporate machine-learning algorithms into gear design (Refs. 14,15), which have proven beneficial for evaluating non-standard gear designs. Nonetheless, a substantial database of existing instances is requisite to adequately train such models.

When compared to steel gears, polymer ones do also have some disadvantages. The most important ones are a lower load-bearing capacity, poorer thermal conductivity, less temperature stability, and poorer manufacturing precision. While the load-bearing capacity is the most important property, several studies have been conducted that relate to improving it, either with a special gear design (Refs. 1,16,17) or improved materials (Refs. 18,19,20). It is speculated that a significant contribution to the load-bearing capacity can also be applied with sufficient quality of the molded gears. While there are studies available discussing the effects of processing parameters (Ref. 21) and tool design on the geometric quality of injection-molded gears, there is a lack of systematic studies addressing these effects on the mechanical and thermal responses of polymer gears.

An extremely wide selection of different plastic materials is currently available on the market. A major limitation, however, is a huge gap in gear-specific material data on these materials, which is a problem that has been persisting for decades now. Providing a step towards a solution is the German guideline VDI 2736, which proposes design rating methods (Ref. 9) along with testing procedures (Ref. 22) to be followed to generate reliable data required in the gear rating process. This paper delves into the current state of the art in plastic gear testing, providing a comprehensive overview of testing methods and supplemented with case studies.

Design of Plastic Gears

To ensure reliable operation of the gearbox, each gear needs to be appropriately designed to avoid failure within the required lifespan and operating conditions. Plastic gears can fail due to different failure modes, i.e., fatigue fracture, wear or plastic deformation, which is usually thermally induced. Examples of the possible failure modes are shown in Figure 1. The fatigue failure mode can result in root fracture (Figure 1a), flank fracture, or, in some cases also pitting. Out of the three, the most common fatigue failure mode is root fracture, while flank fracture is often correlated with unfavorable contact characteristics of the gear pair, and pitting was only observed in some oil-lubricated cases. Wear, shown in Figure 1b, is another common failure mode for plastic gears. The degree of wear the gear exhibits depends on a variety of factors, e.g., operating temperature, lubrication, load, material of the mating gear, etc. Notable wear of the flank profile, deviating from the involute shape, leads to an elevated level of transmission error and worse NVH performance. As the wear progresses significantly, it also results in the breaking of teeth, with cracks originating from the worn tooth profile. The acceptable extent of wear varies depending on the specific use case. In applications demanding high precision (such as robotics and sensors), minimal wear is permissible, whereas in applications with lower precision requirements (like household appliances, power tools, and e-bike drives), a relatively substantial degree of wear is acceptable, involving a reduction in tooth thickness within the range of 20–30 percent of the gear module.

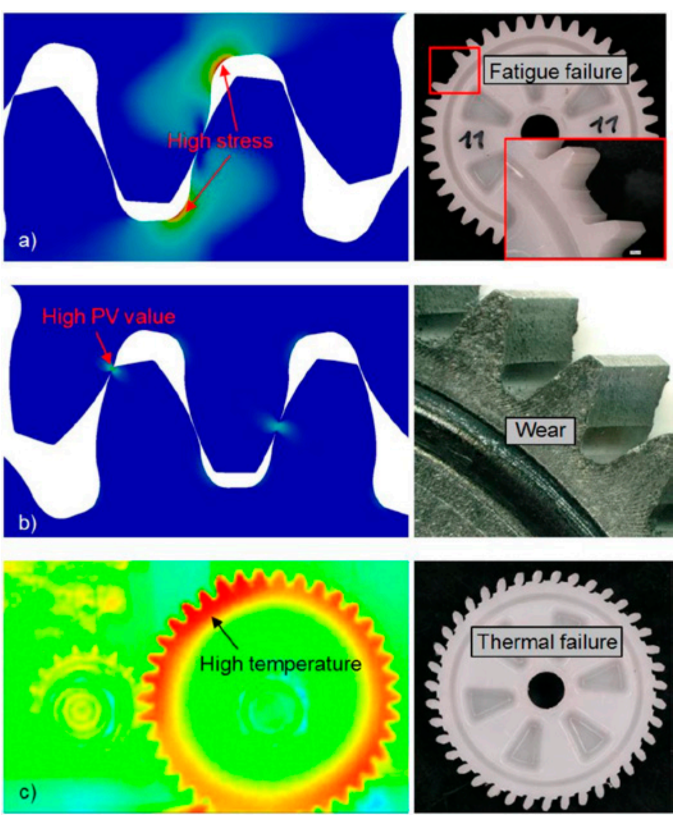


Figure 1—Possible failure modes for plastic gears: a) root fatigue, b) wear, c) plastic deformation due to thermal overload.

There is currently still no international standard available for the mechanical design of plastic gears, which would provide all the required tools and rating procedures to conduct design control against all possible failure modes. The most up-to-date and comprehensive is the German guideline VDI 2736: Part 2 (Ref. 9), where the design rating procedures for each failure mode are proposed. A flowchart representing the entire failure mode control process is shown in Figure 2. While the proposed procedures are feasible, the real problem arises as each control model requires some gear-specific material data, which is very limited. To patch this problem, VDI 2736: Part 4 (Ref. 22) provides testing procedures on how to generate the required material data.

Step 1. Calculate the operating temperature for the gear pair under design

To ensure the reliable operation of a plastic gear, its operating temperature needs to be lower than the permissible temperature for a continuous load. The coefficient of friction for the selected material pair is needed in this step to be able to calculate the heat generated by friction.

Step 2. Root strength control

The actual stress in the tooth's root needs to be lower than the material's fatigue limit at the desired number of load cycles (1 rotation of the gear is 1 load cycle on each tooth). Knowledge of the material's fatigue strength is required to complete this step.

Step 3. Flank strength control against pitting

This step is usually performed only for plastic gear pairs running in oil, as this is the only operating condition where pitting on plastic gears is sometimes observed. For dry-running or grease-lubricated plastic gears, root fatigue or wear are the most frequent failure modes.

Step 4. Wear control

Needs to be conducted for dry running plastic gears. It is recommended to do this control step also for grease-lubricated plastic gears if the plastic material is reinforced with fibers. Pulled out and cracked fiber particles tend to mix with the grease, forming an abrasive medium. The wear factor for the material pair of choice is required to conduct this step.

Step 5. Teeth deflection control

Excessive deflection of teeth should be avoided to prevent teeth jamming and irregular meshing. Elastic modulus is required in this step to be able to calculate the tooth's deflection.

Step 6. Control of the static load

In some applications, the gears are loaded with a high static load, e.g., holding some weight in a defined position. In that case, the gears need to be rated against a static load, and knowledge of the material's tensile strength is required.

It is not necessary to always conduct all the design rating steps. Step 1, Step 2 and Step 4 are advised to be always conducted, while others are case dependent.

