gear TECHNOLOGY®

JANUARY/FEBRUARY 2026

State of the Gear Industry
Gear Manufacturing
Gear Selection
and more

TECHNICAL

Interchangeability of Gears

Influence of Tooth Root Contour Deviations on the Tooth Bending Strength

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JANUARY/ FEBRUARY 2026

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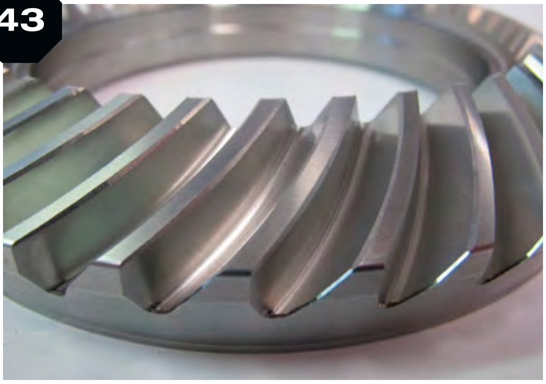

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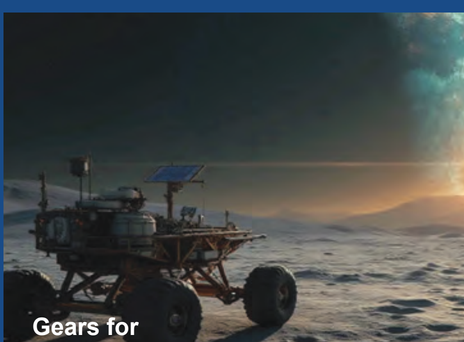

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GT REVOLUTIONS

Control-Expert Days 2026 Offers New Insights into Global QA Market

Industrial quality assurance is undergoing a continuous, dynamic transformation process. Digitalization, automation, and constantly changing standards are constantly defining new requirements and processes. As a two-day specialist event featuring an innovative exhibition and expert presentations, Control-Expert Days 2026 is the ideal complement to the world's leading trade fair, Control 2027.

geartechnology.com/control-expert-days-2026-offers-new-insights-into-global-qa-market

ZF Wind Power and Sirris Launch Mobile Climate Chamber

ZF Wind Power is using a new mobile climate chamber developed in Belgium. This innovation, created by Sirris—the Belgian innovation center for the technological industry—together with the Belgian government (FPS Economy) and local industry partners, represents a world first. The consortium invested €1.5 million in the construction of the mobile chamber, which allows manufacturers to test large, heavy, or confidential machines and products at extreme temperatures ranging from -40°C to +60°C without transporting them.

geartechnology.com/zf-wind-power-and-sirris-launch-mobile-climate-chamber

GT VIDEOS

From Job Shop to Production with the Hera 750

At Gear Headquarters, quality is the foundation of everything they do. Based in Kansas City, the shop manufactures spur, helical, double-helical, herringbone, bevel, internal, spline, and worm gears, sprockets, and timing belt pulleys. Their full-service machine shop also offers manual and CNC turning and milling, grinding, broaching, and slotting. With the Helios Hera 750 CNC hobbing machine, they are expanding beyond one-off job-shop work into repeatable production runs and delivering shorter lead times.

geartechnology.com/videos/from-job-shop-to-production-with-the-hera-750

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Michael Goldstein founded *Gear Technology* in 1984 and served as Publisher and Editor-in-Chief from 1984 through 2019. Thanks to his efforts, *the Michael Goldstein Gear Technology Library,* the largest collection of gear knowledge available anywhere, will remain a free and open resource for the gear industry. More than 40 years' worth of technical articles can be found online at *geartechnology.com.* Michael continues working with the magazine in a consulting role and can be reached via e-mail at *mwg42@hotmail.com.*

THE GEAR INDUSTRY'S INFORMATION SOURCE

Preservation Mode

Aaron Fagan, Senior Editor

As I write this, I am sipping hot coffee at Caffè Dante in an extremely cold New York City. I flew in from Tyler, TX—which got its own battering—and the severe cold lingering here is a remnant of Winter Storm Fern, the system that covered much of the country in snow and ice. The purpose of the trip is to give a poetry recital at the Amant Foundation in Brooklyn, of all things. Outside, people hurry past with their heads down, powering through what's left of the storm. It's a fitting image for the gear industry in 2026: heads down, pushing through conditions not of their own making, waiting for a break in the weather.

Our annual State of the Gear Industry survey arrived against that backdrop—tariff policy that shifted without warning through much of 2025, leaving companies in what Klingelnberg's Prasad Kizhakel called an environment that "rewards preservation over growth and innovation." The results, beginning on page 18, reveal an industry adapting with clear eyes, building relationships that can weather policy storms.

Elsewhere in this issue, MPMA president Matthew Croson lays out the association's 2026 playbook, including a DC fly-in in May. MPMA Technical Services announces the expansion of the Fall Technical Meeting's program. And speaking of new frontiers, MPMA has officially launched its fifth emerging technology committee, this one focused on eVTOL air mobility.

On the technical side, we present the first of four excerpts from Dr. Hermann J. Stadtfeld's new book, *Gear Technology Solutions*. Researchers from RWTH Aachen present findings on how tooth root contour deviations affect bending strength, work that should give quality engineers pause about what they're not measuring.

If your subscription is lapsing, now is the time to renew—or to subscribe if you haven't yet. You can do so at *geartechnology.com/subscribe*. And if you're reading this on a shop floor somewhere, head down against your own weather, know that you're not alone.

Walking back to my hotel through Washington Square Park, I looked up at the Arch, reading its epigraph, taking new courage from the old words: "Let us raise a standard to which the wise and honest can repair."


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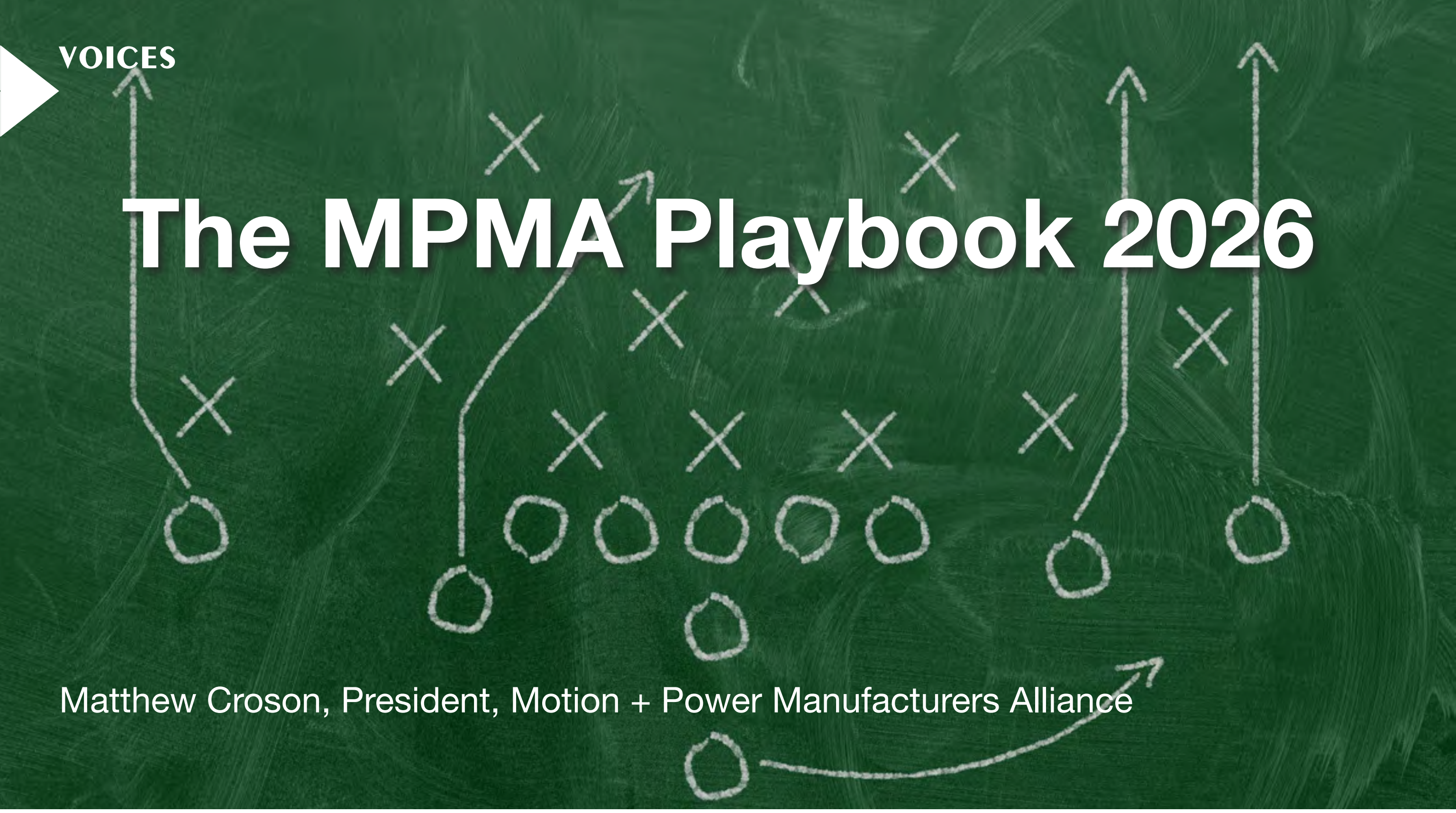


The MPMA Playbook 2026

Matthew Croson, President, Motion + Power Manufacturers Alliance

Motion + Power Manufacturers Alliance's (MPMA) *Gear Technology* magazine publishes its State of the Gear Industry survey results annually in the January/February issue, and this year's provides great insights into the current market and where industry leaders see 2026. Our Senior Editor, Aaron Fagan, does a great job outlining what the industry is saying, and it's clear important market drivers are impacting the power transmission industry: Tariff uncertainty, moderate capital expenditures planned, suppliers needing to address both ICE and EV customers simultaneously, and continued industry consolidation.

As PT Leaders, we are facing many challenges, and here is a plan—leveraging MPMA programs—to turn them into opportunities—let's call it the MPMA Playbook 2026:

- **CHECK IN WITH INDUSTRY**—To understand where things are going, one of the best and simplest ways is to attend MPMA's Annual Meeting. This three-day event, being held April 23–25 at the Sunseeker Resort in Port Charlotte, FL, will bring together 200+ CEOs, owners, and presidents covering the entire supply chain. We will have respected economists, demographers, industry experts, and members discussing the top trends impacting the supply chain, and it's a perfect way to gain quick insights from your peer group.
- **JOIN OUR ADVOCACY EFFORTS**—This May, MPMA will host its second DC fly-in—this two-day event will allow members to express their thoughts and perspectives on tariffs, trade, and other business issues facing our sector, directly to both the Senate and House leaders who create the laws, and the Administration Officials who enact them.
- **PARTICIPATE ON OUR TECHNICAL AND TECHNOLOGY COMMITTEES**—You need to keep up on air mobility trends? Join our newly created emerging technology committee, focused on the up-and-coming eVTOL market. Want to ensure wind-energy solutuons are built to last? Join our MPMA technical working group that will address open engineering issues impacting the growth of the wind market.
- **GEEK OUT ON GEARS AND MORE**—Attend the Fall Technical Meeting, where we will host a joint meeting with MPMA and the Society of Tribology and Lubrication Engineers. More than 50 presentations covering all facets of gearing and bearing technology development will be shared amongst 150+ design and applied engineers. No better way to make sure your team keeps up with the latest and greatest than our FTM. This is where you start addressing ICE and EV challenges, based on technical need.
- **JOIN MPMA's PULSE SURVEY PROGRAM WITH WIPFLI**—We are partnering with Wipfli in 2026 to publish three Pulse Surveys. These detailed reports consolidate data shared by members from MPMA, Precision Metalforming Association, Forging Industry Association, Fabricators and Manufacturers Association, and many others, to provide an in-depth overview of the current market and industry responses. Participants get a unique report that offers insights into how their data compares with the overall market.

MPMA walks into its 110th year ready to serve the industry with practical, affordable, technically focused programming, made by members, and executed by a dedicated 20-person staff.

Consider joining any of these programs in 2026 and make our playbook work for you.

americanbearings.org

agma.org

Rego-Fix USA

OFFERS TOOL CLAMPING SYSTEM FOR STABILITY AND PRECISION

Rego-Fix USA developed its powRgrip system for stable toolholding when machining parts made from all types of materials. Whether machining firearms or tactical gear, the powRgrip's press-fit toolholding delivers higher precision, with greater vibration damping for longer tool life and superior surface part finishes.

The powRgrip tool clamping/unclamping units use automated toolsetters and load a tool into a holder in under 10 seconds and are ready for immediate use. The units achieve a 1,100 Nm clamping torque rating, the industry's highest, and their 0.0001" TIR is guaranteed throughout five years or 20,000 toolsetting cycles. The technology uses neither heat nor hydraulics, so tools are safe to handle immediately after the clamping cycle concludes. The Rego-Fix clamping methodology avoids the limitations and tool-life compromises of other systems.

At a recent firearms show, Rego-Fix highlighted several advanced coolant management systems engineered to overcome the thermal, lubrication and chip-control challenges faced in modern machining. These include PG Cryogen (CO_2) cooling for temperature-sensitive materials, minimum quantity lubrication (MQL) technology for cleaner machining and reduced fluid consumption, and external coolant delivery options that improve chip evacuation and process stability. The company will also feature its metallic-sealed ER-DM collets for applications requiring reliable coolant sealing and high-pressure delivery.

"Meeting modern firearms manufacturing demands requires faster machining, tighter tolerances, and unwavering repeatability," says Jeff Schemel, Rego-Fix general manager, USA. "Our powRgrip system empowers manufacturers to achieve superior accuracy and consistent surface finishes on every part they produce."

regousa.com

Star Cutter

ADVANCES PRECISION REAMING WITH NEW DOUBLE PILOT REAMER DESIGN

Star Cutter Company introduces its new Double Pilot Reamer, a precision-engineered solution designed to deliver superior size control, exceptional surface finishes, and dramatically extended tool life in demanding barrel machining applications.

The Double Pilot Reamer is ideally suited for deep-hole and high precision bore operations where size, control, straightness, and surface finish are critical. Typical applications include hydraulic and pneumatic components, aircraft components, engine and powertrain parts, defense, orthopedic devices and industrial cylindrical components requiring tight tolerances over long bore lengths.

Built around a fully guided cutting approach, the Double Pilot Reamer stabilizes the tool from entry to exit, supporting it through the full length of the bore. By maintaining alignment throughout the cut, the tool minimizes deflection and vibration which can lead to inconsistent results in conventional reaming operations.

A key benefit of the new tool is one of the best reamed surface finishes available in the industry. The Double Pilot Reamer effectively eliminates chatter, scoring and witness lines, three of the most common causes of scrap, rework, and sub-standard quality in precision barrel machining.

"The performance gains with the new Double Pilot Reamer are immediate and measurable," said Rick Rickert, round tool product manager at Star Cutter Company. "In many applications, manufacturers are seeing tool life improvements of up to ten times compared to conventional reamers, while also achieving some of the best surface finishes in the industry."

Beyond measurable performance gains, the Double Pilot Reamer introduces a new level of predictability into the manufacturing process. With consistent results cycle after cycle, manufacturers can confidently reduce inspection time, eliminate secondary finishing operations, and keep production moving without interruption.

This stability is especially valuable in high-precision barrel machining environments, where tight tolerances and surface finish requirements leave little room for variation. By removing common sources of variability, the Double Pilot Reamer helps manufacturers improve throughput while maintaining confidence in part quality.

Designed for manufacturers focused on precision, efficiency, and long-term cost savings, the Double Pilot Reamer reflects Star Cutter's continued commitment to advanced cutting tool solutions that address real-world production challenges.

star-su.com

Seco Tools

RELEASES 3335.18 DISC MILLING CUTTER

Seco releases the 335.18 disc milling cutter, a customizable slotting solution engineered for real-world manufacturing. With over 70 standard variants and full customization via MyDesign, the 335.18 delivers stable, cost-efficient performance for any industry, machine, or material enabling manufacturers to achieve precision and reliability in every slotting operation.

Slotting solutions for the real world

The 335.18 disc milling cutter is designed to tackle the toughest slotting challenges across automotive, aerospace, and general engineering sectors. Its smooth-cutting design ensures fewer vibrations, longer tool life, and reliable results. It is particularly suitable for long overhangs or even in weaker setups, such as robotic arms.

Design your own indexable slotting cutter

With one of the broadest ranges on the market, the 335.18 system features a wide selection of LNKT inserts, various corner radii, integrated wiper flats for fine finishes, and a complete portfolio of grades and geometries. If the standard range doesn't fit, MyDesign allows users to configure and quote a custom cutter body in minutes—no waiting, no guesswork.

Cost efficiency is at the core of the 335.18's design. Double-sided inserts with four cutting edges, high-performance grades, and a durable Swedish steel cutter body deliver extended tool life and fewer replacements, supporting sustainable manufacturing and maximizing value for every investment.

secotools.com

LK Metrology

INTRODUCES CMMS FOR HEAVY-DUTY MEASUREMENT

Two new ranges of bridge-type coordinate measuring machine (CMM), Maxima and Maxima R, have been launched by LK Metrology to meet a rapidly expanding demand for precise measurement of large, heavy components, often of significant complexity. The innovative machines are ideally suited to quality control applications across industries such as aerospace, energy, automotive, heavy engineering, power generation, transportation and industrial machinery, where consistent measurement results and long-term stability are paramount.

LK's advanced, ceramic materials for the beam and spindle guideways, which provide near-perfect stiffness-to-weight ratio, have been combined with a robust structure to deliver consistent accuracy and repeatable results in the order of 3 µm. Low gap, high-efficiency air bearings and zero-hysteresis drive systems ensure unmatched quality and low maintenance.

The Maxima series offers the largest measurement volume on the market, from 12 to 72 cubic meters, of any CMM with a granite table. Its high capacity provides outstanding stability, ensuring the machine maintains peak performance even when supporting the heaviest workpieces. Included in the range are 28 models in six table lengths from nominally three up to eight meters and seven variants of bridge cross section up to three meters.

Complementing this offering, the Maxima R range features an innovative, twin-rail design engineered for heavyweight workpieces. The structure enables safe and efficient loading of heavy components on the floor and seamless integration with automated transfer systems. A key advantage of these models is that the design eliminates the need for special foundations, while offering exceptional stability, simplified installation and outstanding cost efficiency. The Maxima R is available in the same range of sizes as the table-type models.

Both new CMM product lines are equipped with a powerful LK controller and are available in several configurations: either probe-ready for tactile inspection and laser scanning using a PH10MQ Plus multi-sensor indexing probe head with autojoint, or in ScanTek configuration with a multi-sensor REVO2 head to provide 5-axis scanning, or with an SP80 ultra-accurate fixed scanning head with probe builds up to one metre. The PH10MQ-ready models feature a multiwire cable that supports both SLK and L/LC/XC laser scanner technologies, eliminating the need for a separate probe-ready configuration for each type.

lkmetrology.com

Platinum Tooling

OFFERS REV BROACHING TOOLS

Platinum Tooling, the importer and master distributor of live tools, angle heads, speed increasers, Swiss machine products, knurling and marking tools and shrink fit tool holders manufactured by various international suppliers, will now carry REV broaching tools in North America. This announcement was made by Platinum Tooling president, Preben Hansen, at their headquarters in Prospect Heights, IL, near Chicago.

REV S.R.L., located in Northern Italy, is the manufacturer of innovative broaching solutions for CNC lathes and machining centers. The tools are ideal for machining simple keyways or internal and external profiles, both teeth and splines. Common profiles including square and hexagon are easily achieved and custom profiles are available. REV Broaching Tools offer excellent performance with long insert life and high surface quality.

The REV motorized broaching tool is designed for use on live tool lathes. Single machine set-up eliminates the need for secondary operation or outsourcing. REV tools are ideal for high production runs, offer easy installation and fast processing time. These tools are designed for maximum rigidity, offer long tool life and an excellent finish.

REV static broaching tools are for use on CNC lathes with or without Y-axis. They offer a patented eccentric bushing which eliminates alignment errors for machines without a y-axis. The tools have a sturdy two-piece construction and are ideal for smaller runs. They are designed for use in boring bar holders on lathes and for use in collet chucks or Weldon holders on machining centers. REV tools allow for a wide variety of standard and custom profiles and sizes.

REV broaching tools are a perfect complement to the Heimatec live tools that are sold by the extensive network of Platinum Tooling manufacturers' representatives and distributors throughout North America.

platinumtooling.com

EMCO Mecof

POWERMILL G3 PC3 FOCUSES ON LARGE-SCALE PRODUCTION

Although the Powermill G3 PC3 was designed by Mecof to meet the needs of customers with limited space but a strong focus on large-scale production, this machine leaves nothing to chance and is in no way inferior to its larger counterparts. Built for an Italian customer involved in general mechanics, this machine stands out for its ability to combine structural robustness and compactness while ensuring a large working area, high performance and Industry 4.0 digital solutions. Equipped with Heidenhain TNC 640 HSCI numerical control and Heidenhain's Industry 4.0 package, the Powermill G3 PC3 makes integration with the digital world one of its strengths.

With axis strokes of x = 8,000 mm, y = 4,500 mm and z = 1,500 mm, the Powermill G3 PC3 is ideal for machining large components. The 8,000 x 3,000 mm work surface, with a load capacity of up to 15,000kg/m^2 (class II DIN 876), ensures maximum stability even during the most demanding operations.

The heart of the machine is the universal bi-rotary head with automatic millesimal positioning, 38 kW power, maximum torque of 615 Nm and speeds of up to 6,000 rpm, with ISO 50 tool attachment. This combination allows for a wide range of machining operations, from heavy roughing to high-precision finishing.

The picture is completed by a 60-position chain tool changer, a chip evacuation system, a cooling system and advanced solutions for the latest generation of tool and workpiece control. Specifically, the tool changer is fixed to the crossbeam shoulder. This system, combined with the sliding exchange arm, ensures speed and reliability in tool replacement operations, optimizing cycle times. Chip evacuation with longitudinally arranged ramp conveyors is quick and smooth. The cooling system, with dual delivery (near the spindle and through the spindle), ensures tool efficiency and longevity, supported by a multi- stage filtration system up to 25 µm. At the customer's request, this system is served by a collection tank and a filtering tank, each with a capacity of 1000 liters. Filtering degree: 1) 60 µm and 2) 30 µm, carried out by means of cartridge filters positioned on the filtering tank.

emco-world.com

FUCHS

DELIVERS DRIVELINE LUBRICANT FOR E-DRIVE AND E-AXLE ARCHITECTURES

FUCHS Lubricants Co. highlights FUCHS BluEV EDF 4101, a high-performance, sustainable wet EDF driveline lubricant specifically engineered for electric drive unit (EDU) and e-axle architectures with shared sump configurations between the gearbox and e-motor. FUCHS BluEV EDF 4101 delivers exceptional gear and bearing protection while simultaneously maximizing overall vehicle efficiency, combining state-of-the-art additive technology with premium, low-viscosity base oils.

As the demands of e-mobility continue to evolve, FUCHS BluEV EDF 4101 stands out for its ability to address the conflicting requirements of efficiency and durable hardware protection, ensuring reliable, long-term operation of battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs) with common sump systems for both gearbox and e-motor. Highly oxidatively stable, the formulation prevents the formation of conductive oxidation byproducts and provides excellent cooling performance. Additionally, it offers resistance to aeration, shearing and thermal degradation.

In benchmarking tests, FUCHS BluEV EDF 4101 achieved improved efficiency, reducing overall energy consumption compared to key competitors; this results in more range per charge and tangible cost savings for automakers and fleet operators. The lubricant demonstrated two failure load stages better than Dexron VI ATF in the demanding A1016.6R90 FZG test and delivered significant gear scuffing protection, underscoring its capabilities in even the most challenging operating environments.