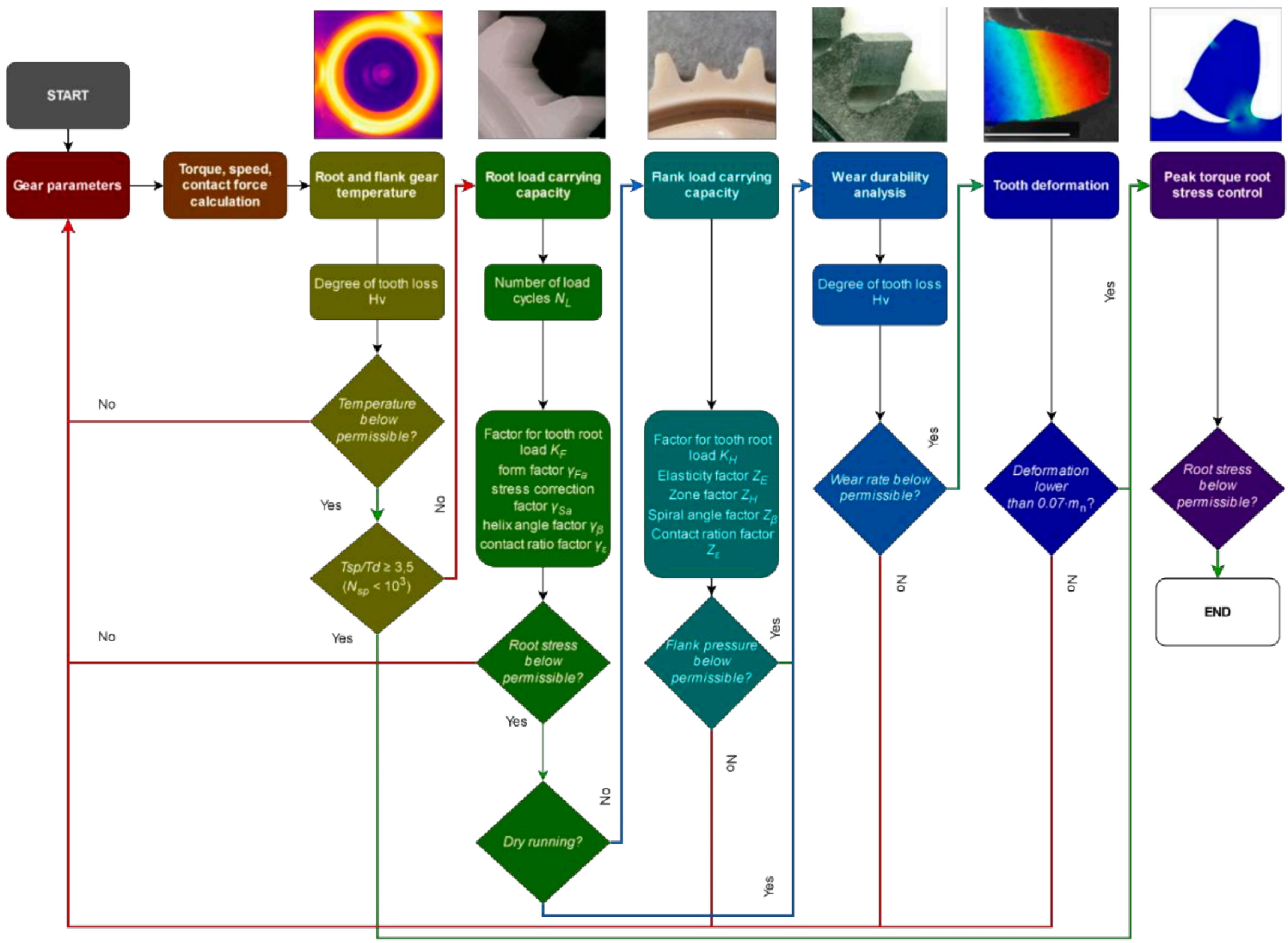


Figure 2—Failure mode control process within the plastic gear's design phase as recommended by the VDI 2736: Part 2 guideline for cylindrical gears.

Gear's Operating Temperature

Gears heat up during operation. An exemplary temperature measurement conducted by a thermographic camera is shown in Figure 3. Friction between the meshing teeth and hysteretic effects are the main reasons for the temperature increase in plastic gears. The rate of heat generation and the resulting temperature rise depend on several factors, e.g., torque, rotational speed, coefficient of friction, lubrication, thermal conductivity, convection, gear geometry, etc. To ensure the reliable operation of a plastic gear, its operating temperature needs to be lower than the material's permissible temperature for a continuous load.

The first rating point for plastic gears is the prediction of the operating temperature to ensure no thermal overload (Figure 1c) occurs under the specified operating conditions. The VDI 2736 guideline employs a slightly supplemented Hachmann-Strickle model (Ref. 23), which was presented in the 1960s. The Hachmann-Strickle model was later supplemented by Erhard and Weiss (Ref. 24). The guideline goes further and proposes a model for calculating the temperature in the tooth's root:

$$\vartheta_{Fu\beta} \approx \vartheta_0 + P \cdot \mu \cdot H_V \cdot \left(\frac{k_{\vartheta,Root}}{b \cdot z \cdot (v \cdot m)^{0,75}} + \frac{R_{\lambda,G}}{A_G} \right) \cdot ED^{0,64} \tag{1}$$

and on the flank:

$$\vartheta_{Fu\beta} \approx \vartheta_0 + P \cdot \mu \cdot H_V \cdot \left(\frac{k_{\vartheta,Flank}}{b \cdot z \cdot (v \cdot m)^{0,75}} + \frac{R_{\lambda,G}}{A_G} \right) \cdot ED^{0,64} \tag{2}$$

Evidently, the equations are almost the same, as there is difference only in one factor, the k_ϑ, where the guideline provides different values for the root region and the flank region. In the proposed equation the most important factor is the coefficient of friction, which is dependent on several parameters, e.g., material combination, temperature, load, lubrication, sliding/rolling ratio, siding speed, etc.

The VDI model is analytic and easy to use, while the accuracy of results is limited. Several scientific studies, e.g., Fernandes (Ref. 25), Casanova (Ref. 26), Černe (Ref. 27), were presented recently which dealt with this topic and each one proposed different, advanced, numerically based temperature calculation procedures.

Root Stress Control

To avoid root fatigue fracture, which is a fatal failure, the root stress σ_F in a gear needs to be lower than the material's fatigue strength limit σ_{Flim} for the required operating lifespan (Figure 4). To account for unexpected effects some additional safety S_F is usually also included.

$$\sigma_F \leq \frac{\sigma_{Flim}}{S_F} \tag{3}$$

To calculate the root stress, the VDI 2736 guideline proposes the same equation as provided by the DIN 3990 (Method C) (Ref. 28), which is a standard for steel gears:

$$\sigma_F = K_A \cdot K_V \cdot K_{F\beta} \cdot K_{F\alpha} \cdot Y_{Fa} \cdot Y_{Sa} \cdot Y_\varepsilon \cdot Y_\beta \cdot \frac{F_t}{b \cdot m} \tag{4}$$

The guideline further simplifies the equation by assuming that for plastic gears, if the condition b/m≤12 is met, the root load factor can be defined as $K_F=K_A{\cdot}K_V{\cdot}K_{F\beta}{\cdot}K_{F\alpha}\approx 1....1.25$.

While Equation 4 is simple to use and familiar to any gear design engineer, the major drawback is that it does not account for the load-induced contact ratio increase, hence overestimating the actual root stress values. A more accurate root stress calculation can be achieved by employing numerical manners, e.g., by FEM simulation. FEM-based methods are, however, labor and cost-intensive.

Assuming the root stress for the gear design under evaluation is calculated, it needs to be compared to a fatigue limit σ_{Flim} which is a material property and needs to be characterized by extensive gear testing on a dedicated test bench. For plastic materials, the σ_{Flim} is temperature dependent; therefore, several S-N curves generated at different gear temperatures are required (Figure 4).

Flank Pressure Control

Flank fatigue failures have been observed mostly in oil-lubricated applications with plastic gears. Assuming the operating temperature does not exceed the limit temperature for continuous operation, in dry running conditions, plastic gears usually fail due to root fatigue or wear. Thus, for dry running conditions, this step is not included, as it is expected that the wear of flanks will be much more severe than the flank fatigue. To avoid flank fatigue failure in lubricated contacts, the flank pressure σ_H needs to be lower than the material's fatigue strength limit σ_{Hlim} for the required operating lifespan. To account for unexpected effects, some additional safety S_H is usually also included.

$$\sigma_H \leq \frac{\sigma_{Hlim}}{S_H} \tag{5}$$

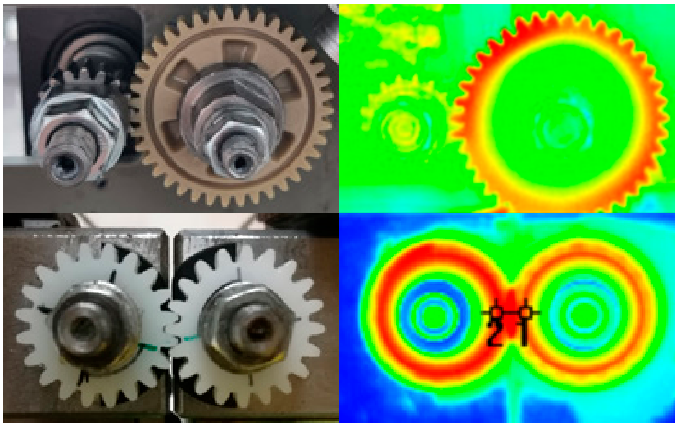


Figure 3—a) Thermal image of a Steel/Plastic gear pair during operation, b) Thermal image of a Plastic/Plastic gear pair.