FUCHS BluEV EDF 4101 offers broad suitability for modern seal, insulation, and electronics materials found within new energy vehicles. Its advanced formulation improves corrosion resistance and electrical compatibility versus leading competitive products, preventing corrosion of copper and other metals, maintaining electrical resistance properties, and extending overall hardware lifespan.

Actual drive cycle testing revealed FUCHS BluEV EDF 4101 delivers a 0.5 percent efficiency improvement over competitive fluids, minimizing energy losses, extending driving range, and reducing required charging cycles, ultimately helping preserve battery life and supporting a more sustainable operation. As part of the FUCHS BluEV product line, designed especially for the requirements of e-mobility, FUCHS BluEV EDF 4101 directly addresses the evolving needs of the electrified passenger car manufacturing sector with solutions that advance the transition to cleaner transportation.

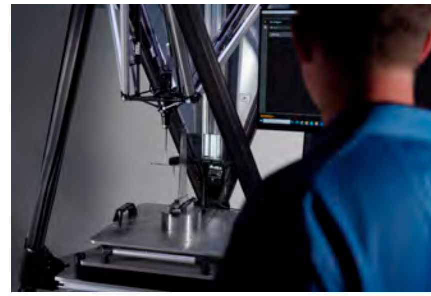
fuchs.com

Renishaw

IMPROVES METROLOGY SYSTEMS WITH *MODUS IM* EQUATOR SOFTWARE

Renishaw's *MODUS IM* Equator software is built on the *MODUS IM* platform, to maximize productivity for Equator and Equator-X gauging system users. *MODUS IM* Equator software is part of Renishaw's continuing investment in innovation with a drive to improve both the capability and customer experience of Renishaw metrology systems.

MODUS IM Equator software represents Renishaw's first step towards intelligent metrology programming and sets a direction of travel for Renishaw in enabling more users to benefit from its inspection equipment. Leveraging over 50 years of Renishaw expertise, it enables a simple way of creating inspection programs and characteristics-based metrology reporting, without requiring in-depth knowledge of metrology or inspection programming.



The new software enables customers to assign simple measurement features easily with a user-friendly CAD interface, and with no code required. It automatically ensures all machine movements are collision-free, and all settings follow metrology best practice. These features enable users to quickly address new part requirements and ensure high uptime for production lines.

"*MODUS IM* Equator software introduces Absolute and Compare inspection functionality to further enhance the new Equator-X dual method systems," says Rob Harrison, Renishaw's director of industrial metrology software. "Empowering our customers to easily create inspection programs, allows them to harness the full potential of our metrology solutions."

The new software offers an intuitive and efficient CAD-driven platform for creating and running inspection programs. This complements the existing *MODUS IM DMIS* software, that is based on the code-driven, *MODUS* software which is also available on the Equator-X gauging system.

As well as now offering two programming options, the *MODUS IM* platform delivers a cohesive user experience across a wide range of use cases, including: inspection planning and programming, shop floor operation, integration into automation, print-formatted reporting, machine monitoring, and measurement connectivity and analytics.

For shop floor process control applications, *MODUS IM* Equator software integrates with the Renishaw Central manufacturing connectivity and data platform to enhance process monitoring capabilities. Renishaw Central provides a clear view of manufacturing metrology data and process control, employing *Intelligent Process Control (IPC)* software to provide automatic updates of tool offsets and machine tool variables.

renishaw.com

Neugart

INTRODUCES NEW RACK-AND-PINION DRIVE SYSTEMS

With a new fully integrated gearbox-pinion-rack combination, Neugart expands its portfolio with a high-performance solution for maximum precision and efficiency in rack applications. The new concept combines optimally matched components that enable powerful, dynamic, and precise power transmission.

The three components mesh seamlessly and ensuring smooth running, maximum feed force, and precise positioning accurately—crucial properties for modern automation and drive systems.

The racks are available with either straight or helical gearing and are made of induction-hardened, quenched and tempered steel. They cover a module range from 1.5 to 5 mm and comply with quality level 6. Subsequent heat treatment and precision grinding of the gearing ensure high surface quality and a long service life. In addition to standard lengths of 1,000 mm and 2,000 mm, customer-specific lengths are also available.

Thanks to its high precision and flexibility, the integrated drive unit can be used in a wide variety of applications. Matching pinions are available for gearboxes of frame size 060 to 200. These include coaxial and right-angle gearboxes in both shaft or flange designs. The Precision Line offers maximum positioning accuracy, while the Economy Line provides robust and economical solutions for standard applications.

A special feature is the gearbox's heavy-duty output shaft bearing. It reliably transmits high radial and axial forces, even under dynamic cycles and heavy loads. This results in smooth, low-noise power transmission, improved process quality, and stable system acoustics.

With the integrated gearbox-pinion-rack combination, Neugart offers a readily available system solution from a single source. It enables simple integration, high power density, and maximum flexibility, setting new standards for precise and efficient rack-and-pinion drives in modern machine and automation applications.

neugart.com

State of the Gear Industry 2026

The gear industry navigates uncertainty, finds pockets of strength, and bets on automation

Aaron Fagan, Senior Editor

Survey Analysis

The Forces at Work

Of the 137 respondents to our annual gear-industry survey, the message was clear: tariffs are the defining challenge of 2026. But the frustration runs deeper than the duties themselves. Manufacturers can absorb cost increases; they can't absorb chaos. When rules shift weekly and exemptions evaporate overnight, planning becomes guesswork. One respondent captured the exhaustion: "In 2025, they were all over the place, without warning, up and down. Terribly disorganized."

Yet within this turbulence, distinct currents run strong. Defense and aerospace work has surged. Oil and gas, buoyed by loosened regulations, is "very active" according to multiple respondents, with mobile power units and gas compression driving demand. Overhaul and repair business is booming—when new equipment becomes expensive or hard to source, companies keep existing machines running longer, and that means gears.

The electric vehicle transition continues reshaping the landscape, though not uniformly. EVs require fewer gears than internal combustion drivetrains, pressuring some manufacturers while others pivot toward the precision demands of EV gear systems—quieter operation, tighter tolerances, micro-geometry that would have seemed exotic a decade ago. One respondent noted customers now demand "noiseless gears," a specification that ripples back through design, cutting, and finishing operations.

The skilled labor shortage has calcified into a permanent condition. Respondents don't speak of it as a problem to solve but as terrain to navigate. Experienced machinists retire; replacements are scarce and take years to develop. "Old time mentality," one respondent observed, warning that without change, "no young people will be attracted to the industry when given a choice otherwise."

The Cautious Apprentice

Most gear companies have experimented with artificial intelligence (AI); few have integrated it into core operations. The

typical deployment involves marketing copy, meeting transcription, and email drafting—useful but peripheral.

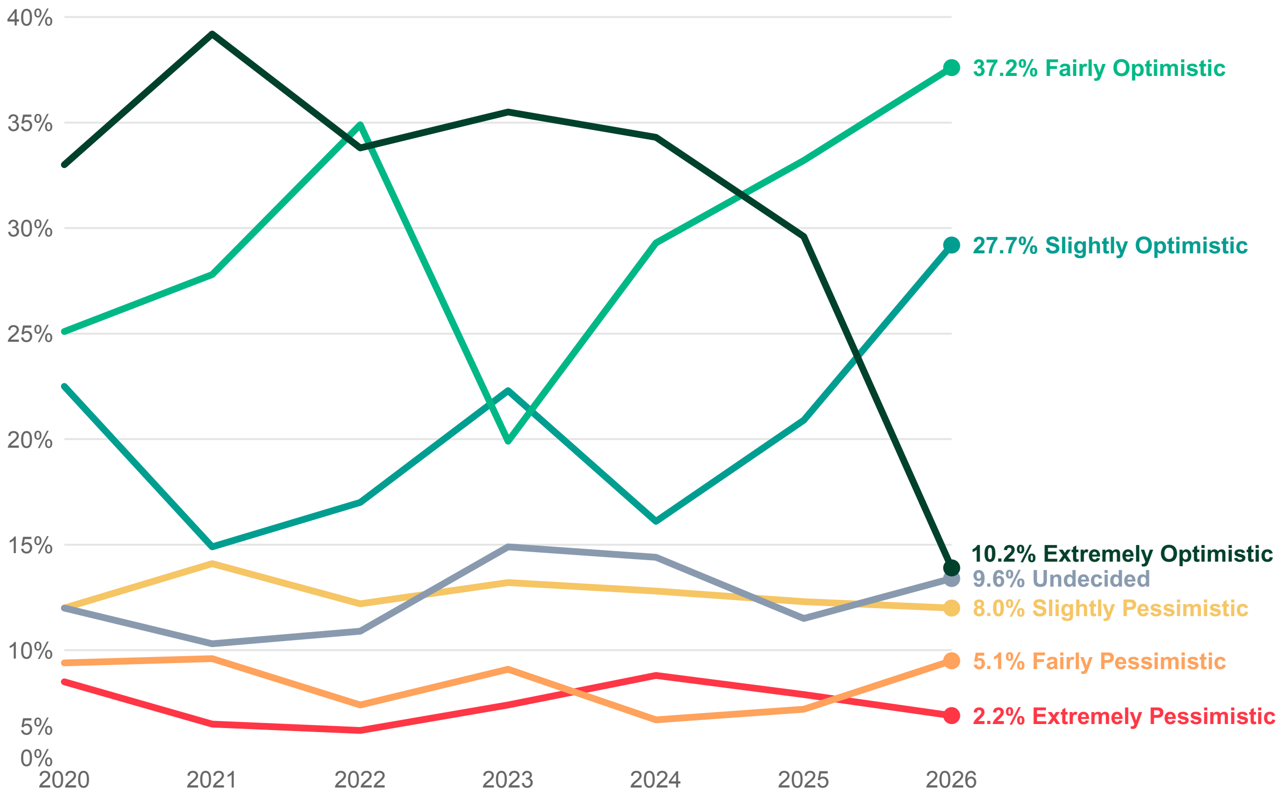
Where companies have pushed further, results vary. One reports that AI-assisted engineering and design is "paying off." Another uses AI to optimize production scheduling against the competing demands of marketing forecasts, manufacturing capacity, and supply chain constraints. These aren't trivial applications.

But skepticism persists, and it's earned. One respondent tried using AI for ratio calculations and watched it fail. Another found AI analysis "often incorrect and inconsistent." The technology works well enough for tasks where errors are easily caught and corrected; it's not yet trusted where mistakes are costly.

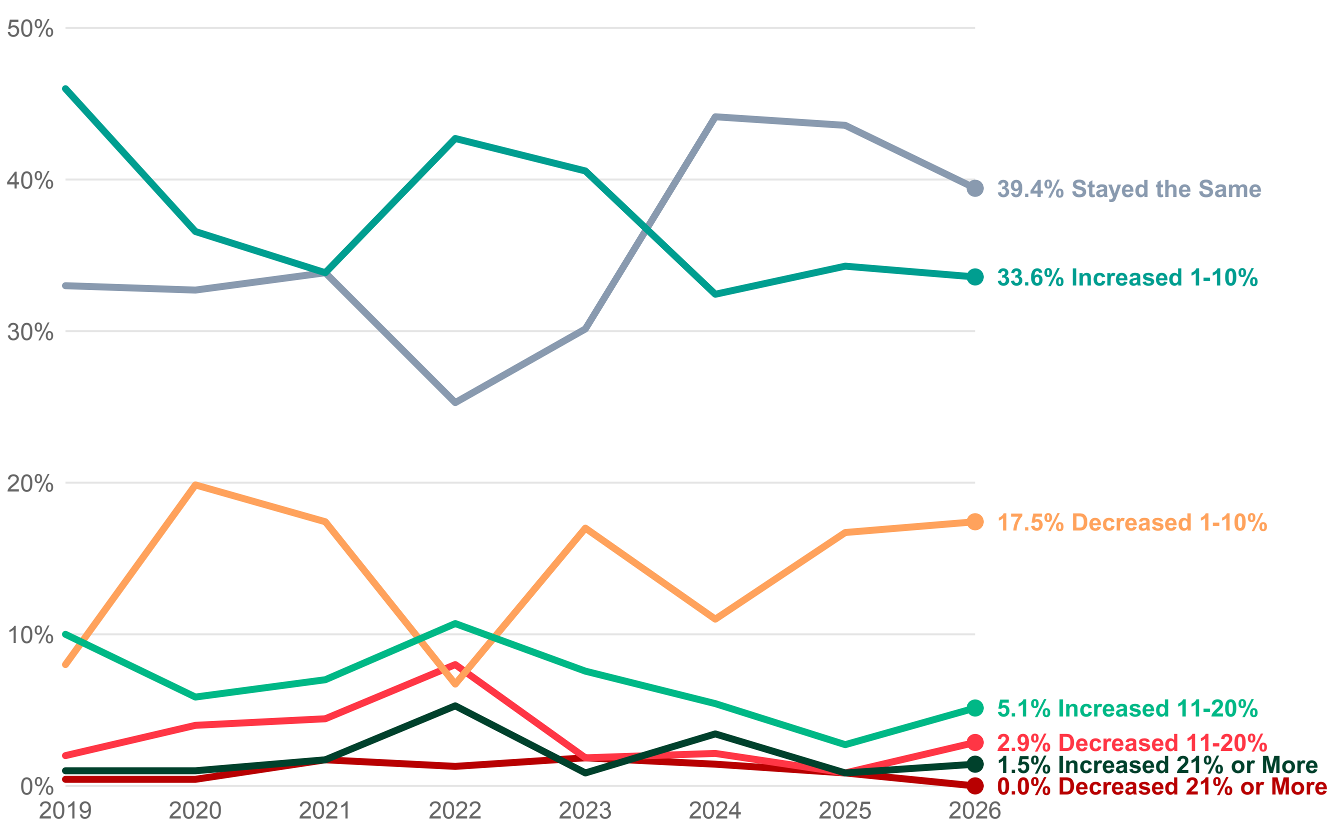
A deeper concern runs beneath the practical objections. Several respondents worry about feeding proprietary knowledge into systems they don't control. The gear industry runs on accumulated expertise—decades of understanding how a particular machine behaves, how a specific material cuts, what tolerances a given application actually requires. That knowledge has value precisely because it's hard-won and closely held. Handing it to an AI feels, to some, like giving away the store.

Still, the trajectory is clear. Companies that dismissed AI entirely a year ago now describe "pilot programs" and "exciting opportunities." The question isn't whether AI will reshape the industry, but how quickly and in what form.

Please describe your level of optimism regarding your company's ability to compete over the next five years.



How much do you expect EMPLOYMENT to change over the NEXT 12 MONTHS?



Pragmatism Over Poetry

Sustainability in the gear industry tends toward the practical rather than the aspirational. Companies pursue initiatives that reduce costs while meeting regulatory requirements; grand environmental visions are rare. This isn't cynicism—it's the reality of an industry operating on thin margins in competitive global markets.

The most common efforts involve recycling and waste reduction: chip briquetting machines that recapture cutting oil, skimmers and filters that extend coolant life, corrugated compactors and pallet chippers that keep material out of landfills. Several companies have installed solar panels. Others have switched to dry cutting where possible, eliminating oil waste entirely. One reports achieving net-zero emissions through recycled groundwater cooling systems.

Energy efficiency drives much of the activity. Newer equipment simply uses less power than what it replaces, and when utility costs rise, the payback calculations sharpen. Digitization helps too—better data means less waste, fewer rejected parts, more efficient scheduling.

But sustainability's prominence has dimmed. One respondent noted its importance has "changed from high to neutral," reflecting shifting political winds. Another called it "a dirty word here." A European manufacturer complained that sustainability bureaucracy has "become a heavy burden, counteracting any gains."

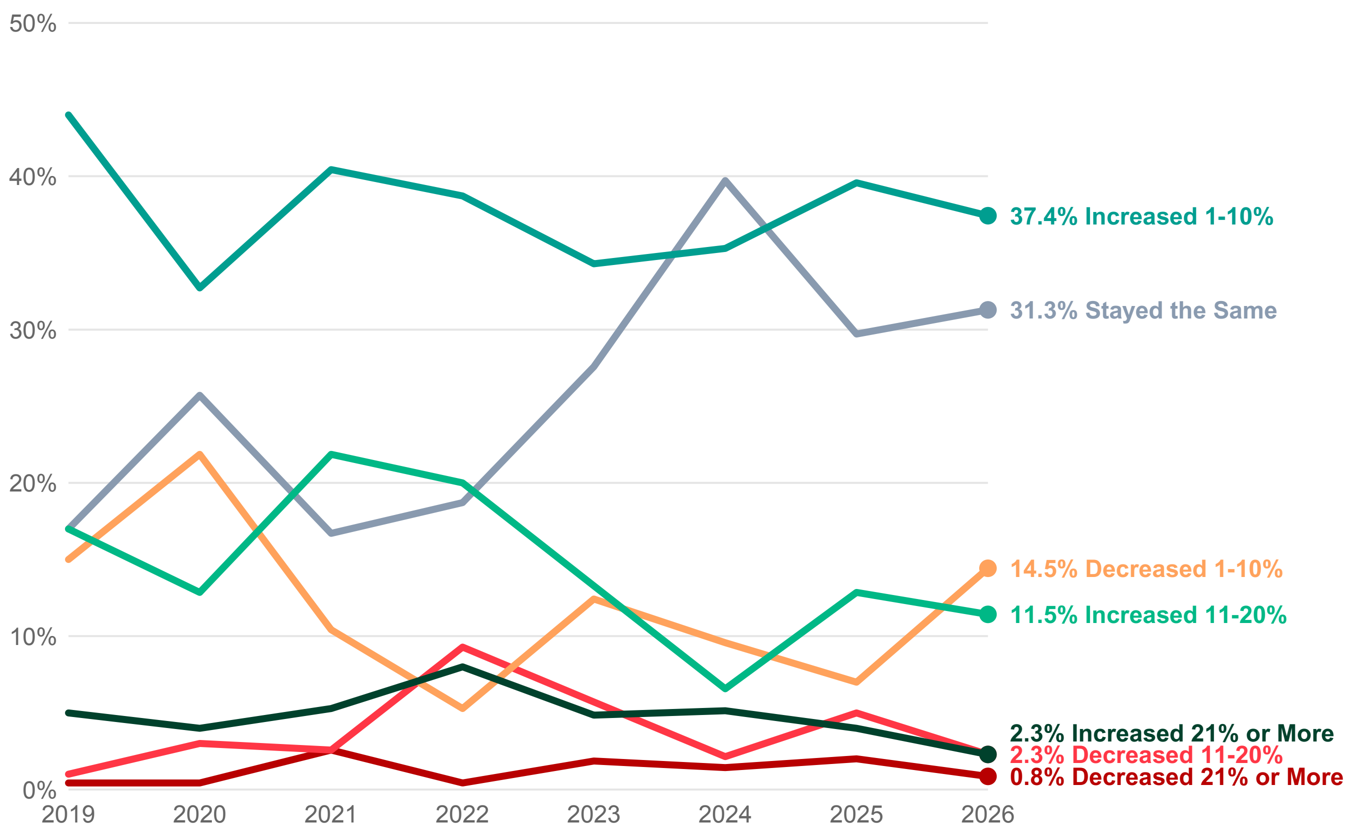
The most honest assessment came from a respondent who noted that sustainability "has to be economically sustainable in the middle and long term." That's not a rejection of environmental responsibility—it's an acknowledgment that manufacturers can't pursue goals that bankrupt them. The initiatives that stick are those that make business sense on their own terms.

Automation's Moment

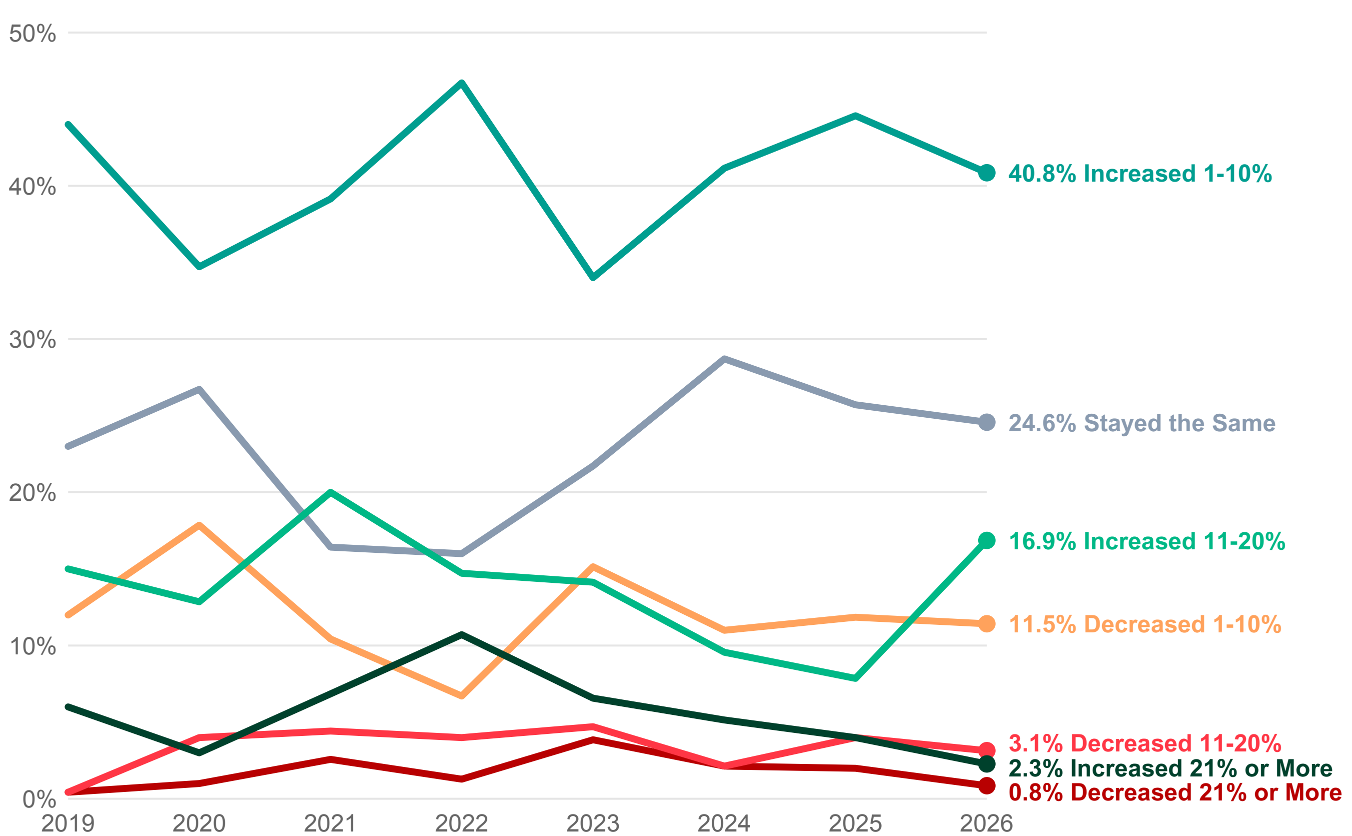
Among emerging technologies, robotics and automation command the most immediate attention. The business case has become compelling: labor costs rise, skilled workers remain scarce, and robotic systems have matured enough for practical deployment. Multiple respondents describe active installation of robotic cells and collaborative robots, with more planned.

The applications suit the industry's characteristics. Gear manufacturing involves repetitive operations requiring consistent precision—exactly what robots do well. Loading and unloading machines, moving parts between operations, even some inspection tasks have proven automatable. One company specifically mentioned Standard Bots cobots as supplementing

How much do you expect PRODUCTION (unit output) to change over the NEXT 12 MONTHS?



How much do you expect SALES VOLUME to change over the NEXT 12 MONTHS?



shop staff. Another noted automation's role in "reducing direct labor cost per part and improving operator ergonomics."

Additive manufacturing generates interest but remains largely peripheral. Most companies use 3D printing for fixtures, tooling, and prototypes—valuable applications, but not production parts. Metal additive manufacturing hasn't yet achieved the material properties, surface finish, or cost structure that gear applications demand. "Still waiting for additive metal to be comparable to standard metals," one respondent summarized. The technology is watched, not adopted.