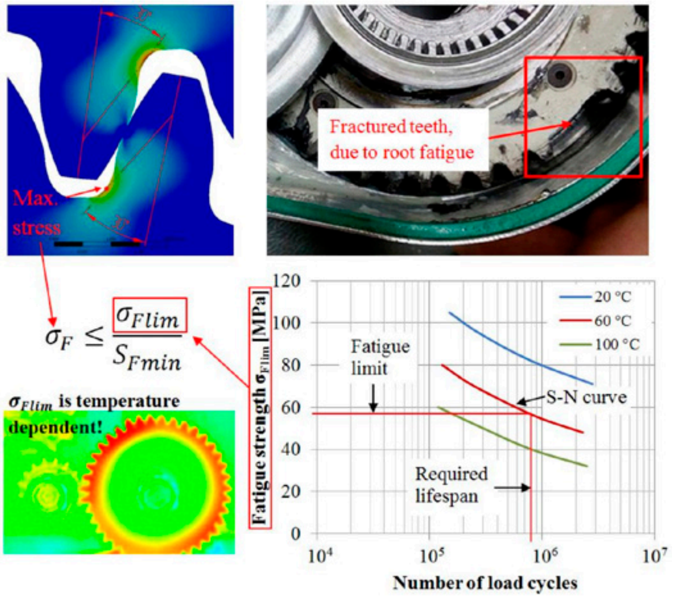


Figure 4—Temperature-dependent S-N curves are needed to conduct root strength control.

To calculate the flank pressure the VDI 2736 guideline again proposes the same equation as provided by the DIN 3990 standard:

$$\sigma_H = Z_H \cdot Z_E \cdot Z_\varepsilon \cdot Z_\beta \cdot \sqrt{\frac{F_t}{b \cdot d_1} \cdot \frac{u+1}{u} \cdot K_A \cdot K_V \cdot K_{H\beta} \cdot K_{H\alpha}} \tag{6}$$

if the condition $b/m \leq 12$ is met, the same simplification as in root stress calculation applies also to the flank load factor $K_H=K_A{\cdot}K_V{\cdot}K_{H\beta}{\cdot}K_{H\alpha}\approx 1....1.25$.

Once the flank pressure for the gear design under evaluation is calculated, it needs to be compared to a fatigue limit σ_{Hlim} which is a material property and needs to be characterized by extensive gear testing on a dedicated test rig. For plastic materials, again, the σ_{Hlim} is temperature dependent; therefore, several S-N curves, with flank fatigue as a failure mode, generated at different gear temperatures, are required.

Wear Control

Wear is a common damage mode for dry runs and some grease-lubricated applications with plastic gears. It can lead to a fatal failure where teeth are worn to the degree that they break instantly under load or that fatigue cracks originate at the worn section (Figure 5a). The wear of plastic gears, in the final stages, leads to fracture (assuming gears are not replaced before). The crack initiation location in such cases often differs from what is expected of a classic root fatigue failure mode (Figure 5b). Due to the reduced tooth thickness, stress concentration and, consequently the crack initiation location can be often found higher in the dedendum area, in the region where the active tooth flank starts. In several applications, the gears might not have failed; however, they do not fulfill the application requirements if they are worn to an acceptable degree, e.g., in high-precision applications. The following equation:

$$W_m = \frac{T_d \cdot 2 \cdot \pi \cdot N_L \cdot H_V \cdot k_w}{b_w \cdot z \cdot l_{Fl}} \leq 0.2 \cdot m_n \tag{7}$$

is proposed by the VDI 2736 guideline for wear control. The only material-dependent parameter is the wear factor k_w which considers the wear properties of the material pair under evaluation. It is important to note that the wear behaviour of plastic gears is dependent on both materials in the pair.

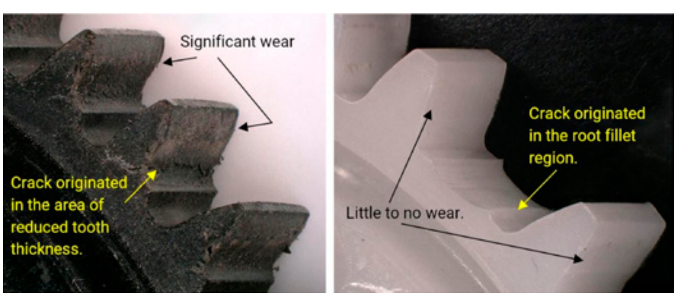


Figure 5—a) Severe wear, leading to fatigue-induced cracks at the worn section of the tooth profile, b) Root fatigue failure mode—crack originates in the filleted root section.

Agile Gear Design Methodology

The design rating procedures presented in the preceding subsections provide valuable tools that enable the evaluation of gear designs against all possible failure modes. Such rating procedures are possible if all the required material data is available, which usually is not. When starting with a new gear drive design utilizing plastic gears, we often face several questions:

1. Which materials should be used?
2. Dry run or lubrication (which lubricant to use)?
3. Are we getting the best performance out of the current plastic gear design?
4. Will the gears survive the req. lifespan without a decrease in performance or failure?
5. Will the drive's characteristics and efficiency be as requested?
6. Will the drive's NVH behavior be satisfactory?

Those questions can be successfully addressed by employing the below presented agile gear design methodology. An agile model for the design of gearboxes with plastic gears, as shown in Figure 6, was formulated based on more than a decade of practical experience. The proposed design methodology has several test stages, resulting in a reduced number of tests and providing reliable material data for the rating procedures of gears for various applications.

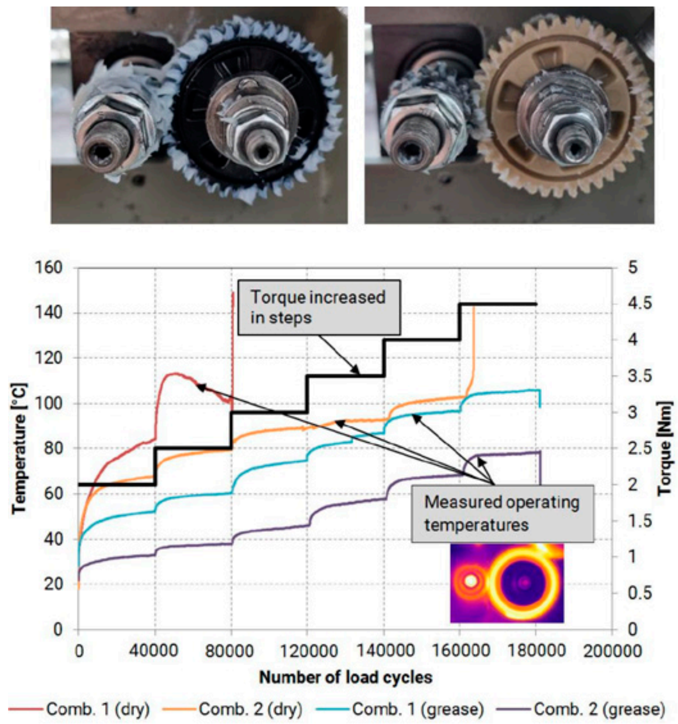


Figure 6—Agile development process for gearboxes with plastic gears.

The procedure consists of several steps:

1. Preliminary gear design based on the input data (material selection, simple design calculations for the gears). If the selected polymer material pair already has known material properties, the procedure can be continued with Stage 3.
2. For initial material screening, accelerated (step) tests can be employed (Figure 7). These enable the evaluation of a large set of different materials (or material pairs) in a rather quick and cost-efficient way. Such tests need to be conducted in precisely controlled operating conditions. Usually, the torque is increased in steps until the final gear failure, and the rotational speed is kept constant. When dealing with plastics, the operating temperature is a highly important parameter. In step tests, there are two possibilities, depending on what the research focus is.
   a. If the focus is to compare the material's load-bearing capacity under fatigue load, it is better if the plastic gear's temperature is controlled.
   b. If the focus is to study tribological behavior, it is more convenient to let the gear pair evolve its operating temperature. This way, material combinations that exhibit a lower friction can be identified. By employing the same approach, different lubricants can also be evaluated and the best one for your gear application can be selected.

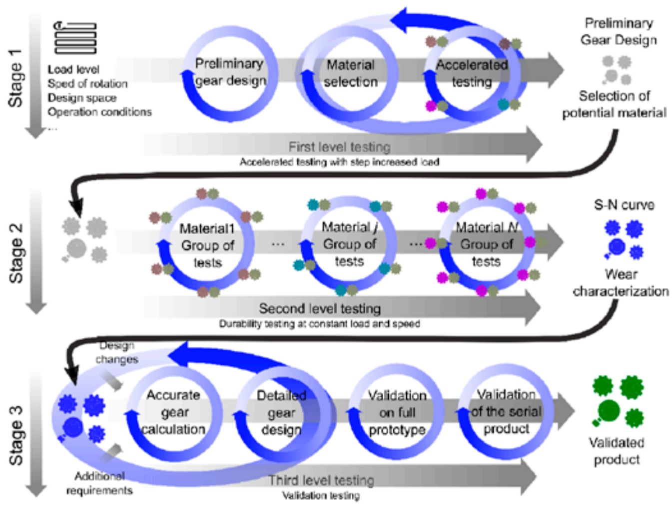


Figure 7—The accelerated gear testing methodology.