Industrial IoT deployment varies by company size and sophistication. Larger operations have integrated condition monitoring, predictive maintenance, and production tracking. Smaller shops often haven't started—the investment is harder to justify when production runs are short, and product mix changes constantly. But the direction is clear; one respondent described plans to use IIoT and AI together "to find machine and process trends."

A potentially significant market emerged in multiple responses: humanoid robotics. Smart gearboxes for robotic applications represent genuine new demand, distinct from automotive or industrial markets. As one respondent noted, these applications require innovative manufacturing solutions—an opportunity for companies positioned to provide them.

Fewer Players, Higher Stakes

The gear industry continues consolidating, reshaping relationships that in some cases span decades. Private equity involvement has accelerated the process, bringing capital but also, some respondents note, eroding the personal relationships that characterized the industry.

The effects ripple outward in multiple directions. Fewer competitors mean opportunities for survivors—when merged entities discontinue low-volume products or exit certain markets, nimble companies fill the gaps. But fewer suppliers mean reduced options and increased vulnerability. One respondent described supply chain consolidation as having "wreaked havoc" on component sourcing. Another noted that remaining suppliers "do not manufacture or carry the range of products that they used to."

Customer concentration creates its own pressures. When major accounts merge, their combined purchasing power increases while the supplier's negotiating position weakens. Lost accounts can't easily be replaced when fewer potential customers exist.

The outlook divides along size lines. Larger companies see consolidation as opportunity—acquisitions that expand capability and market reach, competitors absorbed or weakened. Smaller companies feel the squeeze intensifying. "Only the largest companies will remain," one respondent predicted. "There is no room even for medium-sized ones."

Whether that proves true depends on factors beyond any single company's control. But the trend line points toward an industry with fewer, larger players—and the consequences for innovation, regional manufacturing capacity, and customer service remain to be seen.

Perspectives from Machine Tool Makers

The survey paints in broad strokes. To understand the finer grain—where the debates lie, where the opportunities hide—we turned to executives at eight gear machine tool companies: Gleason, GMTA, Helios Gear Products, Kapp Niles, Klingelnberg, Liebherr, Machine Tool Builders, and Nidec Machine Tool America.

The Weight of Uncertainty

Prasad Kizhakel, chief sales officer of the Klingelnberg Group, frames the current moment starkly: "The current environment rewards 'preservation' over 'growth and innovation.'" When visibility disappears, so does the appetite for the capital investments that drive both equipment sales and the R&D that produces better machines.

John Perrotti, chairman and CEO of Gleason Corporation, observes that geopolitical tensions are "causing our global customers to pause/slow investment." Felix Scholz, managing director of Liebherr Gear and Automation Technologies, notes that reshoring momentum remains strong, but companies are delaying purchases "because they're waiting for clarity on tariffs and industrial policy."

Shane Hollingsworth, vice president of sales at Kapp Niles, saw the effect in real time: "We had strong bookings each month until the tariff announcements. It was a very clear impact to our business and activity." When the EU-U.S. trade agreement was announced in August, opportunities began increasing again—evidence that clarity, even imperfect clarity, unlocks decisions that uncertainty freezes.

For distributors of imported equipment, the math is particularly punishing. Claudia Hambleton, corporate treasurer at GMTA, points out a common misconception: "Many believe foreign exporters are paying for these tariffs, but in our case, these tariffs are being paid for by the importer as we try to supply and service U.S. manufacturers."

Nidec Machine Tool America offers a different angle. Now that tariffs have largely stabilized, says the company, "the real hurdle is the cost of money." High interest rates hit hardest where it matters most—the small and medium-sized shops that form the industry's backbone.

The result: elongated sales cycles and last-minute decisions. Ross Wegryn-Jones, director of sales and marketing at Machine Tool Builders, describes customers as a "fickle mistress"—delays and holds on purchase orders have become routine. Nidec reports that orders now arrive "down to the wire," compressing not just shipping timelines but the process development and testing that complex gear work requires.

Sidebar: Navigating Challenges and Opportunities in Gear Manufacturing

A conversation with Kika Young, president, Forest City Gear

Matthew Jaster, Director, Editorial Content

My recent discussion with Kika Young, president, Forest City Gear, took place in January 2026 to discuss the state of the gear industry. Key talking points included the current skilled labor shortage, lead times, general volatility, AI, smart manufacturing tools and the future of gear innovation..

Kika Young

Skilled Workforce—Perception vs. Reality

Our first topic of conversation addressed the skilled labor gap, a topic regularly appearing in B2B and trade publications involved in both manufacturing and engineering. Today, finding and retaining the right talent with the necessary skillsets remains a challenge.

"Finding and retaining the right talent is still a challenge—not only from a technical standpoint, but in finding people who want to come in every day and work in a factory or machine shop. For a variety of social and cultural reasons, accelerated by COVID, fewer employees are interested in a traditional nine-to-five job. Many are drawn to remote or independent work and greater flexibility."

If it wasn't challenging enough to convince middle-school and high-school students to consider manufacturing as a career, it's become increasingly difficult to convince their parents.

"There remains this kind of negative attitude towards manufacturing across the board. We spend a lot of time talking to local high schools. We even try to get into the middle school level. And honestly, the kids are interested. They think we're making cool stuff. What we're fighting against now is the presumptions of their parents. 'You don't want to work in a shop,' You don't want a career in manufacturing.' So, we must convince the students and their parents on the lasting benefits of getting into the skilled trades," Young said.

Lead Times and General Volatility

According to Young, lead times on special materials is another 2026 challenge.

"Usually due to geopolitical reasons, some specialty materials—needed for defense and aerospace work—tend to lag and can't meet the expectations of customers. Balancing these expectations becomes a huge topic of conversation," Young said. "We live in this immediacy culture, right, and we sometimes need to explain the differences in producing say a prototype gear on a 3D-printer versus a cut gear. Every project is a little different."

Cost pressure remains a key challenge in 2026.

"This is always an issue. There's been a huge increase in labor costs. I think the wage rates in the labor market have been lagging for such a long time and they're finally catching up. This is fantastic, but there are other pieces of inflation—post COVID—that are kind of offsetting that," Young said.

It becomes a careful, strategic dance to manage costs and lead times. The key is the manufacturer's ability to pass along reasonable customer increases to the customers. This becomes a priority.

"These are conversations we're having all the time," Young noted.

AI and Digital Manufacturing

Forest City Gear prides itself on being at the forefront of manufacturing technology. The company is expanding its AI toolkit to enhance shop floor operations.

"Our ERP system has a lot of information but has limited reporting capability. We have a super sharp young man here at FCG who is utilizing AI to pull reports and documentation that used to be very burdensome to track in Excel," Young said. "Our big goal for 2026 is to leverage AI for our hob and shaper cutter inventory. We have a huge number of hobs and shaper cutters in stock. We sharpen a lot of these in house, but the inventory is in this spreadsheet that has existed since DOS."

With all the available information on tool life, tool wear and additional specifications, FCG is hoping to create an interactive inventory using AI resources.

"We're extremely excited about this specific project and in doing so hope to learn other ways to leverage AI tools across the shop floor in the future," Young said.

Future Considerations

Young said she is all-in on the possibilities of AI in manufacturing moving forward. "It's going to be a focal point across all of manufacturing, really across every sector at this point, right? We'll navigate where it makes sense to employ these tools on the floor and figure out where it probably won't. Personally, I'm excited to see such rapid change taking place in gear manufacturing in the next five to ten years through AI deployment."

One area Young will approach with caution is compliance.

"We can take a part that's designed for a refrigerator in my kitchen and plug and play that into AI. But I can't do that for a lot of the parts currently in gear manufacturing. So, getting platforms that are truly compatible with Cybersecurity Maturity Model Certification (CMMC) or even NIST 800-171 is going to be critical to deploy AI tools."

Another area to keep an eye on is mergers and acquisitions. Young knows of at least two players in the industry who are extremely active in acquiring gear companies.

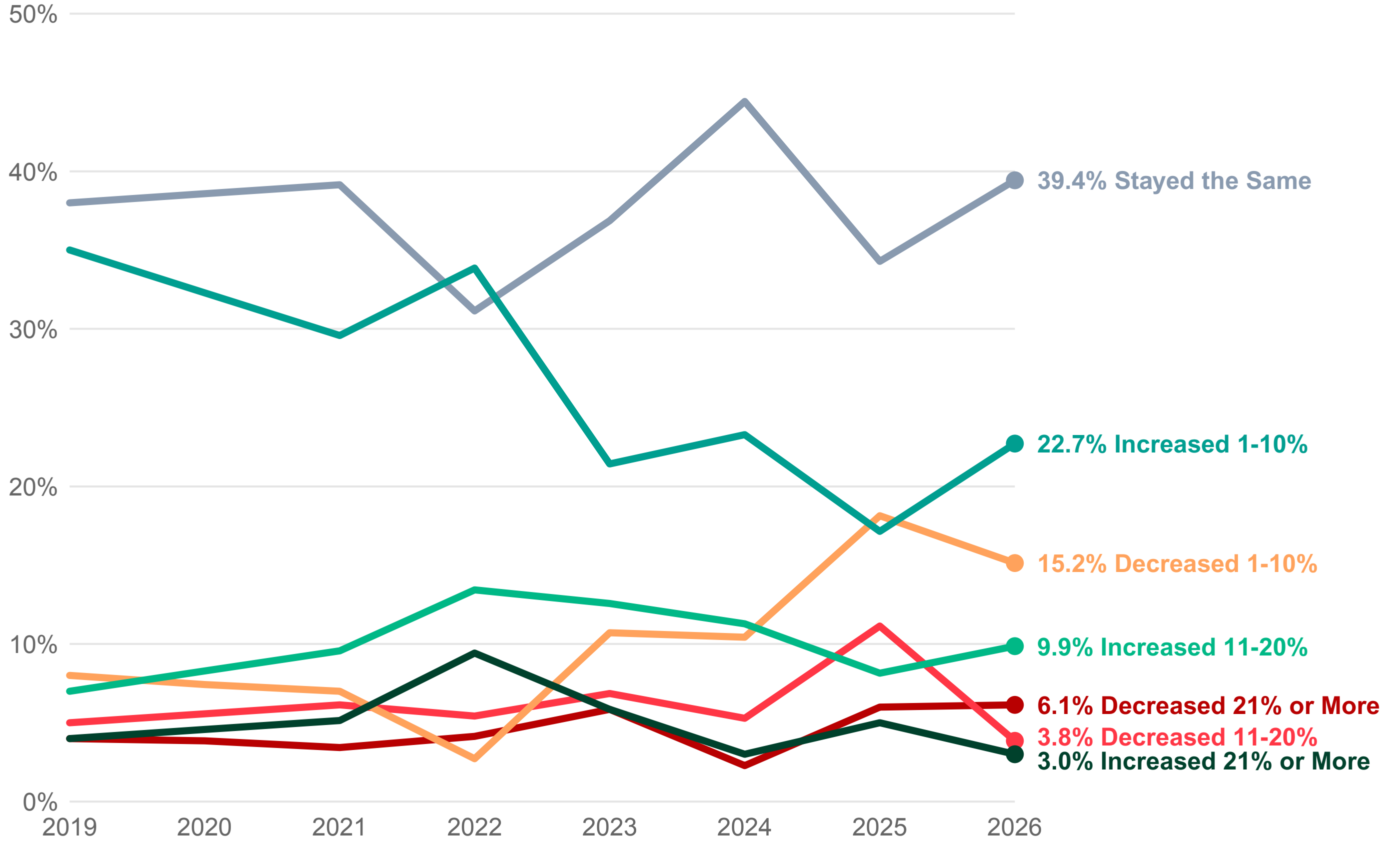
"The face of gear manufacturing is constantly changing. I wouldn't be at surprised to see some additional mergers in the future," Young added.

Lastly, Young believes workforce development in manufacturing is going to change drastically in the coming years.

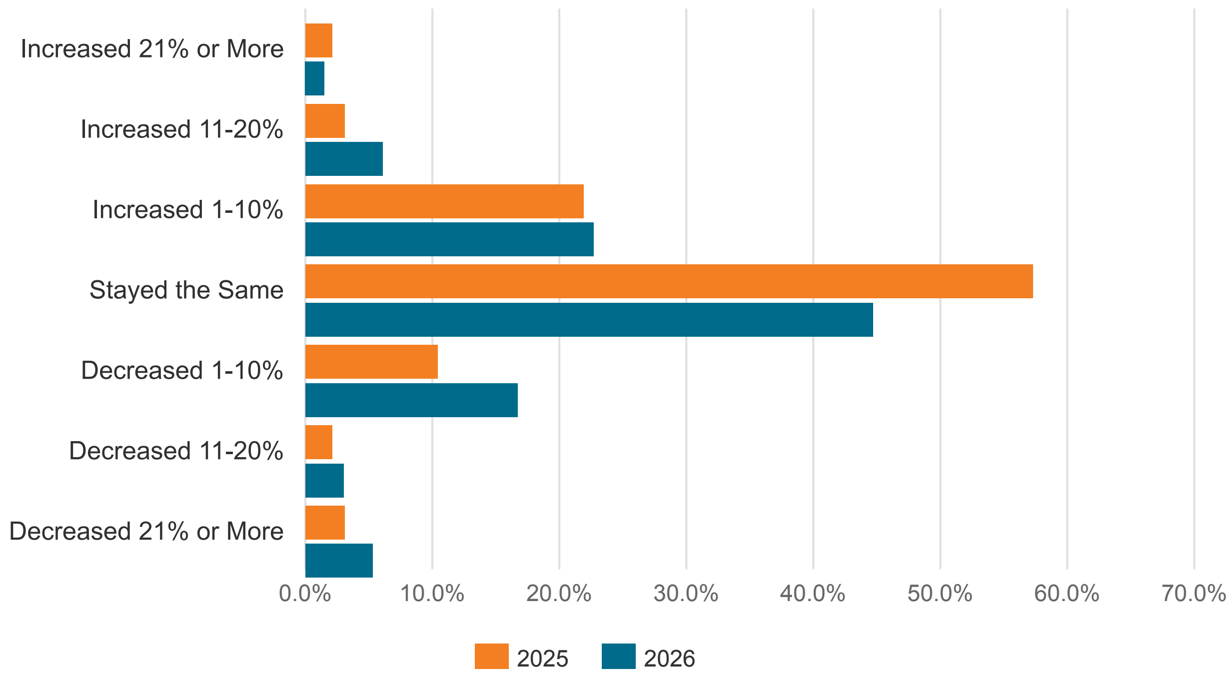
"The jobs where you might see a significant number of reductions due to AI will be white collar jobs. There will be a huge shift in the dynamics between white- and blue-collar workers. We'll see a positive push for sheet metal workers, electricians, plumbers, welders, etc. All these classic skilled trade positions will be sought after, and that's extremely exciting," Young said.

forestcitygear.com

How much do you expect CAPITAL SPENDING to change over the NEXT 12 MONTHS?



How much do you expect MARKETING SPENDING to change over the NEXT 12 MONTHS?



Where Demand Persists

Despite the headwinds, certain markets continue pulling investment. Aerospace and defense remain robust. Energy markets—particularly oil and gas—show strength. And a newer category has captured attention.

Adam Gimpert, president of Helios Gear Products, identifies consumer robotics as "the biggest game-changer on the horizon." This isn't speculation about distant possibilities; it's emerging demand requiring smaller, highly automated gear solutions at scale. Gleason similarly cites robotics among the markets showing relative strength.

Regionally, Asia continues to dominate. Klingelnberg reports that the biggest pull for bevel gear equipment, cylindrical gear grinding machines, and high-end metrology "continues to originate in Asia"—China, India, Japan, and Korea leading. This pattern has held for five years and shows no sign of shifting.

On the process side, hobbing remains "the bread and butter of the industry," as Nidec puts it, because nothing matches its speed and cost per part. But finishing and inspection are gaining ground. Quality demands keep climbing, and shops increasingly recognize they can't just cut gears fast—they have to prove they're perfect.

The Electrification Question

The EV narrative has splintered along regional lines. In China, electrification for passenger cars and light commercial vehicles has reached what Klingelnberg describes as "maturity"—still growing, but at a sustainable pace rather than the frenetic expansion of recent years.

North America tells a different story. Nidec reports that "the full-EV rush has largely disappeared," with hybrids taking the lead as the practical choice for anyone outside major cities. GMTA sees "a reversal narrative." Helios notes that EV programs continue but timelines have stretched.

Perhaps more consequential than the policy shifts: the capacity question. Hollingsworth notes that electrification drove "many new projects post-COVID," but warns that "the volumes are not materializing as expected." Plants built for an EV surge that hasn't arrived may stall further capacity investment—or see resources reallocated entirely.

Europe occupies a middle ground—electrification proceeding, but on "slow burn," as Klingelnberg characterizes it.

For gear manufacturers, the message is clear: flexibility matters more than ever. The companies that bet everything on EV gearing may find themselves exposed; those maintaining capability across propulsion types are better positioned for however the market evolves. Micro-mobility presents its own opportunity—Klingelnberg expects that market to double by 2030, driven primarily by Europe and Asia.

AI and Digital Tools

Where survey respondents offered general skepticism about AI, machine tool makers reveal a wider spectrum. Klingelnberg represents the advanced end, with Daniel Meuris, head of digitalization and virtualization, describing deployment of "big data analytics extending to machine learning technologies and LLM agents," integrated into both internal processes and customer-facing products.

Most companies occupy more modest territory. Helios uses AI for communications support. Machine Tool Builders employs it for contracts, text editing, and reducing reporting burdens. Wegryn-Jones offers a characteristically grounded assessment: "All that AI is actually doing is duplicating what a stenographer would have done in 1960 or a copy editor in 1970 or perhaps an intern in 1980." That said, he acknowledges its spreadsheet capabilities are "remarkable, useful, and do save some significant amounts of time."

Which digital initiatives have delivered real returns? Gleason reports that closed-loop corrections and optimizations are "proven value adders," and its Fingerprint status monitoring solutions provide genuine value for predictive maintenance. Klingelnberg's Meuris observes an inverse relationship between complexity and clear ROI: simple connectivity technologies like MQTT or OPC UA deliver immediate value, while larger initiatives require longer horizons.

Hollingsworth sees condition monitoring as the clearest opportunity: "If you can plan your downtime, you reduce your downtime." The value proposition is straightforward—a moderate investment upfront against reduced unplanned stoppages.

Beyond analytics, Hollingsworth points to a quieter revolution: software has become "an equivalent IP aspect to machines as compared to the inherent mechanical design." The capabilities unlocked through software development, often on essentially unchanged hardware, now matter as much as the iron itself.

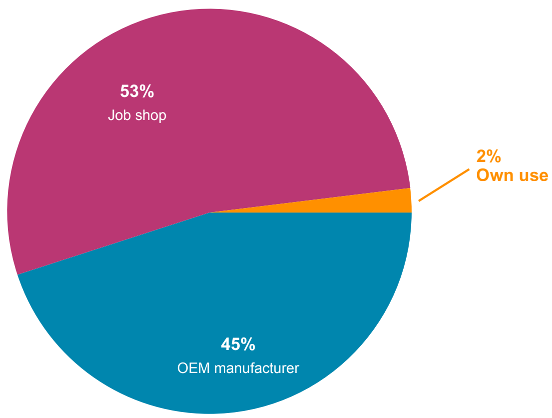
Helios offers a contrarian view on IIoT: it "had its moment," but tariff disruptions and industry uncertainty pushed those projects aside. AI has taken center stage because it delivers immediate, visible value. IIoT will return, but for now it's waiting in the wings.

The Workforce Puzzle

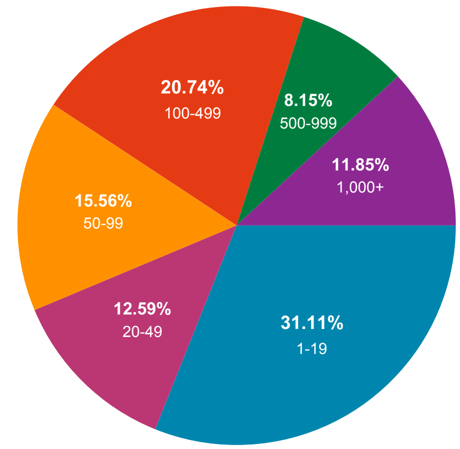
Companies are responding to the experience gap on multiple fronts. Klingelnberg has implemented dynamic digital manuals for manufacturing and assembly that incorporate operator feedback, preserving process knowledge in accessible form. The company's grinding assistant software embeds expert knowledge directly into the operator interface, supporting less experienced workers in setting up effective processes.

Liebherr has expanded remote support capabilities and developed modern training simulators. Helios maintains a pipeline through partnerships with local universities and technical schools, offering internships and part-time positions while documenting processes in digital formats that accelerate onboarding.

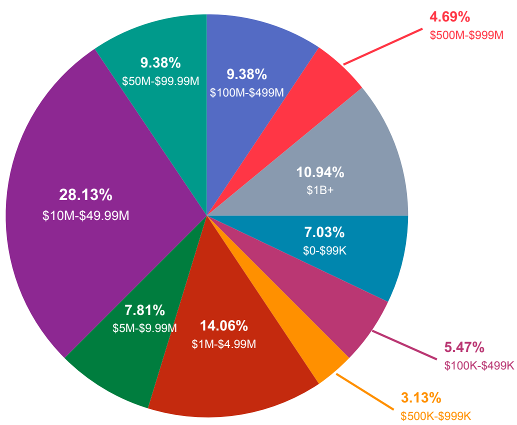
Gears (including splines, sprockets, worms and similar components) are manufactured at this location:



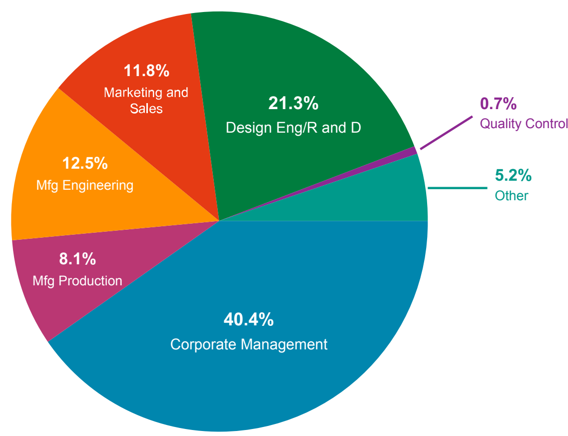
How many employees work at your location?



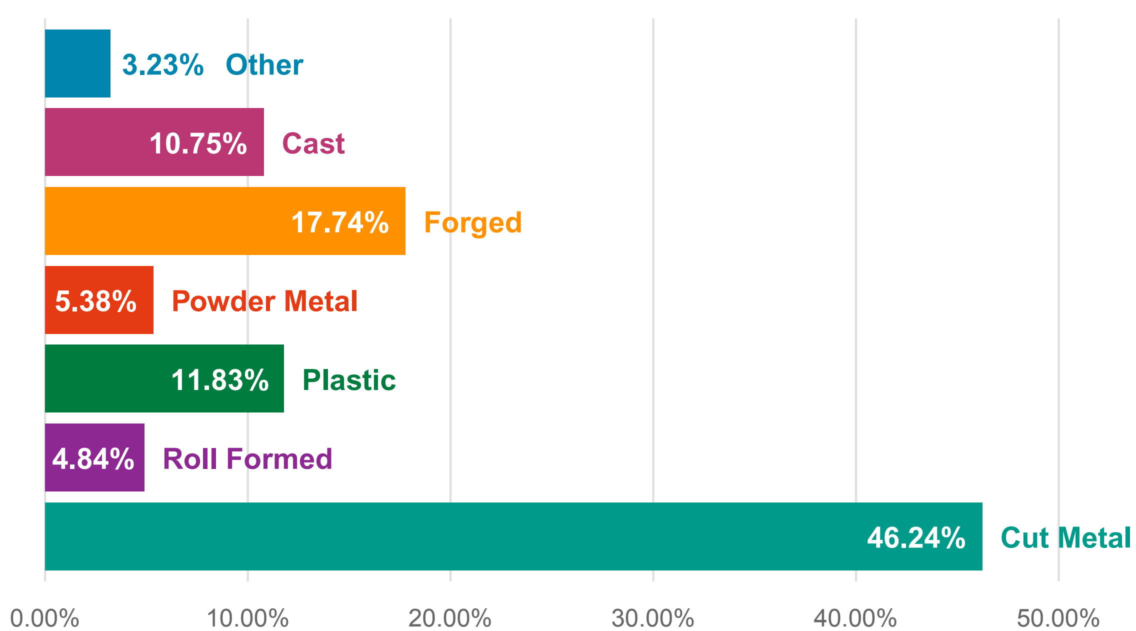
What is the approximate annual revenue for your company?



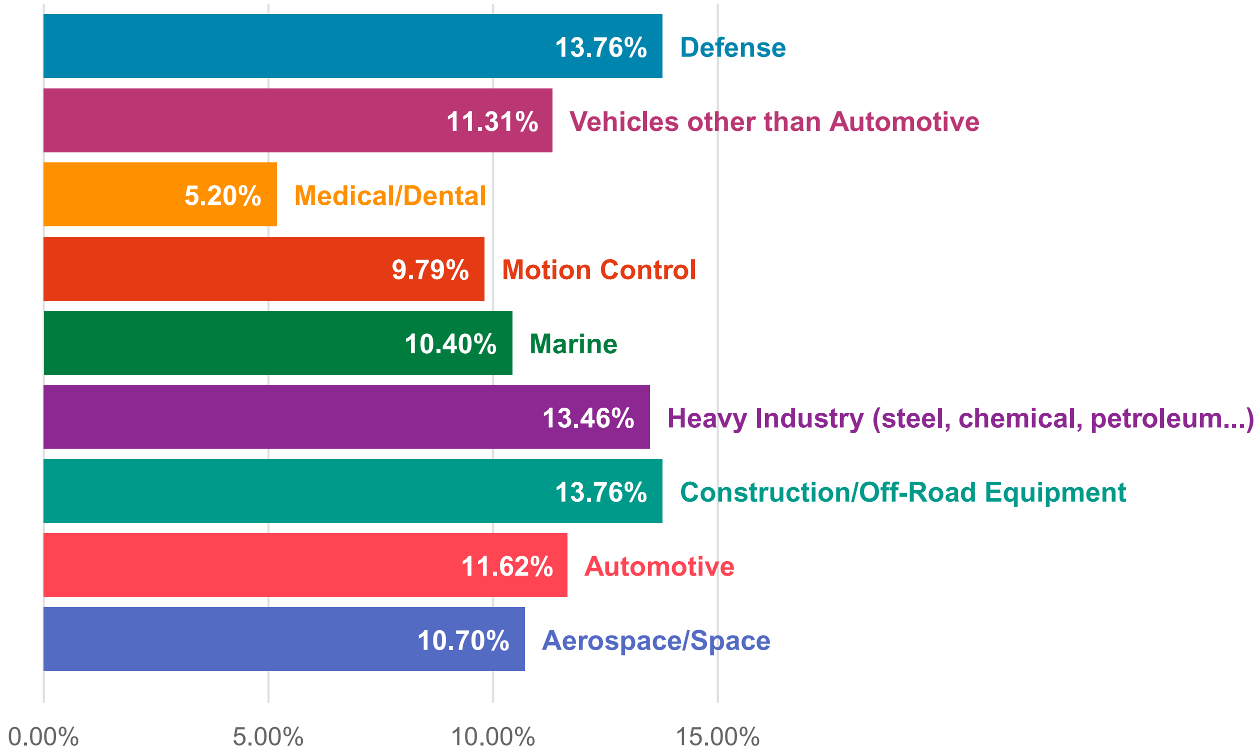
Which category best describes your job title/function?



The gears manufactured at this location are (Check all that apply):



The gears (including sprockets, splines, worms and similar components) made at this facility are used for (check all that apply):



Nidec takes a different approach: making machines themselves more intuitive. "If we can bake the expertise of a 30-year veteran directly into the software and the user interface," the company explains, "it makes the learning curve much more manageable for the next generation entering the trade."

GMTA's Hambleton sees reasons for optimism: "It is exciting to see more companies take the initiative and offer training, apprenticeship, and mentorship programs. Young people need other options to a four-year university degree."

Hollingsworth frames the challenge more bluntly. Germany's apprenticeship programs start young adults early in machine tool careers, but the deeper problem is cultural: "For many years manufacturing was given a negative connotation and tech was the 'pushed' career path in schools. We need to change the culture and perception in North America that manufacturing offers rewarding and successful career options." Training systems exist; the pipeline of people entering them does not.

Gleason's Perrotti connects workforce to strategy. When asked about reshoring, he redirects to what he sees as the prerequisite: "First you need a large enough, trained workforce. This needs to be the top priority to expand the industrial base."

Reshoring: Reality or Rhetoric?

On whether reshoring has translated into actual demand, opinions diverge. Klingelnberg's Fabian Wolf, CEO of the company's American operation, reports that reshoring "is translating into tangible demand in the United States, extending from component production through to the machine tool sector." But he qualifies this: the impact on specialized gear machine tools specifically has been limited, since relatively few gear manufacturers operate in the U.S.

Liebherr sees reshoring boosting overall machine tool demand without necessarily driving purchases of domestically built gear equipment. What is increasing: demand for localized support, service, and integration.

Machine Tool Builders' Wegryn-Jones says that while they "keep hearing about how reshoring is supposed to enhance domestic demand," it's difficult to trace any particular order to that cause. From his vantage point, "it's just strategic discussion." GMTA echoes this: "Demand has always been there, but the supply has not. A shift in global production takes a lot of time."

Hollingsworth is more direct: "No, I don't see that the tariffs will change where the machines are built, at least for the North America market." If anything, the pull is in the other

direction—Asia has been the largest consumer of machine tools for a decade, and builders may expand their footprint there to serve that volume.

Nidec frames the gap between aspiration and reality in economic terms: "Most companies value domestic production, but they aren't always in a position to pay a premium for it if the numbers do not align with their budget."

Competitive Imperatives

Machine tool design has evolved to address the workforce challenge directly. Automation-friendly configurations, tool changers, automatic closed-loop corrections—features that help customers operate effectively with less experienced staff, particularly on night shifts—have become priorities. Connectivity has moved from optional to essential.

Gleason's Perrotti notes a shift toward systems thinking: "We are now designing more with a systems mindset, not just a single machine or tool." Liebherr cites real-time monitoring and adaptive control as becoming core features. Machine Tool Builders reports strong customer interest in converting older manually operated machines to CNC operation.

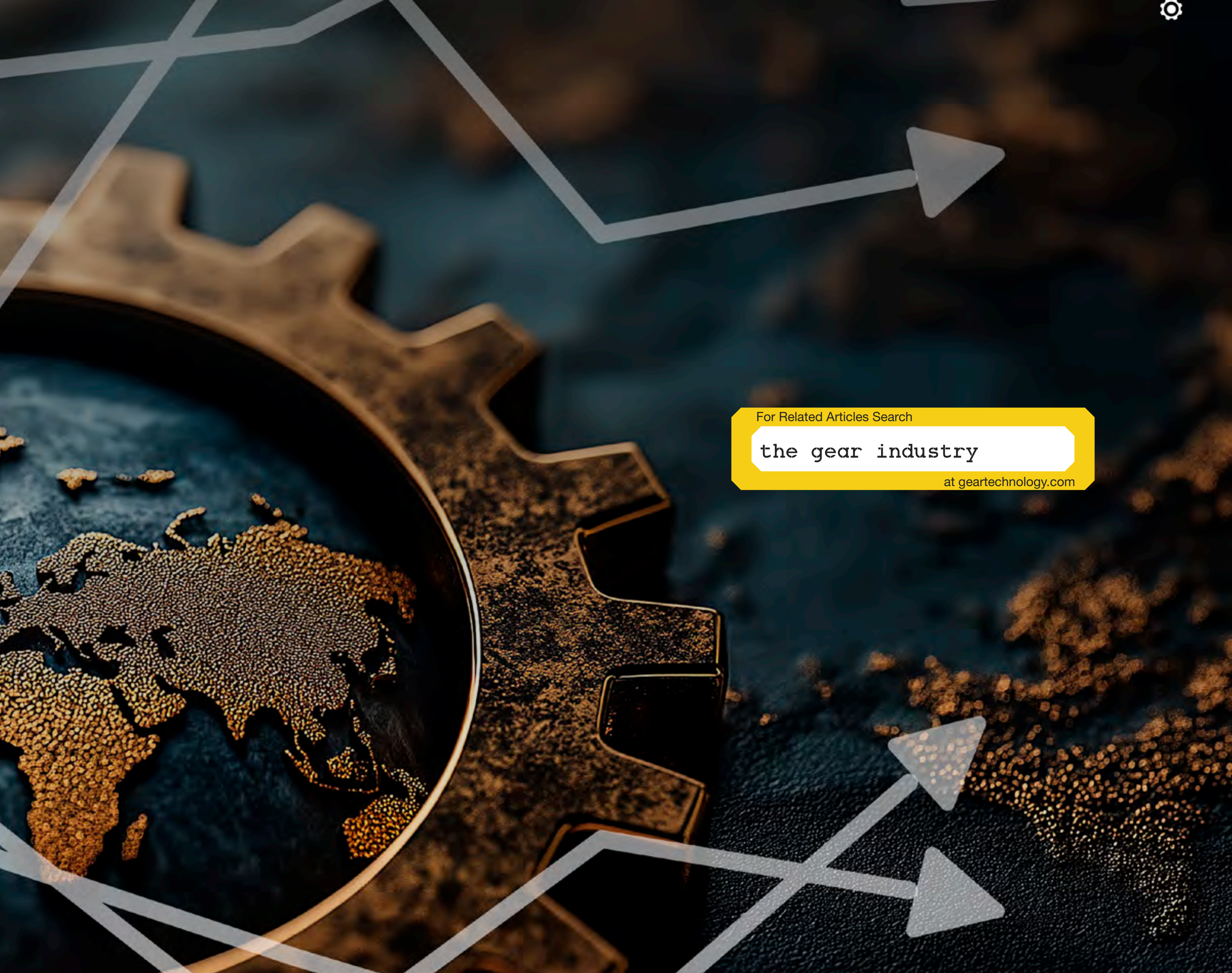
Asked what gear manufacturers must understand to remain competitive over the next five years, the responses converge on continuous investment. Nidec puts it directly: "If you wait until you're forced to upgrade, you've already lost. The shops that will be here in five years are the ones that treat technology as a tool for growth, not just an expense to be avoided."

Liebherr's Scholz argues that automation and Industry 4.0 "are no longer optional." Gleason emphasizes "investing in automated, intelligent systems with a strong partner to support your business."

Hollingsworth takes the long view: "Global competition, regardless of the tariff topic, is not going away and will continue to increase. We must continue to find opportunities to differentiate ourselves to be a world leader in gear manufacturing."

Wegryn-Jones offers counsel rooted in an older tradition: "Know thy market, know thy product, know thy capabilities, and don't take your hand off the tiller. And don't forget how to have a real conversation."

In an industry where tolerances are measured in microns and relationships in decades, both the technology and the wisdom matter.



¡Rápido!

With many of its precision gears produced in small lot sizes, Spanish gear producer Engranajes Juaristi S.L. depends on Gleason machines for exceptional speed and flexibility.

Xavier Vallsmadella, Regional Sales Manager, Gleason Sales Spain

Zarautz, Spain, might seem an unlikely place for a precision gear manufacturer. This beautiful coastal town in the heart of the Basque region is known for its beaches and considered among the top surfing destinations in the world. Surprisingly, the relaxed holiday atmosphere and laid-back surfer 'vibe' turn out to be highly conducive to the production of gears. It is here that you will find Engranajes Juaristi, a renowned gear producer, owned and operated for over 65 years by the Juaristi family. The company specializes in the production of high-precision external and internal gears up to 1,200 mm in diameter, as well as worm gear sets, spline shafts, and other transmission components for everything from wind turbines to tractors, machine tools to trains. Significantly, 30 percent of the many thousands of gears produced by Engranajes Juaristi annually are in lot sizes of just one, and the average lot size is just seven parts. It's a bold strategy that attracts business and gives them a competitive edge. It also requires machines that can deliver faster cycle times and more flexibility.

Doing More with Less

Over the course of the last two decades, Engranajes Juaristi has phased in a new generation of highly productive Gleason hobbing, shaping, and profile grinding machines, for which one of the company owners, Inigo Juaristi, general technical manager, and his son Jokin Juaristi, sales manager, take credit for much of their company's success. For example, two Gleason P400 hobbing machines and one P600/800 hobbing machine have replaced more than six older manual hobbing machines, eliminating countless hours of costly downtime once required for part changeover. "When any of the manual machines needed to be set up for a new part type, it usually tied up the machine operator for hours, thus bringing all the machines to a costly stand-

Gleason P600/800ES mid-size gear shaping machines with electronic helical guide for maximum flexibility.

The two P400 hobbing machines and the P600/800 hobbing machine eliminate countless hours of costly downtime.

still," explains Jokin Juaristi. "With the Gleason machines, this costly bottleneck is all but eliminated. Fewer machines are producing more parts faster, with less changeover time part to part."

Additionally, these hobbing machines are designed with highly accessible, ergonomically designed work areas with large operating doors to aid in manual part loading. The operator's task is further simplified with current Siemens controls and operator-friendly Gleason hobbing software, including support and service functions.

The machines are ideally suited as well to accommodate the widest possible range of workpiece types and sizes and have extended ranges for workpiece diameters and shaft lengths: axial slide travels of 600 mm on the P400 machines, and 1,000 mm on the P600/800 machine, for shaft applications.

The company also says that the machines have operated with exceptional reliability and minimal maintenance over the years. Robust guideways are standard, and the use of proven, reliable direct-drive work spindles or double worm gear table drives delivers the desired high precision cutting results.

New Business Shapes Up

It's not surprising, given Engranajes Juaristi's breadth of products, that shaping is a key capability. For internal gears and those that can't be hobbed efficiently, the company uses two Gleason P600/800ES gear shaping machines. Both machines feature an electronic helical guide–an additional CNC rotary axis–to replace the mechanical helical guides required in the older generation of shaping machines that these machines replace. In the past, the cutting of a new helical gear first required the expensive and time-consuming production of a mechanical guide used to produce the necessary helix by superimposing a rotary motion on the cutting stroke. Then, there was additional time needed to change guides for a new part. Now, changeover on the Gleason machines is done in minutes, via dialog-guided input on the Siemens CNC. All gear cutting, tooling, and part parameters, including the helix angle to be shaped, are entered, and the controller calculates all the necessary machine data and settings automatically. The machines are considerably more productive as well, featuring a backlash-free direct drive for the cutter spindle to deliver flexibility and operating ranges much greater than the previous conventional

Gear shaping tools designed and manufactured by Gleason.

Easy data input with Gleason hobbing software.

shaping machines. An extended stroke length using Gleason's optional shuttle shaping feature accommodates face widths of approximately 400 mm—well beyond what was previously possible. Finally, one of the machines is equipped with a B-axis, which enables an inclination of the column under CNC to produce tapered parts and improve quality when shaping parts made from high-strength steels.

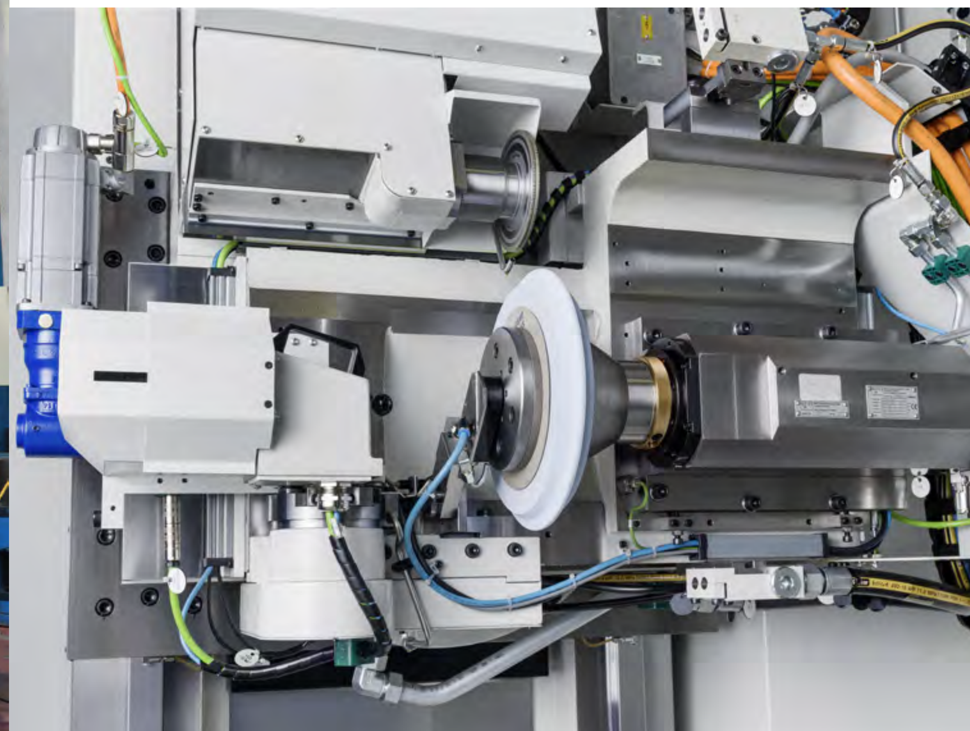
"The added capacity and faster changeover have opened the door to many new gear shaping opportunities, and jobs we couldn't have taken on with the older shapers," says Inigo Juaristi. "For example, we now use the machine with B-axis to produce an important cone-shaped part for a farm equipment application. This would not have been possible before."

Faster Finishing

Strong winds off the shores of Zarautz are good news for surfers, and for Spain's burgeoning windpower industry, which now ranks as the fifth largest by capacity in the world, and second in Europe behind Germany. Wind is Spain's largest and fastest-growing source of electricity. Engranajes Juaristi is keeping pace with this growth, and gears for wind turbines now represent 15 percent of its annual shipments. These gears are characterized by their high-quality requirements, thus enabling them to run smoothly, quietly, and with great reliability in even the harshest conditions.

Engranajes Juaristi uses two Gleason P600/800G Profile Grinding Machines to perform the critical hard finishing operations on external gears. One of the two machines has an extended axial travel of 1,000 mm, enabling the production of several important shaft-type parts for wind turbine gearboxes, such as sun shafts and high-speed pinions.

A one-piece machine bed with excellent stiffness and dampening is the foundation for these machines' high accuracy requirements. Excellent accessibility to the work area of the machine is achieved by doors that open wider and a counter support placed in the corner of the machine.



Gleason provides complete tooling solutions including grinding wheels and dressing tools.

Most importantly, the use of Gleason's proven HSK external grinding head guarantees maximum flexibility and, thanks to the HSK quick-change system, allows the use of different grinding wheel spindles for dressable and non-dressable CBN grinding wheels in a diameter range of 40–350 mm. This has enabled Engranajes Juaristi to take advantage of the latest developments in ceramic grinding wheels that, in just the last few years, have made dramatic reductions in finish profile grinding cycle times.

"It's a testament to the Gleason machines' design," says Jokin Juaristi. "The machines allow us to keep up with tooling innovations that make us more competitive. While we're just doing external gear grinding with these machines, we're now considering adding an internal gear grinding capability. These machines are easily adaptable." An internal grinding device can be added without removing the external grinding spindle. As a result, the machines can be configured to finish-grind a wide range of internal and external gears, as well as worms of all common types.

The machines also include integrated on-board gear measurement and the latest smart dressing technology, which reduces costly, time-consuming dressing time for initial or re-profiling of a grinding wheel. The innovative software function ensures that dressing only takes place on the necessary grinding wheel areas, thus saving time.

Localized Service and Support

Localized Gleason support has played an important role in helping Engranajes Juaristi transition its gear manufacturing from "mechanical to modern."

"It's gratifying to work with a company where ownership is so open to the possibilities of our new technologies," says Xavi Vallsmadella, regional sales manager, Gleason Sales Spain, who has supported Engranajes Juaristi throughout its 20-year modernization journey. "It's an example of how a small company, with the right technologies, can do big things."

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Gear Selection

Question: In your experience helping engineers select power transmission components, what is the most misunderstood concept in gear selection, and how would you explain it to a young engineer?

Brian Dengel

Expert response provided by Brian Dengel, General Manager, KHK USA Inc.

Entry-level engineers are at a disadvantage when selecting power transmission components due to their lack of education and experience. While attending an ABET-accredited engineering school, most students are only exposed to gearing during a single lecture in a course titled Mechatronic Design, which is just one course over their entire educational journey. If they participate in a Senior Project in Mechanical Engineering, they might need to draw on the basics covered in that single lecture. Beyond these two opportunities, recent graduates have next to zero knowledge of gearing.

When designing a gear system, there are various parameters that need to be considered. Many of the parameters are driven by the desired output of the gearing, and others are determined by the laws of geometry and physics. Choosing the proper gear based on these factors is critical to ensuring a reliable gear system.

The most misunderstood concept in gear selection is that the parameter of the size of the gear is not independent but dependent on other parameters, including the operating environment, the material makeup of the gear, the applied loading, the operating speed, and the design life.

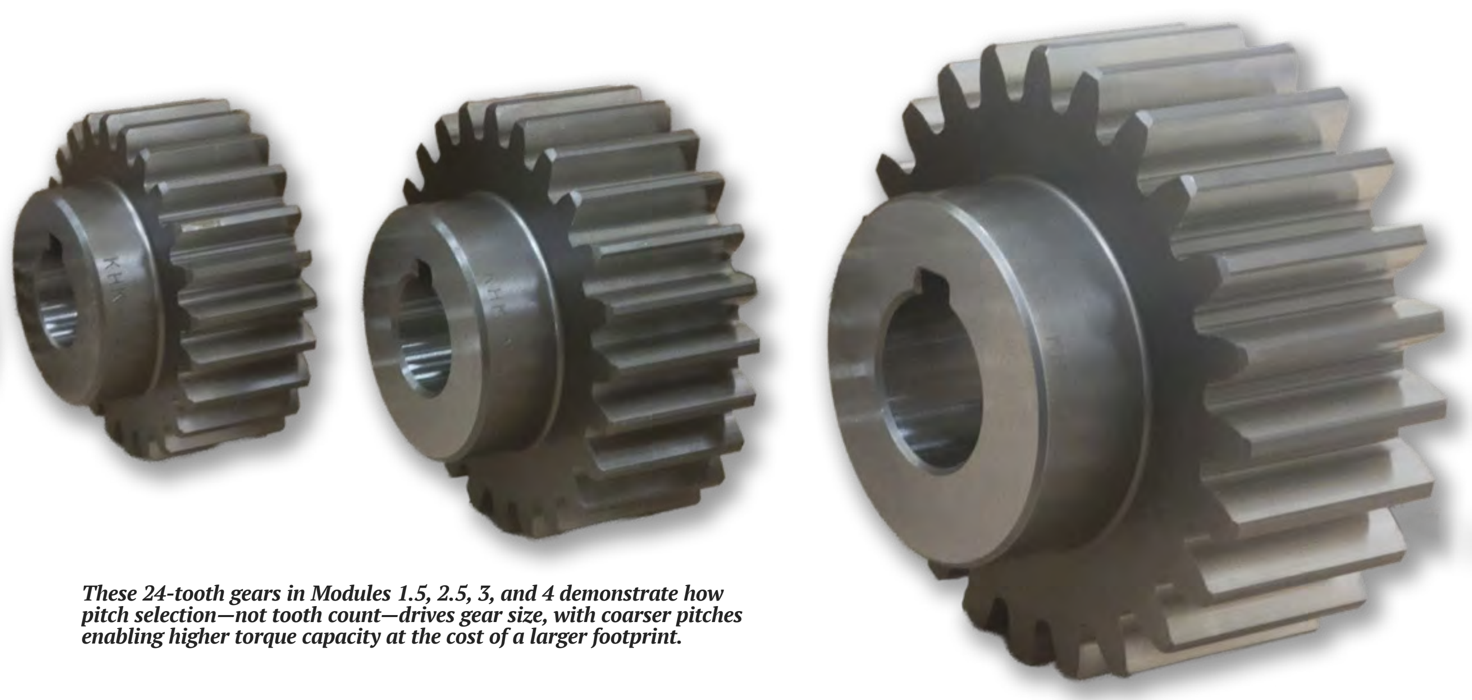
The first consideration that will drive the size of the gear is the environment in which it will operate. Is the gear going to operate inside an enclosure, or will it be exposed? Will it be used in an industrial environment, or a temperature-controlled environment, or will it be exposed to food, rain, dust, or the sun? If the gear is going to be inside an enclosure, then the size of the gear is limited to the interior size of the enclosure. Open gearing does not have this limitation.