3. When the best performing materials are identified, they are further tested to generate S-N curves and characterize wear factors. Once available, this data will enable a reliable and optimized gear design with the best possible material utilization.
4. Detailed calculation and design of polymer gears: Well-defined material properties (Stage 2) enable the reliable calculation of gears. This reduces the number of prototypes required.
5. Testing of gears in the final application—product validation, as shown in Figure 8. The production of tools for injection molding is expensive and time-consuming. It is important to do all the previous steps well and produce the tools only once.

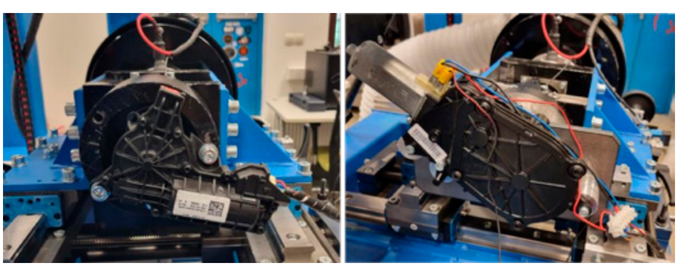


Figure 8—Validation on the final application.

Testing Methodologies—Generation of Crucial Material Data

A complete overview of the current state-of-the-art testing methods is provided in the following sections. Where applicable, problems are highlighted and solutions proposed. All the presented results were generated on the [Anonymized] test bench by testing the VDI 2736 size 1 geometry gear pairs (see Table 1).

Test Sample

To complete each control step for a possible failure mode, as presented in Figure 2, gear-specific material data is required. This data is obtained by dedicated gear testing methods. Currently, there are no standardized test procedures available that could be employed to generate this data. The most up-to-date is VDI 2736: Part 4 (Ref. 22), which provides comprehensive recommendations for the testing methodology. As per the guideline, three gear geometries are proposed for experimental characterization. The proposed gear parameters are presented in Table 1. Being closest to most practical applications with plastic gears, the Size 1 geometry is most used for testing. The lack of standardization results in several other gear geometries being dealt with in scientific and technical reports. It is, however, extremely important for the development of future plastic gear rating standards that the test sample geometries are unified similarly as in most comparable standards dedicated to the characterization of a material's mechanical properties.

The gear's manufacturing quality affects the stress state in the gear when under load (Ref. 29). Controlling the test samples' production quality is equally important for a reliable comparison of test data. The gear manufacturing quality is usually evaluated according to ISO 1328 (Refs. 30,31). For material characterization purposes, gears with most rating parameters in quality 10 (or better) are recommended for testing. Besides the gear's geometrical quality, even more important is that the gears are produced without any significant weld lines and voids. If during gear testing, failure occurs on the weld line or at a void location, the test result is not a function of a material property but rather of the defect in the gear because of a bad-quality sample production. Since the gear tests are used to generate gear-specific data on the material properties, failure should be a single function of the material's performance.

Parameter	Nomenclature	Unit	Size 1	Size 2	Size 3
Type of gear	/	/	spur gear	spur gear	spur gear
Centre distance	a	mm	28	60	91.5
Normal module	m_n	mm	1	2	4.5
Number of teeth	z_1/z_2	/	17/39	30/30	16/24
Gear's face width	b_1/b_2	mm	8/6	13/12	22/20
Pressure angle	α_n	°	20	20	20
Tip diameter	d_{a1max}/d_{a1min}	mm	19.40/19.35	64.916/64.779	82.45/82.36
	d_{a2max}/d_{a2min}	mm	40.40/40.30	63.098/62.902	118.35/118.26
Root diameter	d_{f1max}/d_{f1min}	mm	14.902/14.610	55.916/55.779	61.917/61.215
	d_{f2max}/d_{f2min}	mm	35.866/35.691	54.498/54.301	97.824/97.122

Table 1—Test gear geometries, as proposed by the VDI 2736: Part 4 (Ref. 22).

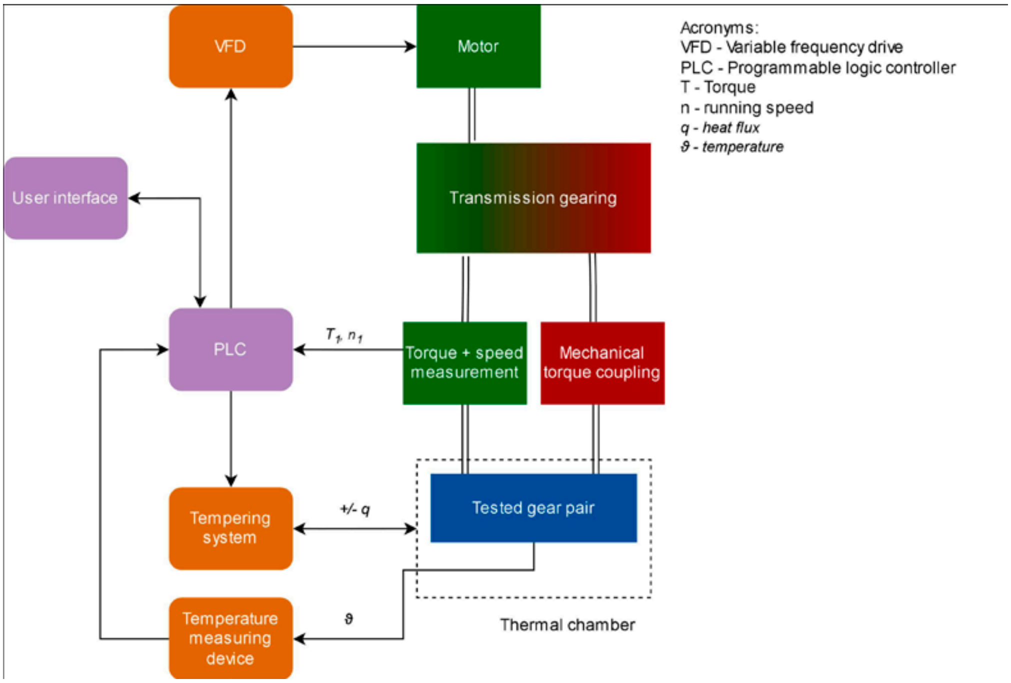


Figure 9—Schematic representation of a closed-loop, back-to-back gear test rig.

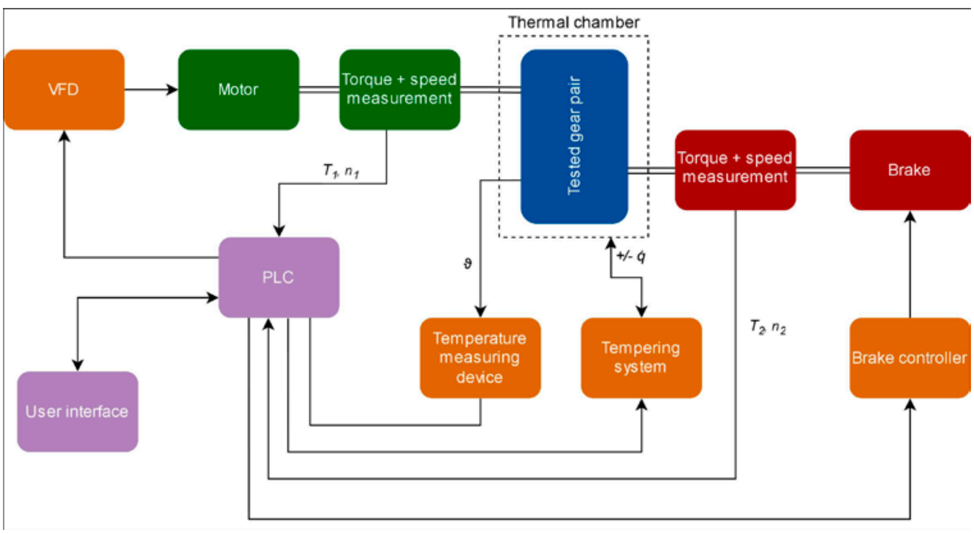


Figure 10—Schematic representation of an open-loop test rig.