The second consideration that will affect the size of the gear is the material. Does the gear need to be lightweight, or does it need to manage significant impact loads? Does the gear need to be washed down, or does it need to be nonmagnetic? Each of these considerations will lead to a different material choice. Lightweight gearing might be produced from aluminum or plastic. Gears in food environments that need to be washed down or gears that need to be non-magnetic will need to be produced from stainless steel. Gearing that is managing large loads most likely needs to be produced from alloy steel. As steel is three times stronger than aluminum and six times stronger than nylon, a gear made from steel can be one-third the size of an aluminum gear or one-sixth the size of a nylon gear and carry a similar load.

The other considerations that affect the size of a gear are the applied load, the operating speed, and the desired design life. As these three parameters are interconnected, the gear design will change proportionally as each is evaluated. The operating speed of a gear is dependent only on the input speed if it is the driver, and it is dependent on the speed ratio of the gear pair when it is the driven. The maximum allowable bending strength is dependent on the size of the gear, the applied load, and the desired design life. Since torque and speed are inversely proportional, a gear running at a speed of more than 10,000 rpm can only manage a small amount of torque, whereas a gear running at one rpm can withstand a much higher torque. If the design life is measured in minutes of continuous use, instead of months, then the maximum allowable torque due to surface failure can also be increased.

The final consideration for the size of a gear is the pitch. The pitch of a gear drives the formulas for size. A coarse pitch gear, such as a Module 4 spur gear with twenty-five teeth, will have a pitch diameter of 100mm and typically a face width of 40 mm. However, a medium pitch gear, such as a Module 1.5 spur gear with twenty-five teeth, will have a pitch diameter of 37.5 mm and typically a face width of 15 mm. If we normalize these two gears with both having a face width of 15 mm and both made from carbon steel with a design life of 40 weeks operating 40 hours per week, the Module 1.5 gear would have a maximum allowable bending strength torque of 26.7 Nm, but the Module 4 gear would have a maximum allowable bending strength of 189.8 Nm. These values show that the tooth size affects the load capacity when all other parameters are equal. However, the larger module gear has a significantly larger pitch diameter, which may not be suitable for the application.

Each of these parameters has an impact on the proper size for a gear that is best for the application. Young engineers need to understand that the size of a gear is an outcome of the needs of the application and not predetermined by the desire for the gear to be a particular size.



These 24-tooth gears in Modules 1.5, 2.5, 3, and 4 demonstrate how pitch selection—not tooth count—drives gear size, with coarser pitches enabling higher torque capacity at the cost of a larger footprint.

MPMA Creates New Emerging Technology Committee Focused on eVTOL

Mary Ellen Doran, VP, Emerging Technology, MPMA

Ted Angel, Executive Director of NAACME, speaks at the 2025 MPT Expo.

Electric Vertical Takeoff and Landing (eVTOL) aircraft are rapidly moving from concept studies to flight testing and early certification, driven by advances in electrification, autonomy, and lightweight materials. While often discussed in the context of urban air mobility (UAM), eVTOL development presents a wide range of engineering challenges that intersect aerospace, automotive, and industrial power transmission disciplines. MPMA is starting its fifth emerging technology committee to explore the driveline technology that propels the new class of air mobility. It will be called the Air Mobility Technology Committee, to keep the scope broad to new designs and new vehicles in this space.

While the first meeting of the committee was held in January of 2026, discussions began in 2025, culminating with an Aerospace Committee presentation at the Motion + Power Technology Expo (MPT Expo). Ted Angel is the executive director of the National Advanced Air Mobility Center of Excellence (NAACME). During his panel presentation, he discussed NAAMCE's collaborative space in Springfield, OH, that currently houses 15 tenants crossing the supply chain for air mobility from government entities to research, and suppliers to eVTOL makers, including JOBY. The facility has created an FFA-approved 225 square mile area where these vehicles can be tested up to 18,000 feet. They have even implemented their own Ground-Based Detech and Avoid system funded through an AFRL and ODOT partnership. They even have a Vertipad prototype and flight simulators. MPMA hopes to further the collaboration with NACCME.

MPMA will similarly evolve this committee to the development of its most recent Electric Vehicle Technology Committee: Study the technology, as information is available, with an emphasis on the use of gears and bearings to see how it advances and where novel concepts arise; monitor the industry to keep track of important players like JOBY, Archer, BETA Technologies, and others; and bring to the MPMA audience speakers relevant to this topic.

The association wants to provide information to its members, as electric motors used in eVTOL applications operate at high speeds and power densities, often exceeding those found in automotive or industrial systems. Gear reduction is frequently required to match optimal motor speed to rotor efficiency, placing strict demands on gear accuracy, surface durability, and thermal performance. Weight constraints drive the use of compact gearboxes, advanced alloys, and optimized tooth geometries, while reliability requirements push designs toward aerospace-grade safety factors and fault tolerance.

Thermal management is another critical challenge. Continuous high-power operation during takeoff and landing generates heat in motors, power electronics, bearings, and gears. Engineers must balance cooling effectiveness with weight and aerodynamic penalties, often using integrated thermal paths and multifunctional structural components.

The Air Mobility Technology Committee will also serve as a conduit for bringing knowledgeable speakers to the wider MPMA events, bridging the technology from emerging technology committee to networking events, the Fall Technical Meeting (FTM), and MPT Expo 2027. Through presentations, discussions, and shared research, the committee aims to provide members with timely insights into an industry that is moving rapidly toward commercialization.

As eVTOL technology continues to evolve, MPMA's new committee ensures that motion and power transmission manufacturers have a seat at the table to help shape understanding, readiness, and innovation in one of the most dynamic segments of aerospace development today.

Big Changes Coming for MPMA's 2026 Fall Technical Meeting

Courtney Carroll, Senior Manager, MPMA Technical Services

For over 40 years, MPMA (as AGMA) has hosted an annual technical conference, called the Fall Technical Meeting (FTM). It is the perfect forum in which to share new research and to disperse knowledge for the benefit of the gear and bearing manufacturing industries at a global level. These industries are faced with emerging trends and innovations that are challenging engineers to stay on course with cutting-edge technology to keep design, quality, materials, manufacturing, and analysis efficient. It is imperative that researchers and engineers communicate ideas with fellow experts in the field.

The 2026 FTM will take place October 5–7 at the Hilton Rosemont–Chicago O'Hare in Rosemont, IL. At the FTM, authors and presenters provide information on topics relevant to the gear and bearing industry. These may include subject matter related to: design and analysis; manufacturing and quality; materials, metallurgy, and heat treatment; operation, maintenance, and efficiency; and bearing or gear failure. Abstracts will be reviewed by members of the TDEC and chairs of the Emerging Technology Committees. Each presentation will have a Q&A portion for those gathered to exchange their ideas. Topics presented must be on relevant technical subjects that are original to the audience.

This year, we are excited to announce some big changes for FTM.

Dual-track format

In 2026, the FTM will expand into a dual-track format for the first time. The first track will maintain the traditional structure—featuring highly technical papers and presentations on new technologies, all peer-reviewed and indexed in Scopus.

The new second track will consist of presentation-only sessions focused on cutting-edge developments, innovative company solutions to market challenges such as case studies or technological advancements in manufacturing or inspection, and emerging technologies poised to influence the future of the bearing and gear industries.

Gears and bearings

Because the American Gear Manufacturers Association (AGMA) and the American Bearing Manufacturers Association (ABMA) merged to form the Motion + Power Manufacturers Alliance (MPMA) in 2025, MPMA is now the organizer of the Fall Technical Meeting – so both gear and bearing submissions are encouraged at this event. We are currently looking for abstracts to be included in the presentation-only second track.

Co-hosting with STLE

Another change for this year's FTM is that MPMA will be co-hosting with the Society of Tribologists and Lubrication Engineers (STLE). STLE is the premier technical society serving the needs of more than 15,000 individuals and 200 companies and organizations that comprise the tribology and lubrication engineering business sector. STLE has professional education, certification programs, publications, and events that allow members to stay ahead in the technology and science of the field.

One session in the presentation track will be dedicated to STLE-curated content. Attendees can expect presentations in alignment with the STLE trends report, based on the following topics: AI and Digitalization; Manufacturing; Thermal Management; Decarbonization; and Megalibrary.

STLE members and those in the tribology and lubrication industry are also encouraged to submit abstracts related to gearing and bearings for the presentation-only track. And, because networking is a main driver for many engineers to attend FTM, this will be a unique opportunity to network with tribologists and lubrication engineers, in addition to your fellow gear and bearing engineers.

We highly encourage you to submit a presentation abstract for this year's new take on the classic FTM. **The presentation abstract deadline is March 27, 2026.** Please see out website at *agma.org/event/2026-fall-technical-meeting/* for more details, or email *FTM@motionpower.org* with any questions.

Interchangeability of Gears

Dr. Hermann J. Stadtfeld

The following chapter is from Gear Technology Solutions *(The Gleason Works, 2025) by Dr. Hermann Stadtfeld. This is the first of four excerpts that have been provided to* Gear Technology *readers to offer a preview of the book's insights into bevel gear theory, design, and manufacturing.*

Exchange of One Member During Gearbox Service

Certain industries that apply large gears in earthmoving and mining equipment request the possibility to exchange a broken, damaged, or excessively worn gear member without replacing its mating member. At first, this appears to be contrary to good mechanical practices. However, these gears in question might have diameters of 500 mm to 2,000 mm and weigh, in some cases, several tons.

The weight and the waste of expensive material, including the value added on the way from a soft steel blank to the finished gear, are compelling arguments not to replace a perfectly good gear. Also, the additional repair hours and the required equipment can be very costly. If the mating member of the damaged gear shows no damage, such as cracks or excessive wear, then the exchange of a single member should be considered.

For Which Kind of Gears Can One Member Be Exchanged?

Couplings and clutches will allow a single member exchange if the mating member does not show any fretting or cracks.

Straight bevel gears can also be exchanged if they are, for example, standard Coniflex gears where the lead function is a straight line and the tooth contact is established by the pressure angle and a standard length and profile crowning.

Spiral bevel gears are more delicate to replace. Here, the cutter diameter, the spiral angle, and the manufacturing method have to match the original components. Face hobbing and face milling are not interchangeable with each other. Generated gears cannot be replaced with nongenerated (Formate) gears. In the case of face hobbing, next to the cutter radius, the number of cutter starts is identical to the original manufacturing method. In critical cases, the damaged gear must be measured with a coordinate measurement machine. The surface measurement results can be used to reconstruct the correct surface form by applying a reverse engineering approach. If the damaged member is too degraded to perform a good measurement, then the mating member must be disassembled and undergo an inspection measurement. Also, in this case, it is possible to create the damaged member with sophisticated computer software. However, in most cases, the latter is unrealistic.

Hypoid gears are, in general, not used for these large applications. It would be considerably more difficult to create a replacement pinion or gear for a hypoid design.

In face gear sets, it is easy to replace the cylindrical pinion. However, if the basic parameters of the cylindrical pinion are known, it is also possible to design and machine a replacement face gear.

The Procedure of Correct Replacement Gear Assembly

The wear of the pinion and gear will increase the backlash in a used unit. If the backlash in the new set is an amount of X, then before replacing a worn or damaged member, the backlash of the gearset should be measured on the outside of the ring gear as shown in Figure 1 (Ref. 1). If it is not possible to measure backlash due to the damage, then the backlash after replacing the damaged member should be adjusted to the maximum of the defined backlash range.

Adjusting the backlash at the time of replacing one member reduces the risk of root interference due to the wear step (see Figure 2) and small flank form changes on the member that is not replaced.

If there is a severe wear step between flanks and root fillet transitions on the member, which is not replaced, then the likelihood of an interference problem still exists. A severe wear step, as shown in Figure 2, can be detected visually or with a drawing pin.

To account for a severe wear step in the root of the undamaged member, the replacement gear must be topland chamfered to prevent interference between the topland corner of the replacement part and the wear step between the flank and root on the teeth of the new member. Topland chamfering is not a widely used standard practice for the case of single-member replacements. The consequence of not applying the service backlash and the topland chamfering is, in many cases, a repeated failure of the unit in question and a costly repeated repair. Topland chamfers, as shown on a pinion (top) and a gear (bottom) in Figure 3, should only have a width of 10 percent of the whole depth of the teeth and an angle that is about 30 degrees to the flank profile at the tip of the teeth. Curved tip roundings are even better than straight chamfers and are recommended if the provision of machining these is available. Rounded top-land corners have advantages over straight chamfers in the case of replacing damaged and worn gears.

Figure 1—Measuring the backlash of a bevel gearset.

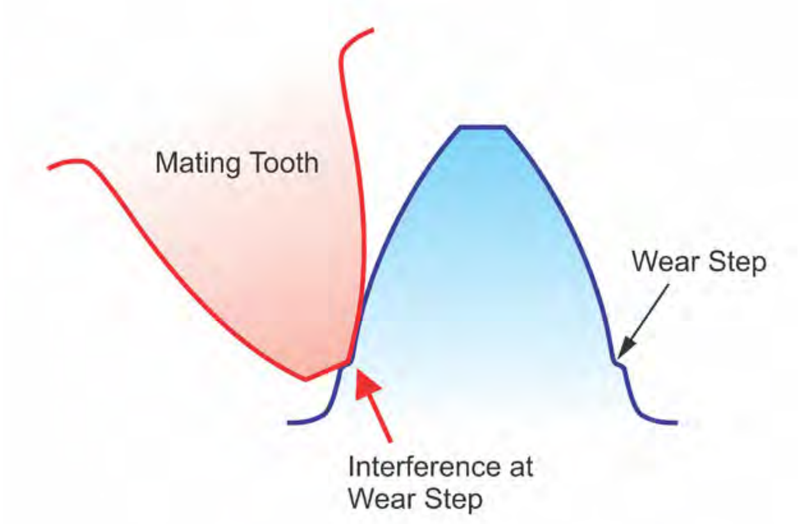


Figure 2—Wear step in the root of a used gear member.

Mixing Straight Bevel Gears Made with Two-Tool Generators and Coniflex Gears Made with Circular Cutters

The question if older straight bevel gears, manufactured with a two-tool generator, can be replaced by Coniflex parts, cut with a circular cutter, is "yes". The flanks are the same, and the differences are only at the root. If the correct build procedure (for new and old single-member replacements) is followed, then the flanks and the tooth tips never get to see the clearance area below the flank root transition of their mating member. The tooth tips only roll down to the wear step. Any complications due to wear-step interference are resolved by the application of topland chamfering.

Figure 3—Topland chamfer on a pinion (top), and on a gear (bottom).

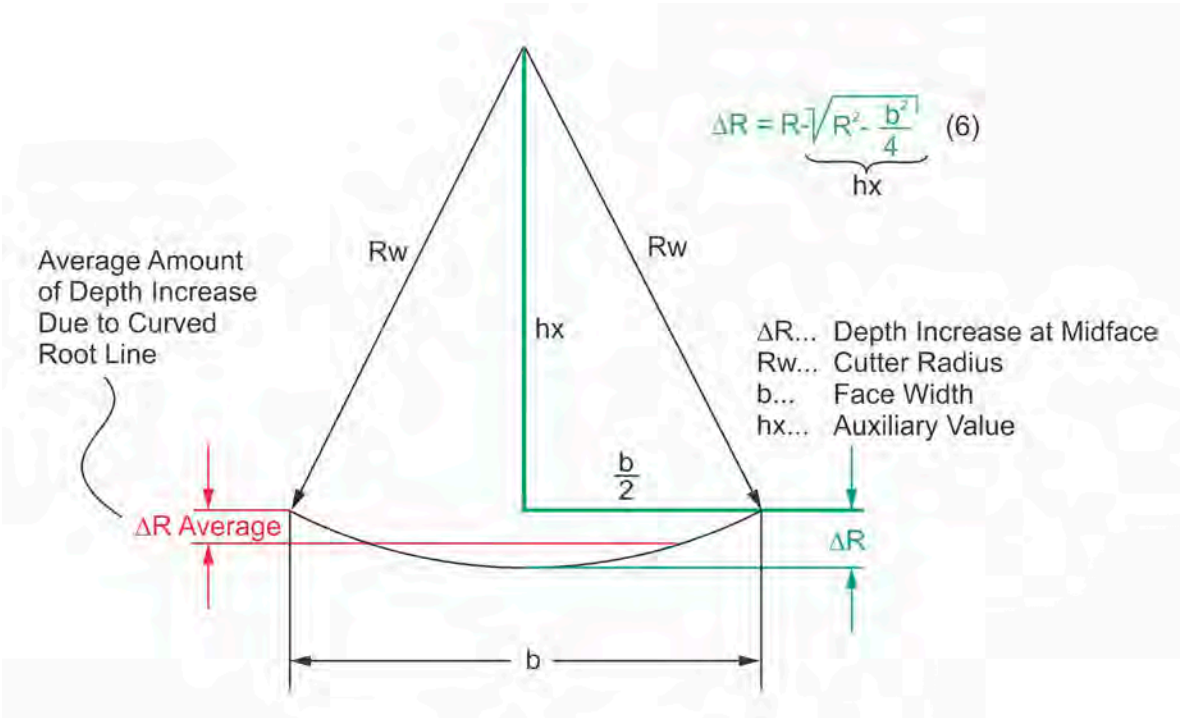


***Figure 4—Relationship between cutter radius, face width, and* ΔR.**

Strength of Coniflex Parts Made with Circular Cutters

Most applications where single gear members are replaced apply to straight bevel gears. For this reason, this section about strength comparison was added to this chapter. The question was raised whether the strength of a Coniflex pinion or gear may be lower than the strength of a gearset that was originally manufactured with a two-tool generator.

Regarding the comparison of Coniflex straight bevel gears, which have a curved root line with straight bevel gears with a straight root line, the following facts can be presented:

The curvature of the root line depends on the cutter radius, which results in a deeper tooth at the center of the face width. The calculation of the additional amount of root depth ΔR is explained in Figure 4.

Several industrial users of Coniflex straight bevel gears claim that they experienced a dam effect, which increases the moment of inertia in the tooth bending direction compared to a noncurved root line.

A second positive effect is caused by the hourglass shape of the root slot width. Not only is the tooth depth larger at midface, but also the tooth thickness below the flank working area increases by:

$$\Delta h = 2 * \Delta R * \sin\alpha \quad (1)$$

In the root bending stress calculation, the increase of root tooth thickness reduces the bending stress quadratic while the moment arm from the force application point to the root (due to the depth increase) only increases linearly. This shows in the root bending stress calculation (e.g., in a deflection beam calculation) as follows:

$$\sigma = M/W \quad (2)$$

$$M = F * l \quad (3)$$

$$W = b * h^2/6 \quad (4)$$

$$\sigma = F \cdot l/(b * h^2/6) \quad (5)$$

Whereas:

- α... Pressure Angle at Flank-Root Transition
- M... Bending Moment
- W... Section Modulus
- b... Face Width
- h... Tooth Root Thickness
- l... Force Application arm = Module
- F... Force
- σ... Root Bending Stress Calculated as Cantilever Deflection Beam

For example, the formal relationship in equations 1 through 8 applied to a straight bevel gear with a straight root, which has a module of 5 mm, a face width of 30 mm, and a root tooth thickness at the center of 7.5 mm, shows that for a force of 12,500 N, the root bending stress is equal:

$$\sigma = 12,500 \cdot 5/(30 * 7.5^2/6) = 222.21\text{N/mm}^2 \tag{6}$$

For a comparable Coniflex bevel gear with a root which is ΔR = 1 mm deeper at the center and 0 mm deeper at the ends, the following assumptions can be made:

Average value of deeper root over entire face = 60 percent of value at center (1 mm• 0.6=0.6 mm). Pressure angle at the stress critical 30-degree tangent is 30 degrees. The resulting root bending stress is equal:

$$\sigma_{\text{Coniflex}} = 12,500 \cdot (5 + 0.6)/(30 * [7.5 + 2 * 0.6 * \sin 30°]^2/6) = 213.38\text{N/mm}^2 \tag{7}$$

The comparison example in Equations 6 and 7 shows that the effect of taller tooth at midface and larger root tooth thickness at midface cancel each other out, such that the Coniflex straight bevel gear shows even some reduction of calculated root stress compared to the straight bevel gear with a straight root.

The limits of this principle are given by the fact that in the case of a too large curvature of the root line, the hourglass-shaped root width will cause the cutter to mutilate the opposite flank. The output of the *Gleason Straight Bevel Gear* software gives a warning in cases where this is critical. The rule is that the relation between face width and cutter radius should be below 40 percent to achieve optimal root geometry.

$$\text{Face Width/Cutter Radius} < 0.26(\text{ideal})0.4(\text{limit}) \tag{8}$$

40 percent of the radius of a cutter with 9 in. diameter is (4.5 in. or 114.3 mm) • 0.4 = 45.7 mm, which leads, in the case of a recommended face width of 33 percent of the outer cone distance, to a maximal ring gear diameter of about 275 mm. This dimension is close to the limit of Phoenix 275 or Phoenix 280 machines, where the maximal Coniflex cutter diameter is equal to 9 in., "which closes the circle" (Ref. 2).

Summary

This chapter explains which bevel gearsets, single members can be replaced. To replace single members, the following types of bevel gears qualify:

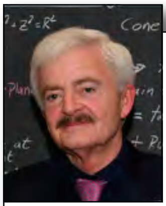
- Couplings and clutches
- Straight bevel gears
- Face gears

In the case of a single member replacement, the following criteria have to be regarded:

- The contact pattern has to be checked, it should be located centrally but slightly towards the toe
- The backlash should be adjusted to the backlash before the disassembly of the damaged gearbox. If this is not possible, then the maximal backlash of the given range for this design should be used
- In cases of severe wear steps between the flank and root transition, the toplands of the replacement member have to be chamfered
- Face gears can be exchanged like straight bevel gears; topland chamfering is required between center and toe if the cylindrical pinion shows a severe wear step

In the case of straight bevel gears, it was explained that a full exchangeability between straight bevel gears with a straight root line and Coniflex gears with a curved root line is given. However, the tooth contact must be adjusted to be away from the tooth boundaries.

It was also shown that the root bending strength of Coniflex gears is comparable or even slightly higher compared to straight bevel gears with a straight root line.



Dr. Hermann J. Stadtfeld is the Vice President of Bevel Gear Technology and R&D at the Gleason Corporation and Professor of the Technical University of Ilmenau, Germany. *Gear Technology Solutions* continues and completes his 2019 work, *Practical Gear Engineering.* Recently awarded a patent for MicroForm, the innovation marks his 70th patented invention.

References

1. Stadtfeld, H.J. "Bevel & Hypoid Gears: Measuring Backlash" *Gear Technology*, June 2014, Pages: 48–50.
2. Stadtfeld, H.J. "Practical Gear Engineering—Answers to common Gear Manufacturing Questions" Company Publication, The Gleason Works, Rochester, New York, 2019, ISBN 978-0-578-46376-6, Pages: 197–198.