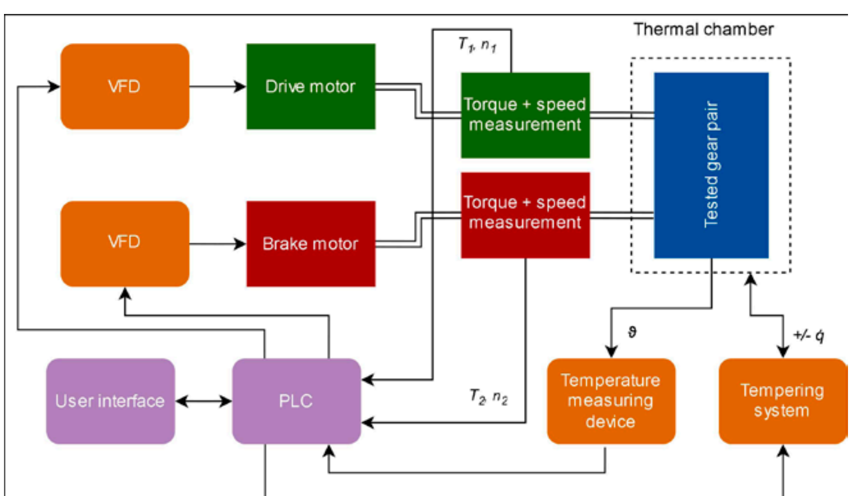


Figure 11—Schematic representation of an open-loop test rig with parallel driving/ braking motor configuration.

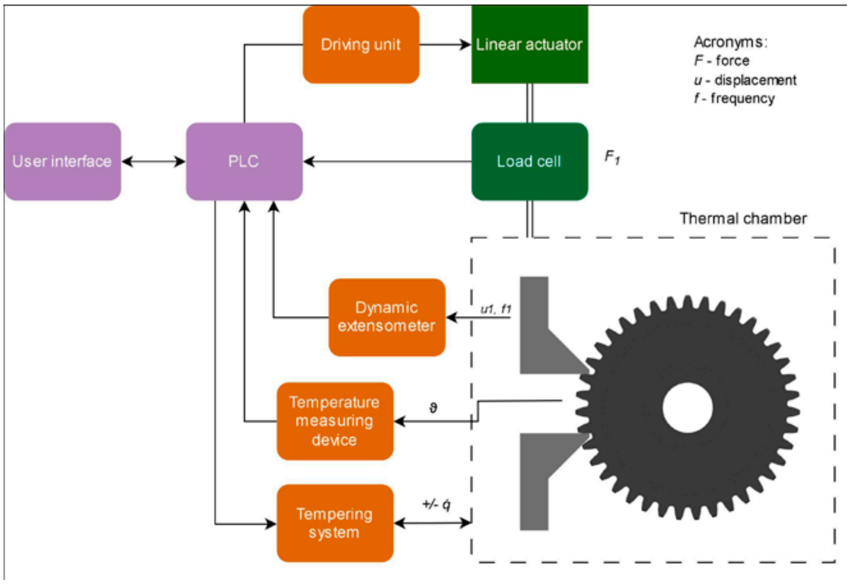


Figure 12—Schematic representation of a pulsator test rig.

Test Rigs

There are three main test rig layouts used for gear testing. The back-to-back test rig, presented in Figure 9, is a very well-known concept that has been widely used for the testing of steel gears. For the testing of plastic gears, the basic concept of this test rig has some limitations. In a back-to-back test rig, the torque on the tested gear pair is applied by a rotational displacement of a loading clutch. Plastic gears deflect under load significantly more than steel ones. Due to the teeth deflection, some of the torque applied with a rotational displacement of the loading clutch is lost. Additional torque loss occurs during the test duration due to the viscous properties of plastic materials and additional deflection of teeth due to creep. As plastic gears wear quite significantly during operation, another portion of torque loss occurs due to tooth wear. This problem can be solved by applying a continuously adjustable electromechanical or hydraulic torque application system, which significantly complicates the test rig's design and control, adding to the overall cost of the test rig. Another disadvantage when it comes to gear testing is that the center distance is fixed and determined by the master gear pair.

Another possible test bench layout is a mechanically open loop system (Figure 10), where on one side, the motion and power are applied by a motor and on the braking shaft, the braking torque is usually applied by employing a brake or a generator. Such a test rig concept allows for a continuously adjustable center distance, enabling the testing of several different gear geometries. By controlling the torque and speed on both sides, the load applied on the tested gear pair can be controlled very accurately.

Additionally, the open-loop type test rig can be formed of a pair of electric motors where one provides the input driving torque to the pinion while the other acts as a brake on the driven side. The drive and brake shafts can be positioned in parallel, one next to the other in which case the motors must be connected to both shafts via belts or chain transmissions. A schematic representation of this configuration is shown in Figure 11.

The fourth possible layout is the pulsator test rig, also called a single-tooth bending test machine (Figure 12). In this type of test rig, a single tooth is subjected to pulsating cyclic loading in the tangential direction relative to the gear tooth. The limitation of the test rig is that it can only be employed to study root fatigue, while other possible failure modes, e.g., wear, pitting or thermal overload, cannot be observed. Another limitation is that the load on the tooth is not applied in the same direction as when gears are meshing, requiring a suitable analytical model to correlate the results with gear-meshing conditions.

Irrespective of the test rig design, the most important testing conditions, i.e., the transferred torque, the plastic gear's temperature and the rotational speed, need to be precisely controlled during the entire test. While torque and speed control can be quite easily achieved, controlling the plastic gear's temperature is a bit more challenging. Tests conducted for S-N curve generation are usually performed at a selected rotational speed and various torque levels. The rate of heat generation and the resulting temperature rise depend strongly on the transmitted torque. A sophisticated gear-temperature control system is therefore required to control the plastic gear's temperature at a selected level, irrespective of the tested torque and rotational speed.

The increase in gear temperature significantly impacts the durability and fatigue resistance of polymer gear pairs. S-N curves, which chart stress against the number of cycles to failure, must be assessed as a function of temperature. Typically, these curves are characterized as a function of bulk root temperature. However, as seen in Figure 13, the choice of a measurement point greatly affects the results. The images depict a gear test conducted under controlled conditions (with a temperature set at 90°C), selecting three different points for measurement. These varying points can yield substantially different outcomes.

VDI 2736 offers general instructions for measuring root temperatures, yet a more precise specification is advisable. It is recommended to place the measurement sensor at the midpoint of the gear's face width and on the passive flank side. This location typically provides an average temperature that accurately reflects the root temperature, given that the passive tooth flank does not heat up substantially compared to the root temperature, and it will therefore influence the measurement only marginally. Conversely, placing the sensor on the side surface beneath the root tends to produce significantly lower temperature readings compared to those at the center of the face width.

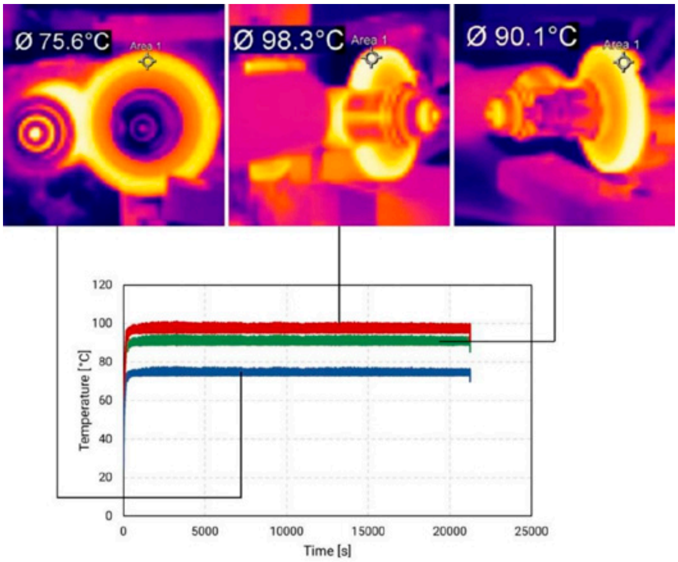


Figure 13—Tested loads and the controlled operating temperature of the plastic gear.

S-N Curve Testing

To avoid root fatigue failure, the root stress in a gear needs to be lower than the material's fatigue strength limit for the required operating lifespan. To account for unexpected effects some additional safety is usually also included. The information on the material's fatigue strength can be summarized in an S-N curve. To generate an S-N curve, several test repetitions need to be conducted at various loads, and all the samples need to be tested until a fatigue-induced failure occurs, as shown in Figure 14. For gears, the S N curves can be generated by extensive testing in a gear-on-gear application or by a single tooth bending test on a pulsator test stand. Both methods have their pros and cons.

In a gear-on-gear test methodology usually a combination of a steel pinion and a plastic gear is employed as presented in Figure 14. The steel/plastic combination is most appropriate for the S-N curve testing since the curve is a property of a single material. Therefore, failure should occur on the gear of which the material is being evaluated. In the case of a plastic/plastic combination, failure would be close to impossible to control, and a situation could occur where it would not be possible to induce a failure on a gear made of material under evaluation. Another problem with a plastic/plastic gear combination would be a significantly increased tooth contact, and the actual stress in the material would further deviate from the calculated one. The one calculated by the analytical equation (VDI 2736 or DIN 3990 or ISO 6336), FEA provides an accurate stress calculation if the numerical model is set up accordingly.