Influence of Tooth Root Contour Deviations on the Tooth Bending Strength

Christian Eggert, M.Sc., Dr. Dieter Mevissen, Dr. Jens Brimmers and Prof. Dr. Christian Brecher

To meet the increasing demands for high-performance applications in power density, new material alloys and heat treatment processes for gears are constantly being developed (Refs. 1–3). The investigation and evaluation of different materials and heat treatments for gears is carried out using S-N curves (Refs. 2,4,5). However, when generating S-N curves for tooth bending strength, the influence of deviations around the tooth root contour is often not considered or recorded with insufficient accuracy, so that an identical tooth root contour is assumed for all variants (Refs. 2,4,5).

Due to the lack of a uniform evaluation standard for the tooth root area, the quality of test gears is usually evaluated only for the tooth flank area using ISO 1328 1:2013 (Refs. 6–10). Stress-increasing effects, such as changes in the tooth root radius due to deformations from the heat treatment, are therefore not considered (Refs. 2,4). In particular, when testing gears with an unground tooth root area, form deviations from the heat treatment and manufacturing deviations from gear hobbing around the tooth root have a direct effect on the test results. These deviations lead to a change in the occurring tooth root stresses and influence the tooth bending strength (Refs. 8,11–16). In the following study, the influence of manufacturing-related geometry deviations around the tooth root on the tooth bending strength is investigated.

State of the Art

Sufficient load carrying capacity of the tooth flank and the tooth root is a basic requirement for gear design as gear damage may lead to a total failure of the gearbox in the worst case (Ref. 17). For this reason, extensive knowledge of the material strength, the heat treatment combination and the occurring stresses in the application are of utmost importance, especially in the design process of high-performance gears.

Factors Influencing the Tooth Bending Strength

The tooth bending strength of gears is obtained by comparing the stress and load capacity around the tooth root (Refs. 14,17). Both stress and load capacity are influenced by various parameters, which, depending on their characteristics, can have a positive or negative effect on the tooth bending strength (Ref. 15).

Factors Influencing the Tooth Root Stress

In addition to the application and the associated load, the stress on a gear is determined by the design of the macro and micro geometry as well as the manufacturing process (Ref. 14). The normal pressure angle, as a macro geometric gear parameter, influences both the length of the bending moment arm and the length of the tooth root chord (Ref. 14). An increase of the normal pressure angle leads to a reduction of the bending moment arm as well as to an increase of the tooth root chord (Ref. 14). Based on the bending beam theory, which can be used to calculate the tooth root stress in a simplified way, a reduction of the bending moment arm leads to a reduction of the bending moment and therefore to a lower tooth root stress (Ref. 17). Increasing the tooth root chord also reduces the tooth root stress because it increases the area moment of inertia of the critical tooth root section (Ref. 18). The area of the critical tooth root section can be further increased by increasing other macro geometric gear parameters, such as the tooth width and the normal modulus, to reduce the tooth root stress (Refs. 14,18). Both the increase of the normal module, with otherwise constant gear parameters, and the increase of the gear width led to a larger area of the critical tooth root section and thus to a reduction of the tooth root stress (Ref. 14,18).

Another geometric factor influencing the tooth root stress is the tooth root contour (Ref. 14). The smaller the existing tooth root radius at the critical section, the greater the stress-increasing notch effect and thus the stress on the tooth root (Refs. 14,15). Taking this relationship into account, various studies have shown that by optimizing the tooth root geometry and leaving the tooth geometry otherwise unchanged, an increase in tooth bending strength of 10–30 percent can be achieved (Refs. 11,12,15,16,19). The optimization potential depends on the initial state of the tooth root geometry and the optimization method used (Refs. 11,12,15,16,19). Conversely, deviations from the specified tooth root geometry due to process variations or manufacturing errors can lead to a reduction in the tooth bending strength (Refs. 13,20).

Factors Influencing the Tooth Root Load Capacity

The load capacity of a gear describes the load limit up to which a gear can be operated without damage and is understood as the strength of the gear material against mechanical load (Refs. 21–23). The load capacity is determined by the selected gear material and the manufacturing processes used, including the process parameters (Refs. 4,5,10,24). A significant influence on the load capacity is the choice of the material and heat treatment combination, as this has a decisive influence on the material properties of a gear (Refs. 4,14,23).

The mean stress sensitivity is one of these material properties and describes the relationship between the fatigue limit stress amplitude and the mean stress present (Ref. 25). In general, the stress amplitude that can be withstood decreases as the mean stress increases (Ref. 25). In addition, surface-hardened components are more sensitive to mean stress in the tensile range than non-surface-hardened components (Refs. 25,26). Nevertheless, gears are usually surface hardened to provide a hard and high-strength surface that can withstand the tangential stresses in the tooth root area and the high pressures in the tooth contact area (Refs. 18,27). Inside the tooth, on the other hand, high ductility is required to withstand the load due to bending stresses and possible impacts (Refs. 18,27). Due to these requirements, case-hardened and nitrided steels are used for gears in many applications (Refs. 17,18).

Another material property is the notch sensitivity, which describes the property of a material to be sensitive to local stress increases due to changes in the shape of the component (Ref. 25). In this context, shape changes are any shapes with high local curvature ratios, such as undercuts in notches or the tooth root of gears (Refs. 14,18,25). Components with such shape changes, if they are made of a material with high notch sensitivity, have a lower load capacity than geometrically identical components made of a material with lower notch sensitivity (Ref. 25). Furthermore, notch effects can also be caused by the structure and condition of the component surface and lead to local stress increases (Refs. 17,18,27). The surface of a gear is determined by the final machining operation and depends on the selected process chain (Ref. 17). For non-ground tooth roots, the surface finish is already defined by the soft machining and the subsequent heat treatment (Refs. 17,18). Feed marks and enveloping cut deviations from soft machining can affect the tooth bending strength negatively due to the notch effect and promote crack initiation on the component surface (Refs. 17,18).

In shot peened gears, the location of crack initiation moves from the surface to the interior of the component due to the high compressive residual stresses near the surface (Refs. 10,28). Crack initiation usually occurs there due to the local stress increase at flaws, i.e., defects in the basic structure, such as non-metallic inclusions (Refs. 10,28). With continued loading, the crack initiation phase then transitions to the crack growth phase, ultimately leading to damage and failure of the application (Ref. 28). Typically, sub-surface damage only occurs at higher numbers of load cycles, in the so-called very-high cycle fatigue (VHCF) and ultra-high cycle fatigue (UHCF) range (Refs. 10,28). Therefore, high-purity steels are used in applications with high load cycles, such as in aircraft engines and rolling bearings, to reduce the number of defects and thus the possibility of crack initiation (Ref. 5).

Procedures for Determining the Tooth Bending Strength

Various procedures and methods can be used to determine the tooth bending strength, some of which differ considerably from each other due to their type and the required effort (Refs. 6,9,14,17,29). One possibility is to carry out experimental investigations in the form of operational and analogue tests to investigate the load capacity (Ref. 17). The tooth bending strength of the tested gears is then derived from the experimental results and the consideration of the occurring tooth root stresses, which can be measured or determined using various calculation methods (Refs. 14,17).

Operational and Analogy Tests

In the industrial environment as well as in the field of research and development, different test rigs are used to test gears and gearboxes. For the investigation of the tooth bending strength, the test rig concepts of the running and pulsator test have prevailed, as they are more economical and ecological than testing on the final product or components of the final product (Ref. 17).

For investigations of the tooth bending strength, the analogy test in the pulsator test rig, also called pulsator test, is often used, since the costs, the time, and the complexity of the investigation method are reduced compared to the running test (Ref. 17). Another advantage of the pulsator test is the decoupling of the variable meshing conditions in the tooth contact, which reduces the number of influencing variables and sources of error on the determination of the tooth bending strength of gears (Ref. 17). This makes it possible to carry out investigations on the fundamental influences of the material and process chain selection as well as the gear geometry on the tooth bending strength (Ref. 17). Due to the changed contact conditions, a conversion factor of $f_{corr} = 0.9$ must be considered for the transferability of the pulsator results to the running test (Refs. 17,30).

Procedures for Calculating the Tooth Root Stress

The term tooth root stress means the maximum local principal stress or tangential stress in tooth height direction at the surface of the tooth root (Refs. 14,17). The calculation of the tooth root stress is usually carried out at the location of the 30-degree tangent around the tooth root, since simulative and experimental studies have shown that the damage-critical stress around the tooth root occurs there (Refs. 14,17,18). The standard procedure for calculating the maximum occurring tooth root stress is the application of standardized procedures, such as ISO 6336 3:2019 (Ref. 14). Since these standard calculation methods are analytical methods based on conventions and abstractions, a comparatively fast calculation of the maximally occurring tooth root stress is possible (Ref. 17). In the following, the procedure of tooth root stress calculation according to ISO 6336 3:2019 method B is explained first and then higher-order calculation approaches, such as the finite element method (FEM) are discussed (Refs. 14,17).

The tooth root stress calculation of the standardized method of ISO 6336 3:2019 is based on the bending beam theory (Ref. 14). Based on this approach, the various factors influencing the tooth root stress are considered with the help of correction factors (Refs. 14,31). These correction factors can be determined using different methods, whereby method B of ISO 6336 3:2019 is frequently used due to the quality of the results and the ease of application (Refs. 10,17,18,32). The basis of calculation method B is the determination of the occurring nominal tooth root stress σ_{F0-B} (Ref. 14). The nominal tooth root stress σ_{F0-B} denotes the maximum local principal stress (tangential stress) in the tooth root area for a flawless gear under static load by means of nominal torque (Ref. 14). The outer point of single tooth contact is used as the point of application of this load for the stress calculation in the running test (Ref. 14). At this point, the nominal torque is transmitted by only one tooth and the bending moment arm of the force application point to the tooth root has the maximum value around single tooth contact (Ref. 14).

With the help of higher-quality calculation methods, such as FEM, the locally occurring tooth root stresses on entire gears can be calculated, taking into account the real gear geometry (Ref. 17). Due to the high calculation effort as well as the required pre- and post-processing for the determination of the relevant results, general commercial FE programs are usually not used for gears (Refs. 17,32). Tooth contact analysis programs specialized for gears simplify this process for the user (Refs. 17,32). Furthermore, due to the combination of analytical calculation methods with the FEM, the required calculation effort can be reduced in FE-based tooth contact analysis, so that extensive variant simulations for micro geometry optimization are possible (Refs. 17,32).

Tolerancing of Gears

Geometric deviations from the designed nominal contour of a gear due to tool wear and process variations during manufacturing can affect the tooth root and tooth flank load capacity. This influence must be considered in the design process with the aid of quantitative manufacturing tolerances to ensure that the manufactured gears meet the required specifications. Due to different geometric conditions and special features, a classic distinction is made between the areas of the tooth flank and the tooth root (Ref. 17).

ISO 21771:2007 provides the basis for tolerancing the tooth flank of involute gears (Ref. 33). It contains clear definitions and specifications of the various gear parameters and explains the geometric and mathematical relationships between them (Ref. 33). In addition to the macro geometric parameters of a gear, the various flank modifications are also described and explained (Ref. 33). Based on this, ISO 1328 1:2013 introduces an ISO tolerance classification system, which enables an objective evaluation of manufactured gears based on defined measured variables and permissible tolerance limits (Ref. 7). The gear quality is differentiated with the help of eleven tolerance classes IT1 to IT11, whereby IT1 denotes the lowest tolerance range and thus the highest quality and IT11 the lowest manufacturing quality with the largest possible tolerance range (Ref. 7). The application guidelines ISO/TR 10064 1:2019 and VDI/VDE 2612 supplement the IT classification system with information on measurement methods, measuring devices and the evaluation and interpretation of the measurement results [34,35]. The standardization of the flank tolerance creates a common basis for gear manufacturers and gear buyers, which enables a uniform conformity assessment of gearing in the area of the tooth flank (Ref. 7).

For the area of the tooth root, no standardized assessment basis or IT classification system has yet been created (Refs. 8,11). Due to the lack of a standard, only the tooth root diameter is usually tolerated in production drawings of gears and sometimes supplemented by the specification of a minimum tooth root radius (Refs. 8,11). On the one hand, this gives gear manufacturers great freedom in designing and optimizing the tooth root contour to increase the tooth bending strength (Ref. 8). However, this freedom also bears the risk that the tooth root contour is neglected during quality control and that unwanted tooth root fractures occur in the application due to manufacturing deviations (Ref. 8).

Objective and Approach

The state-of-the-art shows that a large number of parameters influence the tooth bending strength of a gear. One of these influencing variables is the tooth root geometry, which can significantly increase or decrease the tooth bending stress depend-

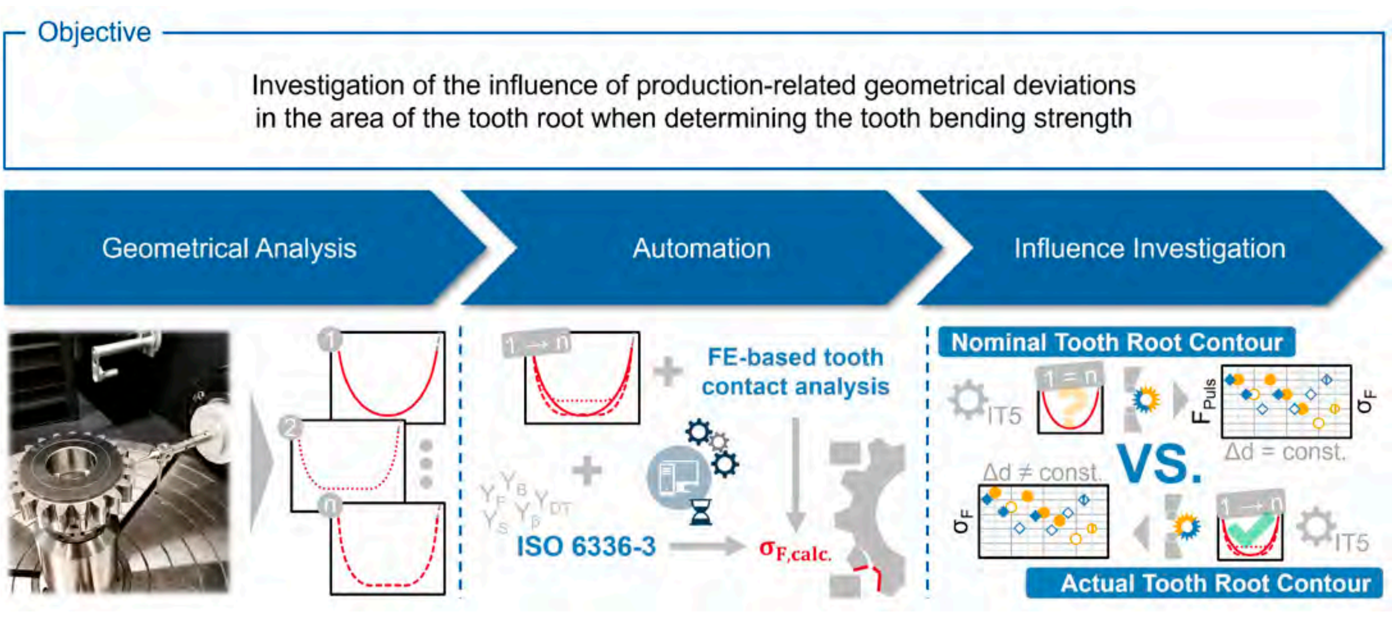


Figure 1—Objective and approach.

ing on its characteristics (Refs. 8,11,15). Nevertheless, there are no uniform evaluation standards for tolerancing the tooth root contour. As a result, only the tooth flank is usually considered in the quality control of gears and classified with the help of ISO 1328 1:2013 (Ref. 7). A missing or insufficiently precise quality control for the area of the tooth root can lead to uncertainties in the application as well as in the performance and evaluation of load capacity tests. For this reason, this study aims to investigate the influence of production-related geometric deviations in the area of the tooth root when determining the tooth bending strength (see Figure 1).

The first step is to measure the manufactured tooth gap contours—space between two adjacent teeth—and then analyze the production-related geometric deviations around the tooth root. In addition to recording manufacturing deviations due to tool wear and process variations, the analysis is also used to investigate the distortion in the tooth root area for different material and heat treatment combinations. Based on the geometry analysis, the tooth root stress calculation is automated, considering the measured tooth gap contours. This allows the calculation of actual tooth root stresses to be considered when performing and evaluating pulsator tests to determine the tooth bending strength. The automation includes both the stress calculation according to ISO 6336 3:2019 and the possibility to calculate the tooth root stresses using the FEA-based tooth contact analysis FE-STIRNRADKETTE (STIRAK) (Ref. 14). A uniform tooth root stress calculation procedure is required for the investigation of several variants with different production-related geometry deviations and is currently not sufficiently standardized to ensure comparability of the results and to avoid errors in the evaluation. The automated tooth root stress calculation is then used to investigate the influence of manufacturing geometry deviations on the tooth root stress and the effect on the determination of the tooth bending strength.

Analysis of Production-Related Geometry Deviations

The following section describes the results and findings of the geometric analysis carried out. To classify the results of the geometry analysis, the test gears examined and their differences are presented. The subsequent measurement of the tooth gap contours of all gear variants is used to determine the respective production-related geometry deviations for each variant and to compare the deviations of the individual variants with each other.

Test Gears—Variation of Material and Heat Treatment

The test gears considered in the following are part of a research project aimed at investigating the gear load capacity of different material-heat treatment combinations at an operating temperature of 180°C (see Figure 2). The gears being measured and tested are spur gears with a normal module of m_n = 5 mm and a normal pressure angle of α_n = 20°. The gears each have z = 21 teeth and a tooth width of b = 20 mm. The flank modification of the gears includes a tip relief of C_a = 90 µm and starts at a diameter of d_{Ca} = 114.3 mm.

Due to the focus of the research project, the investigated variants differ in terms of the used material and the applied heat treatment (see Figure 2). However, the other steps in the manufacturing process chain were identical for all variants. In the first step, the gear blanks were made from the material supplied as round steel and then turned to the required dimensions. This was followed by precutting in the hobbing process using the same process parameters for all variants. The subsequent heat treatment was varied according to the different specifications. The heat treatment was then followed by hard finishing, which involved the profile grinding of the gear tooth flanks. The tooth root was not ground during this process. Finally, the gears were shot-peened and superfinished to further increase the tooth bending strength. Subsequent

Figure 2—Test gears—variation of material and heat treatment.

roughness measurements around the tooth root showed that, due to the superfinishing process, all examined variants had a comparable surface roughness.

In this study, five of the thirteen variants of the research project are examined in more detail. The first two variants are made from 20MnCr5 and have been surface hardened using two different heat treatment processes. The first process is gas carbonitriding with oil quenching, followed by tempering at a tempering temperature of T = 250°C. The second heat treatment is low-pressure carburizing with high-pressure gas quenching, followed by salt bath heating (GS540) and a final tempering at T = 190°C. For the third variant, Hybrid55 (X20NiCrAlMoV6-5-2-1) was used, and the gears were carburized and then plasma nitrided. The gears of the fourth variant are made of Ovako497 (42NiSiCrMo8-7-3) and were produced by a low-pressure carbonitriding process with high-pressure gas quenching and subsequent tempering at T =210–250°C. To produce the fifth variant, the used material was M50NiL, and the heat treatment of the test gears was gas carbonitriding in a double hardening process.

Production-Related Geometry Deviations

To analyze the production-related geometric deviations, it is necessary to record the manufactured tooth contours of all five variants as accurately as possible. The necessary measurements were carried out using a Klingelnberg P16 tactile precision measuring center. The required nominal tooth gap contour was created using the FE-based tooth contact analysis based on the tool reference profiles of the soft and hard machining processes. Using this nominal contour, the tactile precision measuring center can measure the manufactured tooth gap contours and determine the deviation between the specified nominal contour and the manufactured tooth contours. The tooth gap contours were measured for all teeth of the five variants that will be loaded in the pulsator during the testing. Since four pulsator tests with two clamped teeth each can be carried out on every test gear, eight tooth gaps per gear have been measured. The tooth contours were always recorded as a 2D line in the center of the tooth width. This allows the actual tooth root stresses to be considered in the subsequent evaluation of the fatigue tests. In addition, the measurement results can be used to analyze production-related geometry deviations, both within a variant and between the different variants.

The results of the tooth gap contour measurements carried out to investigate the geometry deviation within a variant are shown in Figure 3 as an example for variant II (20MnCr5 bainitization). Looking at the entire gap contour, the measured mean gap contour of variant II is in good agreement with the nominal contour (see Figure 3—top center). However, closer examination of the gap contour in the tooth root area shows that the median gap contour in the tooth root area is below the nominal contour (see Figure 3—right). For a better classification of the deviations, the distance in normal direction Δn_{Dev} between the nominal contour and the measured contour, also called the actual contour, was calculated for each measuring point of all measured gears. Since the tooth flank area was ground during hard finishing without machining the tooth root area, the evaluation of the production-related geometry deviations is carried out separately for the tooth flank area and the tooth root area (see Figure 3—bottom center). The box plot shows that the interquartile range IQR of the normal distance between the nominal and actual contour for the tooth root area ($IQR_{II,root}$ = 24.6 µm) is significantly larger than that for the tooth flank area with $IQR_{II,flank}$ = 4.3 µm. As the interquartile range is the difference between the 75 percent and 25 percent quantiles, it can be concluded that the geometry deviations are significantly more scattered in the root area than in the flank area. This difference in the tooth flank area results from the removal of the grinding allowance, which compensates for any deviations from tool wear during the hobbing process or distortions from heat treatment. However, there is no correction for this deviation in the tooth root area because, as in many applications, the root has not been ground. This results in a median geometry deviation of $\Delta n_{Dev,root,median}$ = -11.5 µm for the tooth root area. However, an evaluation of the minimum and maximum normal distance is not possible because

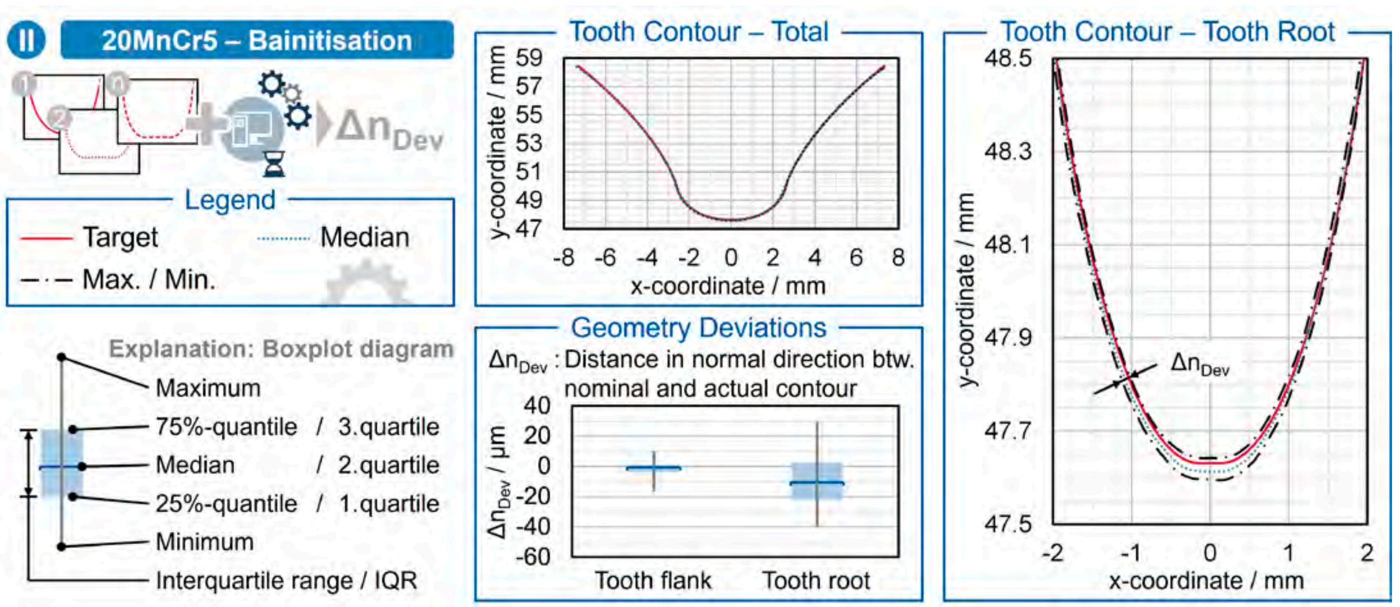


Figure 3—Comparison of production-related geometry deviations within a variant.

measurement outliers due to contamination in the measurement process, for example, due to dust, cannot be excluded. However, for the sake of completeness of the geometry analysis, the scatter range between the minimum and maximum normal distance is plotted in the box plot diagram (see Figure 3).