While operating, the gears heat up. Friction between the meshing teeth and hysteretic effects are the main reasons for the temperature increase in plastic gears. The rate of heat generation and the resulting temperature rise depend on several factors, e.g., torque, rotational speed, coefficient of friction, lubrication, thermal conductivity, convection, gear geometry, etc. The mechanical properties (strength, hardness, elastic modulus) of polymers and polymer composites are strongly temperature dependent. Therefore, several S-N curves, generated for different temperatures of the tested sample, are required for the design of plastic gears. Precise temperature control of tested gear samples is therefore crucial for the characterization of S-N curves for plastic gears. Advanced stopping algorithms need to be applied as well since the test needs to be stopped instantly once the first tooth is fractured (Figure 14).

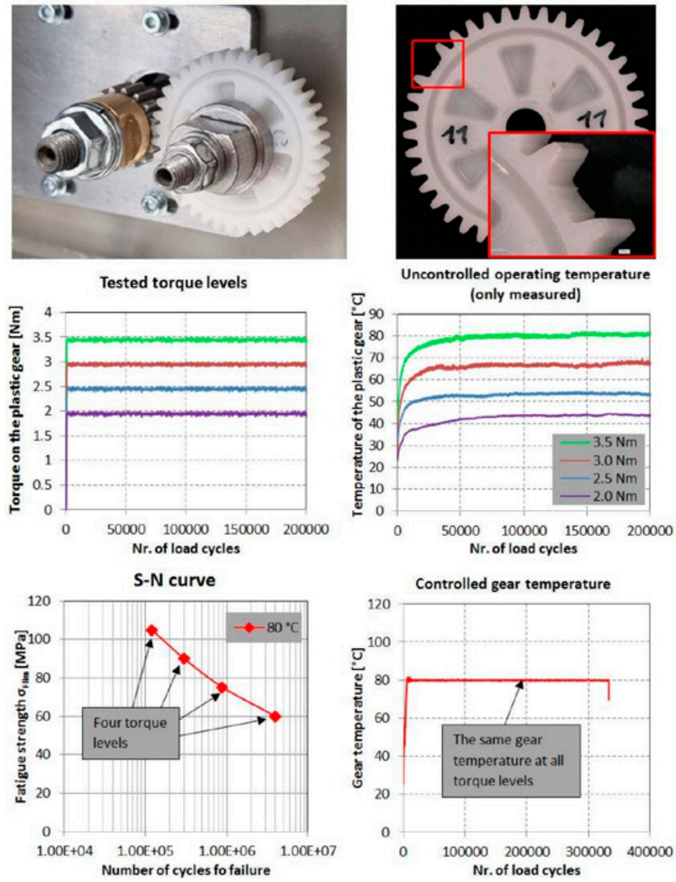


Figure 14—S-N curve generation.

A combination of a steel pinion and a plastic gear is usually employed for the S-N curve generation. As the purpose of testing is to generate fatigue data on the selected plastic material, the failure needs to occur on the plastic gear. The test needs to be stopped when the first tooth is fractured. In a plastic/plastic configuration, the failure would be impossible to control, and usually, both gears get damaged at the end of the test. Furthermore, the load-induced contact ratio increase would be even higher for a plastic/plastic gear configuration. Tested gears need to be tested at a minimum of four different load levels, where the torque is accurately controlled during testing. The operating temperature of the plastic gear needs to be controlled at a selected level at all tested torques. At least three test repetitions need to be conducted at each tested torque level to ensure repeatability. All tests need to be conducted until there is a fatigue-induced failure.

Wear Characterization

The wear behavior of plastic gears can be best studied by conducting gear tests. Simple tribological tests, e.g., disk-on-disk, can provide basic information about materials' behavior in a rolling-sliding motion under nonconformal contact, but for an in-depth understanding of the wear behavior in the gear contact, gear testing needs to be conducted.

The contact conditions between the two meshing flanks are shown in Figure 15; rolling and sliding motions are present between the surfaces in contact. The direction of sliding and the frictional force are reversed when passing through the pitch point C. On the driven gear, the direction of sliding points always towards the pitch point C, so the kinematic line is usually clearly visible on the worn gear surface. The main difference, when compared to the disk-on-disk test, is that with the disk-on-disk test, the sliding rate is constant all the time, and the direction of the frictional force remains the same. The pin-on-disk test is even less suitable since there is only sliding motion present in contact without any rolling.

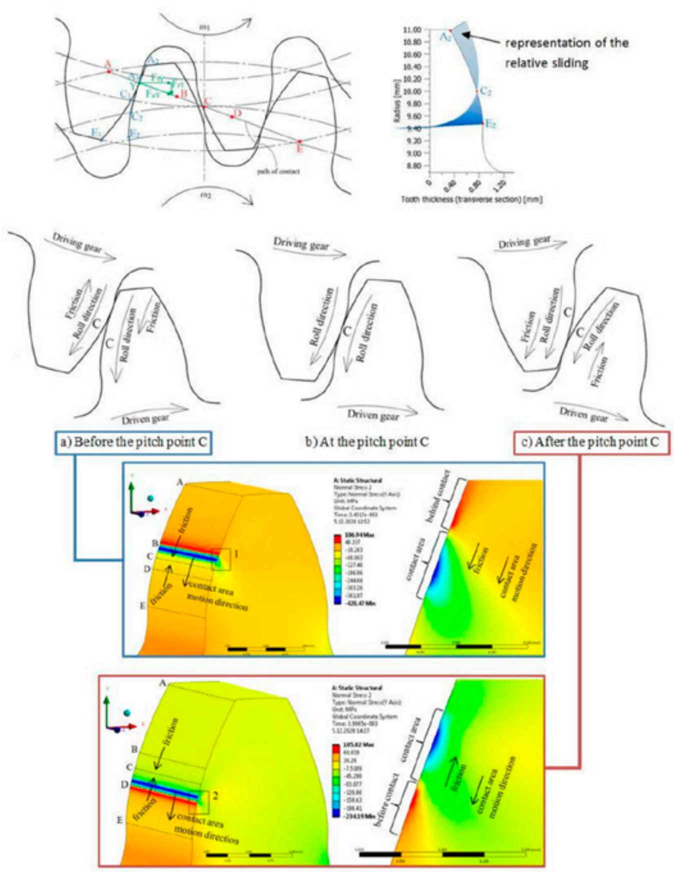


Figure 15—Contact conditions during gear meshing. The direction of friction changes once the contact passes the pitch point. The frictional force is on the driven gear and always oriented towards the pitch point and vice-versa on the drive gear.

The gear-meshing process is presented in Figure 15. The theoretical path of contact of the involute gears pair has the shape of a straight line. During operation, gears transfer torque, which results in a normal force F_{nY} acting in an arbitrary meshing point Y between the two teeth in contact (Figure 15). The normal force F_{nY} can be decomposed to radial F_{rY} and tangential force F_{tY}. In involute gear pairs, the normal force acts along the path of contact. The gears start to mesh in point A, this is point A_1 on the flank of the drive gear and point A_2 on the flank of the driven gear. In the meshing area A-B, two pairs of teeth are in contact; therefore, the transmitted load is divided between them. Point B is the highest point of single tooth contact for the driven gear. In the B-D area, the total load is transmitted only through one pair of teeth. Point D is the lowest point of single tooth contact for the driven gear. At this point, the next pair of teeth comes into contact and the load is in the area D-E again transmitted via two pairs of teeth. Hence, the load on a single tooth is not constant during meshing along the path of contact. Meshing ends in point E, this is point E_1 on the flank of the drive gear and point E_2 on the flank of the driven gear. When gears are meshing from A to C, the flank part A_1C_1 on the drive gear is meshing with the flank part A_2C_2 on the driven gear. Due to the different lengths of the flank parts in contact, specific sliding occurs between the surfaces in contact (Figure 15). Analogously, the same happens in the meshing part from C to E, except that when passing through the kinematic point C, the direction of sliding is reversed. Most sliding occurs in the root part of the tooth, where the greatest wear is to be expected. In theory, there is no sliding at pitch point C, only pure rolling due to tooth deflection; sliding also occurs at point C. Such specific contact conditions can be best represented by a gear-on-gear test.

Different wear characterization methods can be used, as presented in Figure 16. The most used ones are the gravimetric method and the tooth thickness reduction method. When employing the gravimetric method wear is characterized as the loss of mass, while in the tooth thickness reduction method, the wear is determined as the reduced tooth's chordal thickness. Several advanced methods can also be used, e.g., image processing or optical measurements; however, these are more costly and labor intensive. The wear can be tracked during testing by conducting regular checkpoints or the wear is measured after a specified number of load cycles. Different stages of wear a presented in Figure 17.

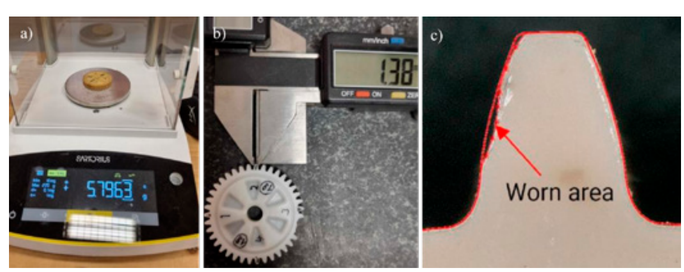


Figure 16—Wear measuring techniques: a) gravimetric method, b) tooth thickness reduction method, c) image processing method.

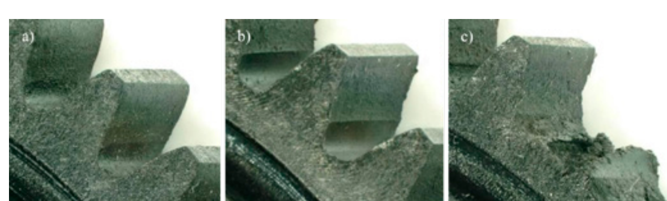


Figure 17—Wear in different stages: a) Initial wear, b) Significant wear, in practice usually still acceptable, c) Critical wear which led to failure.

COF Characterization

There are currently no methods that enable measuring the coefficient of friction (COF) directly during gear operation. However, some methods enable measurement of COF in conditions much closer to a gear contact. The coefficient of friction can be assessed well using the disk-on-disk test configuration, as shown in Figure 18. In such a test configuration, two disks made of selected materials are pressed together with a controlled force and rotate, each with a respective rotational speed, to generate a rolling and relatively sliding contact between them. All possible material combinations can be tested in such a test configuration; however, when testing plastics, the plastic sample's temperature must be rigorously controlled as the coefficient of friction is also temperature-dependent. Another possibility to get a very good assessment on the COF is by employing an implicit characterization method as proposed by Černe et al. (Ref. 32).

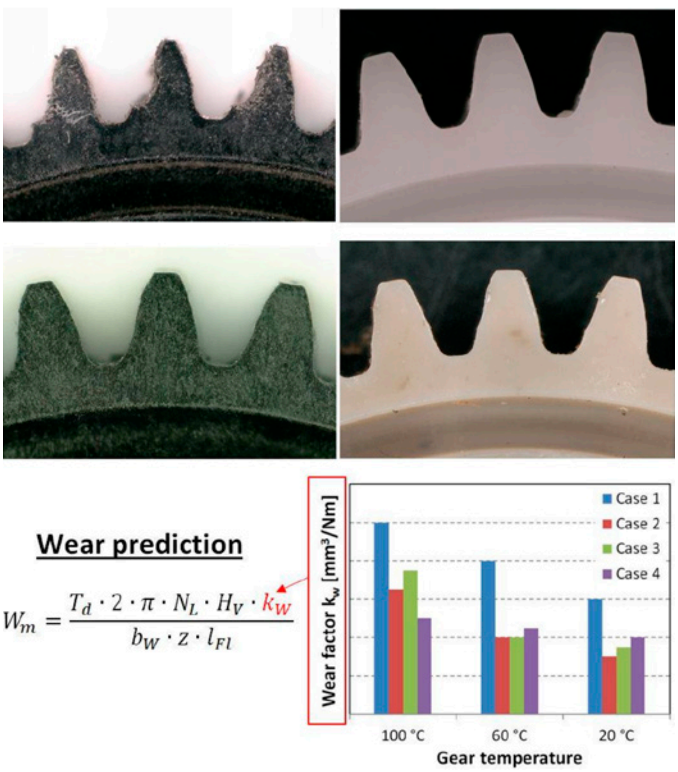


Figure 18—Disk-on-disk test configuration.

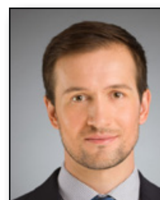
Conclusions

Plastic gears offer several advantages over metal gears. With an increase of e-mobility and the growing demands on the user experience where the NVH needs to be held at a minimum, plastic gears show great potential. They also provide great benefits in terms of cost optimization and energy savings.

For the reliable design of plastic gears, several different failure modes need to be considered. The VDI 2736 guideline provides methods and models to control individual failure modes in the gear design phase. A major problem preventing the use of these methods is the lack of gear-specific material data, which is required to conduct the required design and control calculations.

Outlook

The lack of reliable gear-specific material data is still a major problem for the design of plastic gears. The data currently available in the guidelines and commercial software packages was in large part generated in a non-consistent way without a traceable and repetitive process. For the generation of reliable material data, a standard is required which would define the test geometries, sample-production process, sample quality requirements, testing methods and post-processing of the test data. With the emergence of an international standard and high-quality material data generated according to the procedures defined by the standard, the actual growth potential of plastic gears would be reached.



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Dr. Borut Černe is a cofounder and Co-CEO at RD Motion. With more than 11 years of experience in the fields of solid mechanics, polymer testing, programming, engineering design, and power transmissions, he holds a pivotal role in R&D operations and test rig development at the company.

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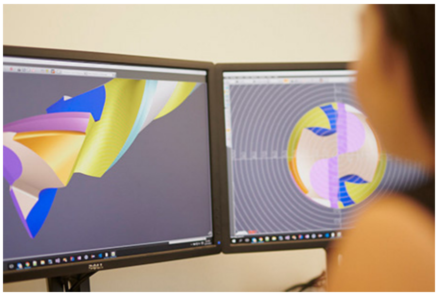
ANCA

LAUNCHES E-LEARNING PLATFORM



ANCA CNC Machines launches ANCA Academy, a new e-Learning platform for their customers, designed to elevate skills in operating ANCA CNC machines and application software. Offering a mix of free and paid courses, ANCA Academy provides a professional platform to meet the needs of the evolving precision tool manufacturing industry through expert-led technical education.

Simon Richardson, global technical sales support manager, said: "At ANCA, we know how much our customers love to learn—our weekly Tool Tips prove it! With our machines and software being so powerful and versatile, continuous learning is key to unlocking their full potential. It is very true that you don't know what you don't know, but our structured e-learning modules mean that highly trained and proficient users can push boundaries, boost productivity, and take their capabilities even further. We are helping our customers learn more to grind smarter!"

ANCA Academy provides comprehensive training programmes that not only enhance individual competencies but also deliver measurable benefits for businesses. According to an IBM study, employees trained via eLearning can increase productivity by 25 percent. By equipping teams with advanced skills, companies can expect improved machine efficiency, reduced downtime, enhanced production quality, and minimised operational errors.

The ANCA Academy e-Learning Platform features courses tailored to a wide range of roles and skill levels. From foundational modules for beginners to advanced technical training for seasoned professionals, the courses cover essential topics in CNC machine operation, programming, and application software. This ensures that every participant, regardless of their experience levels, gains valuable, actionable knowledge.

machines.anca.com

Forest City Gear

CELEBRATES THREE ANNIVERSARIES

Forest City Gear has recognized several employees for their long-term dedication to the company, including Roger McMullin (10 years), Paul Cristoph (5 years), and Mark Javurek (5 years).

Roger McMullin is Forest City Gear's most experienced lathe setup tech, with his focus primarily on the Hardinge and DMG Mori Twin Spindle machines. He started in Forest City Gear's High-Volume department, running hard part turning. He was quickly recognized by his peers as their "go-to guy." In 2019, he was one of the originals in the revival of the CNC Machining Department within the Roscoe Works building and has been a pillar in the growth of the department throughout the years. There, he was able to quickly learn how to machine complex parts to tolerances only held previously on cylindrical grinder.

Roger McMullin

Paul Cristoph is a hardworking member of the team who has held multiple roles in his five years at Forest City Gear; he has worked in the lap/hone area, the OD/ID grinding area, and recently found his home working as an operator in the Roscoe Works facility running turning and milling machines. Cristoph is a valued asset to Forest City Gear in the respect that he is willing to work in any department at any time without hesitation. "As a matter of fact, he has worked in every department as needed," says Kent Blatchford, Cristoph's supervisor. "He is reliable and can be counted on to get the job done. It is an absolute joy to work with him."