In the following, the production-related geometry deviations between the variants I to V are presented. For the sake of clarity, only the mean tooth gap contours of the five variants are shown in Figure 4. Looking at the median gap contour, there is no difference between the variants (see Figure 4—top center). However, a closer look at the tooth root area shows that the median root contour of variant IV (Ovako497) and variant V (M50NiL) clearly deviates from the nominal contour and the other variants (see Figure 4—right). The root diameter of variant IV ($d_{F,IV}$ = 95.44 mm) is $\Delta d_{F,IV}$ = +174 µm above the root diameter of the nominal contour ($d_{F,nominal}$ = 95.26 mm). variant *V*, on the other hand, has a root diameter of $d_{F,V}$ = 95.13 mm, which is $\Delta d_{F,V}$ = -133 µm smaller than the nominal contour. The deviations of the other three variants are smaller in comparison. The tooth root contour of variant III (Hybrid55) shows the highest agreement with the nominal contour.

The box plot diagram, which shows the normal deviation distances of all measurement points in the tooth root area from the nominal contour, confirms these findings (see Figure 4—bottom center). It can also be seen that the scatter of the normal deviation distances varies with each variant. The lowest scatter in the root area is found for variant I with IQR_I = 14.1 µm and variant IV with IQR_{IV} = 13.0 µm. In comparison, the interquartile ranges of the other variants are IQR_{II} = 24.6 µm, IQR_{III} = 27.9 µm, and IQR_V = 21.9 µm. As the manufacturing process chain of the variants differs only regarding the applied heat treatment, it is reasonable to assume that the deviations are due to this difference. However, the influence of the hobbing process cannot be excluded, as no tooth contour measurements were made between soft machining and the heat treatment process. Therefore, for future studies focusing on the identification of the process step with the greatest manufacturing variation, it is recommended that the tooth root geometry be recorded after each manufacturing step.

Automated Tooth Bending Stress Calculation with the Consideration of Measured Tooth Gap Contours

Based on the geometry analysis carried out, the following section presents a procedure for the automated tooth root stress calculation, considering the measured tooth gap contours. The automation includes both the stress calculation according to ISO 6336 3:2019, hereafter referred to as the standard-based method, and the possibility of calculating tooth root stresses using the FE-based tooth contact analysis STIRAK (Ref. 14). The automation allows a reproducible and consistent calculation of the actual tooth root stresses when performing and evaluating tooth bending strength tests on the pulsator. A consistent stress calculation procedure is essential when investigating multiple variants to ensure comparability of results and avoid errors in the interpretation.

As input variables for the automatic tooth root stress calculation, the results of the gap contour measurements, an input file of the test gears for the FE simulation program, and the pulsator forces for the pulsator tests are required. All three input data are used for the stress calculation according to ISO 6336 3:2019 and for the FE simulation. Figure 5 shows the procedure for the standard-based tooth root stress calculation. In addition to the known macro geometric gear parameters, such as normal module, normal pressure angle, number of teeth, and some other parameters, the actual manufactured root diameter and tooth root radius, as well as the generating profile shift coefficient used to machine the tooth gap contour, are required to perform the stress calculation. Therefore, the first step is to create a hypothetical manufacturing tool that could theoretically produce a measured root gap contour in one operation. The data of the manufacturing tool in the input file is used as a starting value for the iteration of the hypothetical manufacturing tool. If the data is a protuberance tool, only information describing the basic rack profile of a simple production

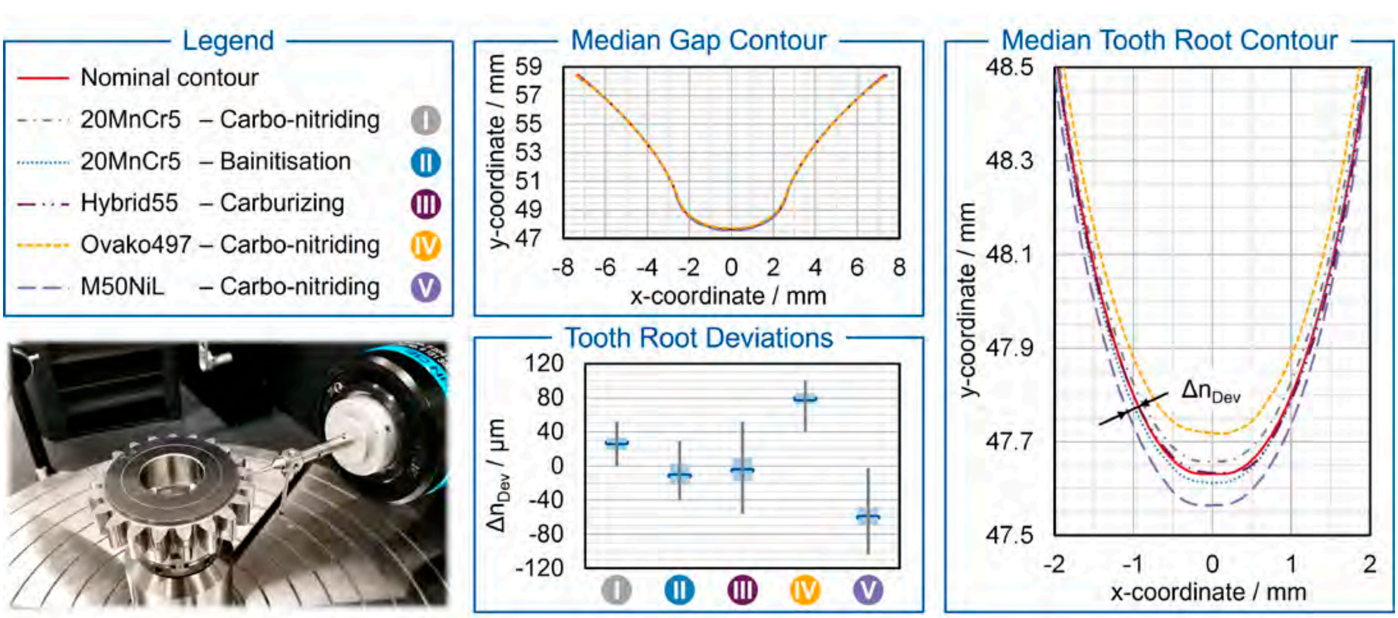


Figure 4—Comparison of production-related geometry deviations between the variants.

tool is considered, such as the reference profile angle, the addendum coefficient, the dedendum coefficient, and the tool tip corner rounding coefficient. The start value for the tool tip corner rounding factor is set to $\rho_{aP0,Start}$ = 0.05, regardless of the used basic rack profile, to ensure that the basic rack profile of the hypothetical manufacturing tool is generated and to avoid a tool tip that is far from reality. The iteration then starts with a stepwise adjustment of the generating profile shift coefficient in order to fit the generated FE-based contour to the measured contour in the area of the tooth flank. The fitting quality is assessed using the median normal distance deviation $\Delta n_{Dev,median}$ between the two curves in the tooth flank observation area (see Figure 5). The addendum coefficient of the hypothetical finished gear tool is then adjusted using Equation 1.

$$h^{*}_{aP0,new} = h^{*}_{aP0,old} + \frac{d_{F,FE-based} - d_{F,actual}}{2 \cdot m_n} h^{*}_{aP0,new} = h^{*}_{aP0,old} + \frac{d_{F,Stirak} - d_{F,actual}}{2 \cdot m_n} \quad (1)$$

where

h^{*}_{aP0}	is addendum coefficient
$d_{F,FE-based}$	is tooth root diameter of the FE-based contour
$d_{F,actual}$	is tooth root diameter of the actual contour

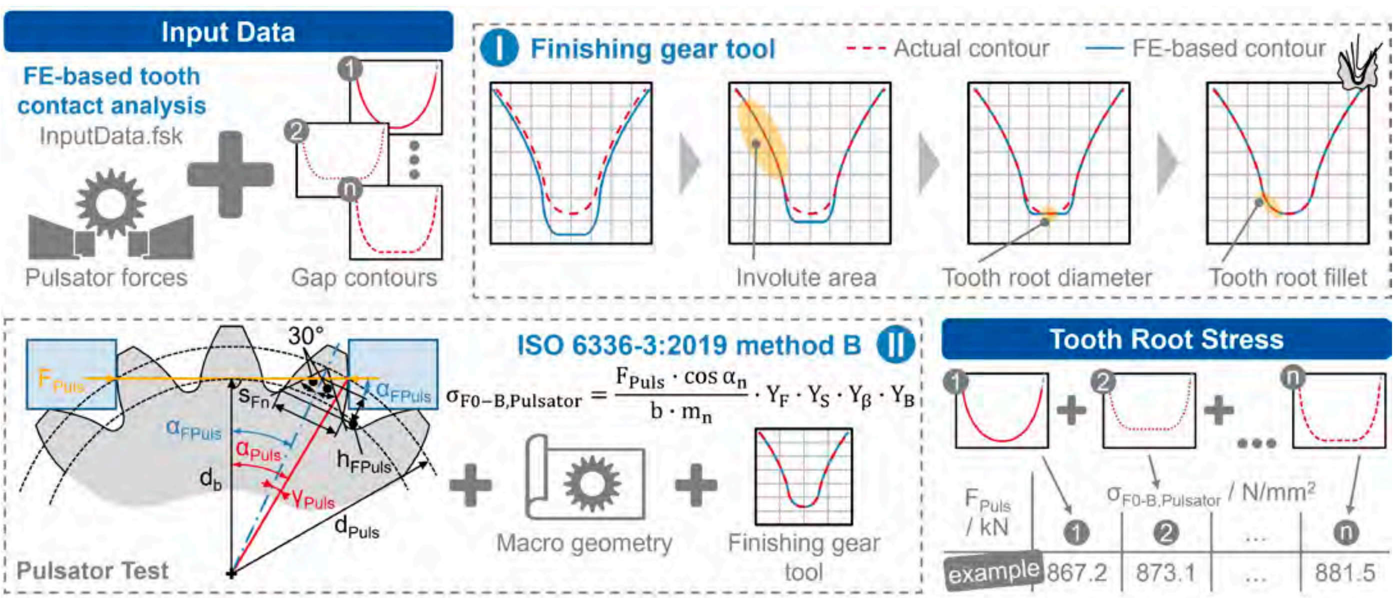


Figure 5—Procedure for automated tooth root stress calculation using ISO 6336-3:2019.

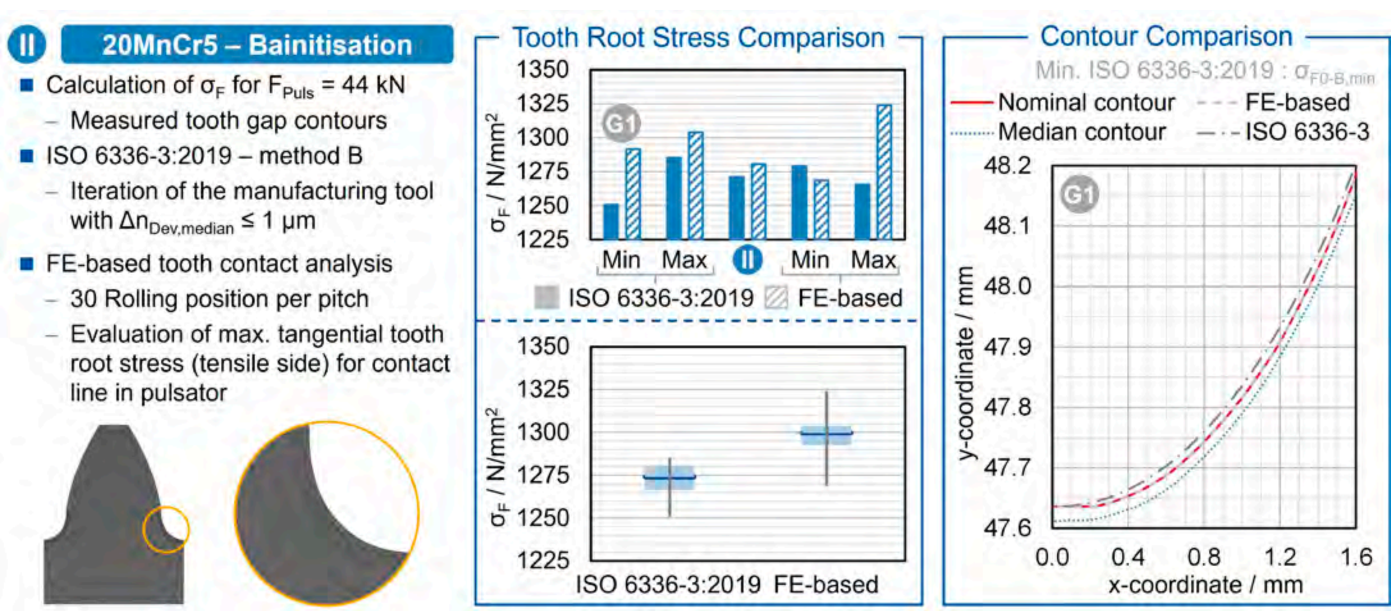


Figure 6—Influence of manufacturing scatter on the tooth root stress.

The third adjustment to the basic rack profile of the manufacturing tool concerns the area of the tooth root that is machined by the tool tip corner rounding of the manufacturing tool. To achieve the best possible match between the FE-based contour and the actual contour, the tool tip corner rounding coefficient is changed step by step in an iterative process. As with the tooth flank iteration, the fitting quality is checked after each iteration step using the median normal deviation distance $\Delta n_{Dev,Median}$ between the two curves in the tooth root area. A maximum deviation of $\Delta_{Dev,Median} \leq 1$ µm was used as a stop criterion for the iteration of the flank area and the tooth root area.

Once the basic rack profile of a suitable hypothetical manufacturing tool has been fully determined, the second step is to calculate the actual tooth root stress using the equation shown in Figure 5 (Ref. 14). When calculating the required correction factors, it should be noted that the point of force application in the pulsator is often not at the outer point of single tooth contact and is dependent on the number of teeth clamped. The resulting geometric relationships are shown in Figure 5, bottom left, and must be taken into account when calculating the correction factors Y_F and Y_S. In addition, the generating profile shift value from the tool iteration must be used. The required tooth root radius results from the tooth root radius of the basic rack profile of the gear ρ_{fP} and corresponds to the tool tip corner rounding ρ_{aP0} of the hypothetical manufacturing gear tool (Ref. 37). Considering the relationships above, the equations from ISO 6336 3:2019 are then used to calculate the actual tooth root stress of the tooth gap contour under consideration (Ref. 14).

For the tooth root stress calculation with the FE-based tooth contact analysis, the measured tooth gap contours are first smoothed using a spline approximation. The smoothed tooth gap contours can be read directly by the used tooth contact analysis program and considered when building the FE-model. The implemented FE meshing process of the program requires a smoothed tooth gap contour as the contour normally used to determine the meshing direction of the FE mesh. Any contour discontinuities in the measured and unsmoothed tooth gap contours would therefore lead to an unfavorable FE mesh in some cases and thus negatively affect the results. Furthermore, the rolling position of the FE-based simulation, which corresponds to the contact conditions in the pulsator test, must be determined, as the tooth contact analysis simulates the quasi-static tooth flank contact of a running test. The rolling position is determined by comparing the pulsator diameter d_{Puls}, which represents the diameter of the force application in the pulsator test, with the contact line diameter of all rolling positions of the FE-based simulation. The pulsator diameter d_{Puls} results from the base tangent length W_K of the number of clamped teeth k and defines the position of the contact line on the tooth flank in the pulsator test. The rolling position with the best fit is used for further tooth root stress calculation. The required simulation torque is determined by iteratively adjusting the torque until the sum of the tooth normal forces of the selected contact line matches the desired pulsator force. Finally, the tooth root stresses occurring in the pulsator are calculated for each measured tooth gap contour, considering the simulation torque and the selected rolling position.

Influence of Geometry Deviations on the Tooth Bending Strength

In the following section, the influence of the geometry deviations on the tooth bending strength is examined. Using the two calculation methods presented, the effect of the measured geometry deviations on tooth root stress is first determined, and the difference between the two calculation methods is examined. Furthermore, the influence of considering the measured tooth root contours in the determination of the tooth bending strength is shown by means of experimental investigations on the measured test gears.

The results of the investigation into the influence of production-related geometry deviations on tooth root stress are shown in Figure 6 as an example for variant II (20MnCr5 – bainitization). The tooth root stresses were calculated for all measured tooth gap contours of variant II at a uniform pulsator force of F_{Puls} = 44 kN with four clamped teeth. A median normal distance of $n_{Dev,median} \leq 1$ µm was chosen as the stopping criterion for the iteration of the hypothetical manufacturing tool for the calculation method according to ISO 6336 3:2019 Method B (Ref. 14). For the tooth root stress calculation using the tooth contact analysis *Stirak* (version 4.3.2.6), a resolution of 30 rolling positions per pitch was used. This is a compromise between the required calculation time and the resolution accuracy. Any increase in the number of rolling positions reduces the distance between the selected contact line and the desired pulsator diameter d_{Puls}, thus improving the calculation accuracy. On the other hand, the required calculation time is increased as a higher number of rolling positions is calculated in the tooth contact analysis. To compare the results between the two calculation methods, the tooth contact analysis evaluates the maximum tangential tooth root stress under tensile load.

The bar chart in Figure 6 shows the calculated tooth root stresses of five different tooth gap contours with both calculation methods. The five selected tooth gap contours are the gap contours with the minimum and maximum tooth root stress of both calculation methods, as well as the tooth root stress of the median tooth gap contour from Figure 4. As can be seen from the bar chart, the two calculation methods provide different tooth root stresses for any of the five selected tooth gap contours. Furthermore, the minimum and maximum tooth root stresses of the two calculation methods occur on different tooth gap contours. These differences can be attributed to the fundamental differences between the two calculation methods as well as to the different fitting quality of the tooth gap contour (see Figure 6—right). Due to the iteration of the hypothetical manufacturing tool for the standard calculation, a highly accurate fit of the actual tooth root contour is not possible for every tooth gap contour, as can be seen, for example, in the contour comparison of gap contour G1 in Figure 6. The fitting quality is defined by the stop criterion for the iteration $n_{Dev,median} \leq 1$ µm, and by the rolling simulation of the hypothetical manufacturing tool for generating the tooth root contour. Deviations between the measured and the used tooth root contour for calculation cannot be excluded. For the FE-based simulation, the measured tooth root contours are only smoothed to achieve a higher fitting quality (see Figure 6). Due to these limitations, the FE-based calculation tends to calculate higher tooth root stresses than the standard calculation (see Figure 6—boxplot diagram).

In the following, the influence of the tooth root contour on the determination of tooth bending strength in the pulsator is investigated for the presented variants I to IV (see Figure 7). For this purpose, pulsator tests were carried out on the measured and presented variants at an ambient temperature of T_{Test} = 180°C. The limiting number of load cycles in the pulsator was NL = 3·106 load cycles and the test frequency was approximately $f_{Test} \approx 35$ Hz. The tests were evaluated using the IAGB/Hück staircase method for a failure probability of P_A = 50% (Ref. 37). The pulsator forces were converted for the corresponding tooth gap contour using the calculation method presented according to method B of ISO 6336 3:2019 (nominal contour vs. median tooth root contour of the respective variant) (Ref. 14). The fracture surfaces of all variants showed no conspicuity. Final material tests on the influence of the operating temperature T = 180°C on the material structure are still pending.

Assuming that all variants have the same tooth gap contour, the test results of all variants can be plotted on the same graph with the ordinates of the pulsator force F_{Puls} (load) and the ordinate of the equivalent tooth root stress σ_{F0-B} (stress) (see Figure 7—top center). With the same load for all variants and assuming the same tooth gap contour, the tooth root stress is the same for all variants. However, this is not the case when considering the measured mean tooth contour of the variants. In this case, the variants can only be plotted on a graph with only one ordinate, the load or stress (see Figure 7—top right). For example, the consideration of variant IV shows that by considering the median tooth root contour, the top load level is reduced by $\Delta\sigma_{F0-B,IV}$ = -44.5 N/mm² compared to the assumption of the nominal contour. On the other hand, considering the median tooth root contour makes only a small difference in variant III. This is due to the smaller deviation between the nominal contour and the median tooth root contour (see Figure 4). This difference becomes particularly clear when comparing the variants (see Figure 7—bottom center). Considering the median tooth root contour, the mean bending strength of variant IV is reduced by Δ_{IV} = 3.3%, whereas the tooth bending strength of variant III remains almost unchanged. The difference in tooth root stress between variant III and IV is $\Delta\sigma_{F0-B,IV\ III,nominal\ contour}$ = 54.8 N/mm², using the nominal contour, and is reduced to $\Delta\sigma_{F0\ B,IV\ III,mean\ tooth\ root\ contour}$ = 10.6 N/mm² when the respective mean tooth root contour is considered.

This means that the two variants are much closer to each other due to the consideration of the mean tooth root contours. This change shows that the geometrical influence should be included in the evaluation of durability tests focusing on material and heat treatment, as it is not a material influence but an influence of the manufacturing process chain. A further improvement in the evaluation of material tests for tooth bending strength could be achieved by considering the actual tooth gap contours. However, this would require an adaptation of the test procedure to obtain a constant step distance, as a constant step distance is a requirement for the evaluation according to IAGB/Hück (Ref. 37). An alternative is to use another evaluation method, such as maximum likelihood, which does not require a constant step distance for the evaluation (Ref. 38). However, statistical research has already shown that a maximum likelihood estimation does not provide estimates of mean and variance that are true to expectation, making this method of limited use for determining fatigue life values (Ref. 39).

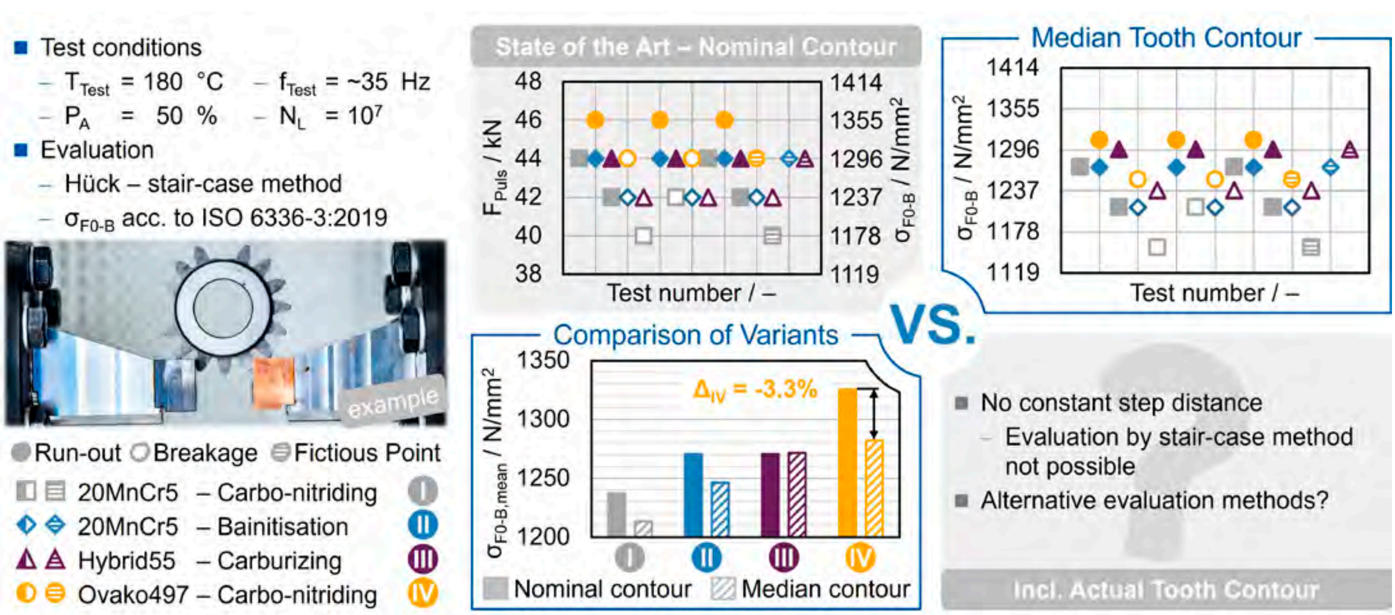


Figure 7—Influence of the tooth root contour on the determination of tooth bending strength in the pulsator.