Paul Cristoph

Mark Javurek is a manufacturing engineer, focusing on the facilitation of manufacturing operations for efficient product realization and customer satisfaction. He is responsible for troubleshooting problems that arise during machining operation setup, nonconformance avoidance, root cause analysis, and the continuous improvement of manufacturing processes. Since joining Forest City Gear in 2020, he has served as primary liaison between engineering and production, cultivating operational efficiency and integrity. Mark has earned consistent applause from customers, coworkers, and suppliers alike for his amiable nature, clear communication, and results-driven attitude.

Mark Javurek

Forest City Gear thanks McMullin, Cristoph, and Javurek's above-and-beyond commitment and their years of dedication to Excellence without Exception.

forestcitygear.com

JUNE 2–5

Reliable Plant 2025

This three-day event (Schaumburg, IL) offers attendees learning sessions and case studies on the latest industrial lubrication and oil analysis technologies. The comprehensive conference schedule covers every facet of the machinery lubrication industry and includes workshops on topics such as employee performance, lubrication fundamentals, condition-based maintenance and planning. Reliable Plant attendees come to the conference to connect with suppliers and service providers who can help them achieve bottom-line results in maintenance, reliability, and operations. From technicians and planners to management and leadership, you will be able to meet and influence entire buying teams at Reliable Plant. The event is co-located with Machinery Lubrication.

geartechnology.com/events/reliable-plant-2025

JUNE 2–5

Realize Live Americas

Realize Live Americas (Detroit) is the digital transformation conference designed for professionals in engineering, manufacturing, product lifecycle management, design and IT/software administration. Connecting users, industry experts and partners to share insights and explore the latest trends, technologies and best practices. Highlights include the Solutions Center, Trials Lab, Student Design Hack, Community Corner and more. See firsthand how customers are bringing their ideas to life with Siemens solutions. Whether designing products, simulating complex systems, optimizing manufacturing processes, or collaborating on innovative solutions, attendees will leave inspired to apply new strategies and techniques to their creations.

geartechnology.com/events/realize-live-americas

JUNE 15–18

PowderMet2025

PowderMet2025 (Phoenix) is dedicated to metal powder and particulate materials-based processes including press and sinter, metal additive manufacturing, metal injection molding and more. The show provides an energetic forum to showcase PM, metal AM, and MIM equipment, powders, products, and services. MPM2025, colocated with PowderMet 2025, is a technical conference and exhibition dedicated to metal additive manufacturing. Attendees can dive deep into the latest advancements in the field through insightful technical presentations and explore exhibits showcasing additive manufacturing technologies. Sessions include topics on material development, standards, metal density, and more.

geartechnology.com/events/powdermet-2025

JUNE 24–27

Automatica 2025

Automatica 2025 (Munich) examines how robotics and smart automation is changing the future. Focus topics include digitalization and AI, sustainable production, and workforce development. Apart from concrete practical applications and product innovations, attendees can exchange ideas with key players and industry experts. Showcases include mobile robots, service robots, smart maintenance, AI technology, connected machines, testing, startups and more.

geartechnology.com/events/automatica-2025

JULY 9–10

Dritev 2025

The automotive congress Dritev (DRIvetrain Transmission Electrification Vehicles) offers the powertrain community an optimal platform for exchange. Every year, decision-makers, experts, and industry leaders from around the world meet in Baden-Baden, Germany. Here, vehicle manufacturers and suppliers exchange ideas and capture innovations, developments and challenges in drive technology. During the two-day congress, experts from OEMs, suppliers and universities present practical lectures on new trends as well as classical topics in drive technology. Join the community to discuss the latest developments, innovations and perspectives of various concepts in the field of powertrain and transmissions.

geartechnology.com/events/dritev-2025

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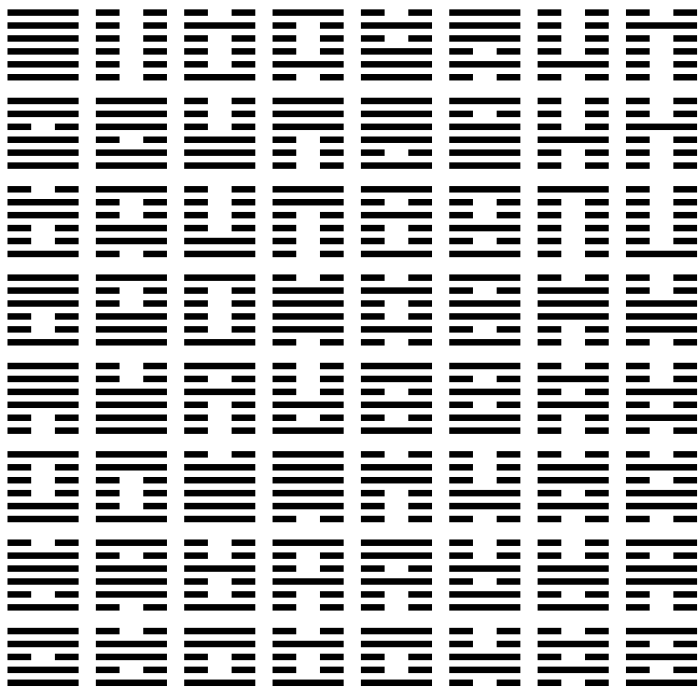
ADDENDUM

Sacred Gear Ratio

Aaron Fagan, Senior Editor

From a purely mathematical standpoint, 64 is a power of two (2^6), making it ideally suited for systems that rely on binary logic, such as digital timekeeping, signal processing, and modern CNC controllers. But its elegance doesn't stop there. Sixty-four divides cleanly into halves, quarters, eighths, and sixteenths, allowing for easy subdivision of time. This makes it especially practical in mechanical timekeeping systems, where 64-tooth gears often serve as indexing wheels, escapement components, or intermediate wheels in horological gear trains, providing precise and consistent intervals critical to accurate clocks, chronographs, and timing devices.

The world of gears is a realm of precision, cycles, and mathematical harmony. Gear mesh ensures smooth motion and accurate speed or torque ratios that power everything from micromechanical devices to industrial-scale automation. However, the notion of a "sacred gear ratio" reaches beyond the mechanical, weaving through the very fabric of life itself. Interestingly, this ratio—or more precisely, this structure—can be found in the DNA code and the I Ching, two systems—one governing biological processes, the other offering a philosophical framework for timekeeping aligned with the deep cycles of change that underlie the universe.



The King Wen sequence is an arrangement of the 64 hexagrams because each figure is composed of six broken or unbroken lines, which represent yin or yang, respectively.

While not ratios in the strict mathematical sense, the 64 codons in DNA and the 64 hexagrams of the I Ching represent complete systems of transformation—symbolic counterparts to the role gear ratios play in mechanical systems: structured, cyclical, and exact. These "ratios" reflect the presence of an underlying mathematical order that governs complexity across disciplines.

The number 64 in the I Ching embodies cyclical change—the continuous flow of energy between opposites. Just as gears convert input to output through fixed yet adaptable motion, the hexagrams model the transitions between states of being, behavior, or time. These changes follow predictable permutations, not unlike the behavior of a compound gear train operating within defined tolerances and timing arcs. The I Ching interprets the timing of transformations in the world, offering guidance on the rhythms of existence. The 64 hexagrams can be seen as symbolic "gears" in the vast machinery of the cosmos—each one driving the next, creating a system of interconnected cycles. The ancient system, translated as The Book of Changes, is a classical Chinese text used for millennia to understand the cycles of nature, consciousness, and social dynamics. Each hexagram is composed of six lines, either broken or unbroken. These line states resemble 1s and 0s, forming a structure closely related to modern digital logic and to the yin-yang principle in Taoist thought. The resulting patterns reflect binary permutations: $2^6 = 64$.At the most fundamental level, life is encoded in the language of DNA, where sequences of nucleotides form the building blocks of genetic information. These sequences consist of codons—triplets of nucleotides corresponding to specific amino acids. There are exactly 64 possible codons in the genetic code, arising from the four DNA bases (adenine, thymine, cytosine, and guanine). This precise number emerges from combinatorics: $4^3 = 64$.

Much like a mechanical gear set, codon translation into amino acids is precise, regulated, and error-checked. The 64 codons coordinate the production of proteins, enabling the functions of cells, tissues, and entire organisms. This complex process of transcription and translation reflects the same ideals of reliability and repeatability that gear engineers strive for. The unity of the codon system mirror the optimized meshing found in finely machined gears.

The presence of 64 in both DNA and the I Ching suggests a kind of universal design, one that bridges the boundaries between biology, philosophy, and engineering. In the same way that gears power machines with exactitude and purpose, the 64 codons regulate life's internal machinery, while the 64 hexagrams offer insight into life's external rhythms. As engineers and thinkers, we can look to these patterns for inspiration, recognizing that the principles of balance, structure, and cyclic motion transcend machines and echo across biology, cosmology, and human thought.