Summary and Outlook

The investigation of various combinations of materials and heat treatments is usually carried out by the evaluation of S-N curves. When generating S-N curves for the tooth bending strength, the influence of deviations around the tooth root should be considered so as not attribute the influence of manufacturing deviations to the S-N curves of the investigated materials. Unfortunately, an evaluation of the test gear quality is usually only carried out for the area of the tooth flank by means of ISO 1328-1:2013 due to the lack of a uniform evaluation standard for the area of the tooth root. Accordingly, stress-increasing effects, such as tooth root radius changes due to deformations from different heat treatments, are often not considered.

For this reason, the objective of this study was to investigate the influence of geometry deviations around the tooth root when determining the tooth bending strength. In the first step, geometry deviations of various test gears of different material-heat treatment combinations were measured. The analysis of the deviations showed that a grinding process can reduce the geometric deviations after heat treatment. Furthermore, the extent of the geometric deviations depends on the material-heat treatment combination. To reduce sources of error and standardize the stress calculation, the tooth root stress calculation was then automated with the consideration of measured tooth gap contours using an FE-based method and the procedure according to ISO 6336 3:2019. With the aid of the automated calculation method, it was possible to show that a consideration of the measured tooth gap contours is necessary when comparing different material-heat treatment combinations with non-ground tooth roots. Without taking the measured tooth gap contours into account, the evaluation of different variants is only possible with a high degree of uncertainty, since the material difference is not exclusively examined, but is superimposed by the influence of the different tooth root geometries. Therefore, the recording and consideration of the tooth root contours is necessary for the determination of the tooth root strength of different materials and should be considered in every material investigation.

Currently, there is neither a standard for the evaluation of the tooth root contour, nor have systematic investigations been carried out on the influence of contour deviations in the tooth root area, with the focus on the tooth bending strength. Therefore, investigations to determine quantifiable measured variables that can be used to evaluate the gear quality in the tooth root area are necessary. Based on these findings, an evaluation standard for the area of the tooth root can then be derived. Furthermore, a test specification for carrying out tooth bending strength tests would increase national and international comparability. Due to the statistical differences between different evaluation methods, a uniform test procedure and evaluation are necessary to ensure comparability between different studies.

Christian Eggert is currently a research assistant in the Gear Department of the WZL at RWTH Aachen University. He specialized in tooth bending strength of gears. As part of his PhD, he works on projects related to the simulation and testing of gears to improve their load capacity.

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Prof. Dr.-Ing. Christian Brecher is ordinary professor for Machine Tools at RWTH Aachen's WZL and Director of Production Machines at Fraunhofer IPT. His many honors include the Springorum Commemorative Coin, Borchers Medal, Scholarship Award of German Tool Manufacturers, and the Otto Kienzle Memorial Coin for contributions to production technology.

References

1. Brecher C., Löpenhaus C., Goergen F. and Mevissen D., 2017,"Crack Propagation Analysis of Pitting Damages of High-Strength Material Systems in Gear Applications," VDI-Berichte(2294.1), pp. 283–292.
2. Zoch H.-W., Stahl K., Saddei P., Schurer S. and Günther C., Eds., 2017. Alternative mehrphasige Randschichtgefüge beim Einsatzhärten zur Steigerung der Festigkeitseigenschaften von verzahnten Getriebebauteilen, Frankfurt a.M.
3. Goergen F., Mevissen D., Masaggia S., Veneri E., Brimmers J. and Brecher C., 2020,"Contact Fatigue Strength of Austempered Ductile Iron (ADI) in Gear Applications," *Metals*, Vol. 10 No. 9, pp. 1–11.
4. Stenico A., 2007,"Werkstoffmechanische Untersuchungen zur Zahnfußtragfähigkeit einsatzgehärteter Zahnräder," Ph.D. thesis, TU Munich, Munich.
5. Trippe M., Löpenhaus C., Brecher C., Kamjou L. and Löthman E., 2020,"Tooth Root Testing of Steels with High Cleanliness," *Gear Solutions*, Vol. 18 No. 7, pp. 29–36.
6. Zuber D., 2008,"Fußtragfähigkeit einsatzgehärteter Zahnräder unter Berücksichtigung lokaler Materialeigenschaften," Ph.D. thesis, Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen, RWTH Aachen University, Aachen.
7. ISO 1328-1:2013,"Cylindrical gears—ISO system of flank tolerance classification—Part 1: Definitions and allowable values of deviations relevant to flanks of gear teeth".
8. Chaphalkar N., Hyatt G. and Bylund N., 2014,"Analysis of Gear Root Forms: A Review of Designs, Standards and Manufacturing Methods for Root Forms in Cylindrical Gears," *Gear Solutions*, Vol. 12 No. 2, pp. 48–56.
9. Henser J., 2015,"Berechnung der Zahnfußtragfähigkeit von Beveloidverzahnungen," Ph.D. thesis, Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen, RWTH Aachen University, Aachen.
10. Schurer S., 2016,"Einfluss nichtmetallischer Einschlüsse in hochreinen Werkstoffen auf die Zahnfußtragfähigkeit," Ph.D. thesis, TU Munich, Munich.
11. Kapelevich A. and Shekhtman Y., 2009,"Tooth Fillet Profile Optimization for Gears with Symmetric and Asymmetric Teeth," *Gear Technology*, Vol. 26 No. 7, pp. 73–79.
12. Frühe T., 2012,"Berechnung und Minimierung der Zahnfußspannung von Standard- und LowLoss-Verzahnungen," Ph.D. thesis, TU Munich, Munich.
13. Nigade V. and Wink C. H., 2018,"Impact of root geometry manufacturing deviations from a theoretical hob rack on gear bending stress," AGMA Fall Technical Meeting.
14. ISO 6336-3:2019,"Calculation of load capacity of spur and helical gears—Part 3: Calculation of tooth bending strength".
15. Pollaschek J., 2020,"Fertigungsgerechte Zahnfußoptimierung von Stirnrädern," Ph.D. thesis, Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen, RWTH Aachen University, Aachen.
16. Chao C.-X., 2022,"Strategies for Optimizing the Tooth Root Load Capacity of High-Performance Gears," Ph.D. thesis, BTU Cottbus-Senftenberg, Cottbus and Senftenberg.
17. Klocke F. and Brecher C., 2017. Zahnrad- und Getriebetechnik: Auslegung-Herstellung-Untersuchung–Simulation, Hanser, Munich.
18. Linke H., 2010. Stirnradverzahnung: Berechnung-Werkstoffe–Fertigung, Hanser, Munich.
19. Uelpenich R. and Tenberge P., 2019, "Fast tooth root load capacity optimization based on improved design of hob geometry," MATEC Web Conf., 287, pp. 1–9.
20. Wirth X., 1977,"Über den Einfluss von Schleifkerben oberflächengehärteter Zahnräder auf die Dauerfestigkeit und die Lebensdauer im Zweistufenversuch," Ph.D. thesis, TU Munich, Munich.
21. Radaj D. and Vormwald M., 2007. Ermüdungsfestigkeit: Grundlagen für Ingenieure, Springer, Berlin.
22. Arndt K.-D., Brüggemann H. and Ihme J., 2011. Festigkeitslehre für Wirtschaftsingenieure, Vieweg+Teubner, Wiesbaden.
23. ISO 6336-5:2016,"Calculation of load capacity of spur and helical gears—Part 5: Strength and quality of materials".
24. Bretl N. T., 2011,"Einflüsse auf die Zahnfußtragfähigkeit einsatzgehärteter Zahnräder im Bereich hoher Lastspielzahlen," Ph.D. thesis, TU Munich, Munich.
25. FKM Guideline, 2003,"Rechnerischer Festigkeitsnachweis für Maschinenbauteile".
26. Brinck P., 1989,"Zahnfußtragfähigkeit oberflächengehärteter Stirnräder bei Lastrichtungsumkehr," Ph.D. thesis, TU Munich, Munich.
27. Niemann G., and Winter H., 2003. Maschinenelemente–Band 2 (Machine Elements-Volume 2), Springer, Berlin.
28. Murakami Y., 2019. Metal Fatigue: Effects of Small Defects and Nonmetallic Inclusions, Elsevier Ltd., London.
29. Fuchs D., Schurer S., Tobie T. and Stahl K., 2019,"A model approach for considering nonmetallic inclusions in the calculation of the local tooth root load-carrying capacity of high-strength gears made of high-quality steels," *J. Mech. Eng. Sci.*, Vol. 233 Nos. 21–22, pp. 7309–7317.
30. Höhn B.-R., Winter H. and Stahl K., 1999. Lebensdauerstatistik, Research Association for Power Transmission Engineering (FVA), Frankfurt a.M.
31. ISO 6336 1:2019,"Calculation of load capacity of spur and helical gears—Part 1: Basic principles, introduction and general influence factors".
32. Hemmelmann J. E., 2007,"Simulation des lastfreien und belasteten Zahneingriffs zur Analyse der Drehübertragung von Zahnradgetrieben," Ph.D. thesis, Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen, RWTH Aachen University, Aachen.
33. ISO 21771:2007,"Gears—Cylindrical involute gears and gear pairs—Concepts and geometry".
34. VDI/VDE 2612:2018,"Messen und Prüfen von Verzahnungen".
35. ISO/TR 10064 1:2019,"Code of inspection practice—Part 1: Measurement of cylindrical gear tooth flanks".
36. DIN 867:1986,"Bezugsprofile für Evolventenverzahnungen an Stirnrädern (Zylinderrädern) für den allgemeinen Maschinenbau und den Schwermaschinenbau."
37. Hück M., 1983,"Ein verbessertes Verfahren für die Auswertung von Treppenstufenversuchen," Werkstattstech. 24, pp. 406–417.
38. Dixon W. J. and Mood A. M., 1948, "A Method for Obtaining and Analyzing Sensitivity Data," *J. Am. Stat. Assoc.*, Vol. 241 No. 43, pp. 109–126.
39. Müller C., 2015,"Zur statistischen Auswertung experimenteller Wöhlerlinien," Ph.D. thesis, TU Clausthal, Clausthal-Zellerfeld.

AILOS Robotics

LANDS €3.5M SEED FOR ADVANCED ROBOT GEARBOXES

AILOS Robotics has raised €3.5 million to industrialize a new class of robotic gearboxes that combine the agility of quasi-direct drives with a far higher torque density. This breakthrough enables robots that are lighter, safer, more affordable, and more energy efficient.

The seed round is led by QBIC and High-Tech Gründerfonds (HTGF), with participation from Wallonie Entreprendre and finance&invest.brussels, reinforcing Europe's commitment to developing local, strategic component supply for the rapidly growing humanoid and collaborative robotics markets.

"Modern robots demand a new category of actuation," said Pablo López García, CEO and co-founder of AILOS Robotics. "We combine quasi-direct drive-like back drivability with the high torque density of advanced gearing, finally removing one of the main barriers to agile, lightweight, and safe robots that can operate alongside humans."

AILOS is a spin-off from the Vrije Universiteit Brussel (VUB) and its BruBotics research powerhouse. After a decade of research supported by VLAIO (Flanders) and Innoviris (Brussels), the company has built and validated its Minimum Viable Product (MVP) — the R2poweR gearbox.

Designed for humanoids, cobots, exoskeletons, and prosthetic devices, the R2poweR architecture:

- Enables smooth human-friendly interaction (low backdrive torque)
- Provides extreme torque density for highly loaded joints
- Reduces robot weight, energy demand, and noise
- Supports low-cost industrialization and future scalability
- Is ideally suited for high-volume robotics manufacturing

AILOS is now moving from lab to factory, and actively engaging:

- Robot manufacturers — seeking first pilot projects
- Industrial partners — for joint manufacturing and supply chain scale-up
- Investors — supporting EU leadership in strategic automation technologies

"AILOS addresses one of the biggest bottlenecks in humanoid and collaborative robotics," said Cédric Van Nevel, partner at QBIC. "Europe needs strong hardware manufacturers, and this team has the technology, IP position, and industrial vision to deliver. We are happy to support the founding team in bringing years of academic research to the market."

Anne Umbach, investment manager at HTGF, said: "AILOS has the potential to become a new European tech champion – despite the challenge of entering the market as a component supplier within an established value chain. Their hardware-level innovation unlocks a unique combination of mechanical parameters, addressing key challenges faced by robot manufacturers in the future markets of cobots and humanoid systems. We're investing in strong IP and a diverse, ambitious team with a clear technological vision."

ailos-robotics.com

Star SU

WELCOMES DAVID KRUISE AS MARKETING & COMMUNICATIONS MANAGER

Star SU, the marketing, sales and service affiliate of Star Cutter Company, announces the appointment of David Kruise as marketing and communications manager.

Kruise has nearly 30 years of experience in marketing and communications, with a strong background in technical documentation and sales support within the manufacturing sector. His early career as a machine repair technician gives him firsthand knowledge of tooling assembly and quality control, equipping him with a unique perspective that connects technical expertise with strategic marketing.

"David's strong technical communication skills and direct manufacturing experience make him an excellent fit for this role," said Andreas Blind, president at Star SU. "His ability to bridge the shop floor with strategic marketing will help us clearly communicate the value we deliver across all Star Cutter brands."

David Kruise

In his new role, Kruise will lead all marketing activities for the Star Cutter, Star SU, and H.B. Carbide brands across four business divisions: Round Tools, Gear Tools, Machine Tools, and Carbide Material Technologies.

For more information, contact *sales@star-su.com*

star-su.com

Blaser Swisslube and Nidec Machine Tool America

ANNOUNCE PARTNERSHIP

Blaser Swisslube, Inc. and Nidec Machine Tool America recently announced a strategic partnership designed to help manufacturers achieve higher productivity, precision, and process reliability.

By combining Blaser Swisslube's Liquid Tool approach, which positions metalworking fluid as a driver of performance, with Nidec Machine Tool America's advanced gear manufacturing and precision machining technologies, the companies will provide integrated, application-driven solutions that deliver measurable results on the shop floor.

Under the collaboration, customers will gain coordinated access to:

- Joint process evaluations that optimize machine, tool, and fluid interactions
- Application-specific metalworking fluid recommendations and on-site support
- Data-driven trials to improve cycle times, tool life, and surface quality

When speaking about the partnership, Carsten Witthuser, Head of Americas at Blaser Swisslube, Inc. said, "We partner with machine tool builders who align with our mission: delivering high-performance fluids, technical expertise, and full-service solutions that help customers optimize their machining productivity. That's why our collaboration with Nidec Machine Tool America matters. Seeing our fluids run in their machines, day in and day out, means manufacturers are getting the performance, reliability, and value they deserve."

"Our customers expect world-class precision and uptime," said Scott Knoy, vice president of sales, Nidec Machine Tool America. "By aligning with Blaser Swisslube, we're strengthening process performance, improving tool life, consistency, and surface finish while reducing total cost of manufacturing."

As the partnership progresses, the companies will collaborate on initiatives intended to enhance customer outcomes across a range of machining and manufacturing applications.

blaser.com

nidec-machinetoolamerica.com

Teradyne Robotics

ANNOUNCES NEW OPERATIONS HUB IN MICHIGAN

Teradyne Robotics will open a new U.S. Operations Hub in Wixom, MI, in 2026. This strategic expansion reflects Tera-

dyne Robotics' commitment to operating close to its customers and meeting the growing manufacturing demand in the U.S. and the Americas.

The new facility will manufacture Universal Robots (UR) industrial collaborative robots (cobots), with future potential to include MiR autonomous mobile robots (AMRs). It will also serve as a regional customer training center, service hub, and visitor experience center.

The new U.S. Operations Hub will support the re-industrialization of America with advanced robotics. The company seeks to support the evolving needs of American industry, including productivity, reshoring, upskilling, and increased automation to address workforce challenges and enhance global competitiveness.

This facility expands Teradyne Robotics' presence in the Detroit area, creating over 200 jobs over the coming years and an all-new robotics technology hub supporting advanced manufacturing in Michigan, the Midwest, and throughout America.

"This new U.S. Operations Hub is a pivotal step to support the growth of advanced robotics in America and demonstrates our commitment to customers in the United States," said Jean-Pierre Hathout, President of the Teradyne Robotics Group. "Our customers are looking to robotics not only to boost competitiveness, but also to make factory floors more attractive to the next generation of workers. With this facility, we're investing in both automation and education - scaling up deployment, service, and training capabilities to meet the evolving needs of U.S. manufacturing, logistics and warehousing."

A recent survey shows that 73 percent of North American manufacturers cite productivity improvement as their top reason for investing in automation. Of the companies already using cobots, the vast majority (87 percent) are already seeing double-digit productivity improvements. Eighty-three percent of all respondents reported positive employee sentiment towards robotics adoption.

Teradyne Robotics produces a range of robots designed to work alongside people, augmenting existing workforces and creating better workplace environments for employees. Its scalable, AI-enabled robotics platforms are built for agility, flexibility and future-proof performance.

Teradyne already has a large robotics customer base in North America and a regional robotics office in Novi, MI. The company is based in North Reading, MA, with its robotics R&D based in Denmark.

The location of the new Operations Hub was a strategic choice based on the area's strong manufacturing heritage and industrial future.

"Locating this hub in Metro Detroit puts us at the center of U.S. manufacturing and innovation," said Justin Brown, chief commercial officer of the Teradyne Robotics Group. "Being close to leading manufacturers allows us to deliver automation solutions to some of our biggest customers, enabling Teradyne Robotics to be even more agile and responsive. The region's industrial foundation, strong talent base, world-class universities, and growing aerospace sector make it an ideal base to support advanced manufacturing in the United States."

"We are pleased to support a new U.S. Operations Hub for Teradyne, whose products and solutions are an incredible complement to the innovative and valuable supply chain that is found in Michigan. The partnership between the company and the State of Michigan presents an incredible opportunity and competitive advantage for all involved," said Quentin L. Messer, Jr., CEO of the Michigan Economic Development Corporation. "Team Michigan stands ready to continue our work with the company for many years after this announcement. I wish the Teradyne team success and prosperity, and I look forward to celebrating their accomplishments in Michigan for years to come."

teradyne.com/robotics

FEBRUARY 24–26

Additive Manufacturing Strategies – New York

This industry touchstone conference (New York, NY) brings together AM stakeholders from all over the world. AMS includes panels and keynotes on topics most critical in the fast-growing world of additive manufacturing. Bringing together the industry's leaders in a contained networking environment makes AMS the place for startups to access capital, for financial institutions and investors to sharpen their radars, and for the AM industry to focus on the business of AM. Topics include energy, medical devices, aerospace, defense, future forecast, software and more. MPMA's VP of Emerging Technology, Mary Ellen Doran, joins moderator Filippos Voulpiotis, managing director, 3Dnatives, Kevin Kassekert, chief executive officer, VulcanForms and Michael Corliss, vice president of technology, SBO/Knust Godwin for a panel on high-volume industrial part production at 9:55 am, Feb. 25, 2026.

geartechnology.com/events/additive-manufacturing-strategies-new-york

MARCH 3–7

CONEXPO-CON/AGG 2026

CONEXPO-CON/AGG (Las Vegas) brings the entire construction ecosystem together in one place, giving over 139,000 construction professionals access to equipment manufacturers, technology innovators, workforce trailblazers and the thought leaders who are changing the world through infrastructure, innovation and leadership. CONEXPO-CON/AGG 2026 will feature 2,000 exhibitors across 2.9 million square feet of exhibit space and 50 first-class educational sessions designed to help construction and aggregate industry professionals stay ahead of the emerging technologies, workforce trends and sustainability practices shaping the industry's future. Debuting in 2026, The Ground Breakers Stage, is spotlighting the people, policies, and technologies driving the construction industry forward. Sessions include AI, sustainability strategies for reshaping materials and methods and workforce growth and mental health across the construction sector.

geartechnology.com/events/conexpo-con-agg-2026

MARCH 17–19

Lubricant Expo North America 2026

Lubricant Expo North America (Detroit) is a destination for connecting lubricant solution providers with end-user buyers and the entire supply chain. The Lubricant Expo brings together exhibitors and attendees from over 80 countries, covering everything from finished lubricants to formulation ingredients and equipment. The show is co-located with The Bearing Show, connecting the evolving needs of bearing end-users with the latest technologies serving, OEM development, maintenance professionals and R&D engineers. Meet visitors from OEM's, machine manufacturers, industrial plants, global distributors and more. Gain insights into emerging trends such as energy efficiency, sustainability, and cost-effective maintenance strategies.

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APRIL 23–25

2026 MPMA Annual Meeting

In an era defined by economic uncertainty, supply chain disruption, and rapid workforce change, senior manufacturing leaders need more than tactical updates—they need strategic clarity. The 2026 MPMA Annual Meeting held at the Sunseeker Resort in Charlotte Harbor, FL, is designed specifically to deliver that clarity. Hosted by the Motion + Power Manufacturers Alliance (MPMA), this member-only gathering convenes top executives from across the power transmission and motion control industry for high-level dialogue, peer connection, and forward-looking insight. Speakers include Jim Meil (ACT Research), Cam Marston (author), Laurie Harbour (partner, manufacturing, retail, and distribution) and more.

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MAY 20–21

Control-Expert Days 2026

Control has always been the international benchmark for quality management. Control-Expert Days 2026 turns this claim into a focused format that addresses the key questions facing the industry: What does modern quality management need to become faster, more resilient, and more sustainable? Stuttgart provides the ideal place for this event. As an industrial hotspot, the region brings together companies, decision-makers, and industry professionals who are responsible for audit processes daily.

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ADDENDUM

May the Force Be with You!

Aaron Fagan, Senior Editor

Courtesy of LEGO Group

I've been meaning to write about this for a while now, but like that one project that's been sitting on your bench for months, sometimes things get away from you. I've always wondered about a scene in the original *Star Wars* that I've seen at least a hundred times, but have never been able to resolve, and perhaps there is no way to. I'm talking about the iconic trash compactor 3263827 scene—specifically, the terrifying moment when Princess Leia desperately shouts, "Don't just stand there, try to brace it with something!" as the walls begin close in.

And what does she grab from the heap of garbage? A large shaft with three splined sections and three rounded knurled-looking sections. Its form has the whiff of something familiar—it looks like a precision-machined shaft designed for torque transmission, with the knurled sections possibly for gripping or processing material.

Then today, committing myself to write about this, I stumbled across a Reddit thread that both solved and complicated the mystery. Nearly 45 years after *Star Wars* premiered in 1977, that piece of scrap was retroactively identified in *The Book of Boba Fett* as a "cryogenic density combustion booster"—a component from a starfighter.

But what's a cryogenic density combustion booster? If it's a combustion booster for a starfighter, what's it doing mechanically? The name suggests it's part of a propulsion or fuel system—something involving temperature control (cryogenic), fuel mixture (density), and ignition (combustion). But looking at it, those machined sections don't quite fit that description.

Are those really splines designed to transmit rotational torque? Or could they be cooling fins, heat sinks to dissipate thermal energy from a high-temperature combustion process? The "cryogenic" part of the name suggests extreme temperature management, which would make cooling fins logical. But then what about the knurled sections? Are they worn-down diamond knurls? Why are they rounded? Another type of heat sink design to modulate the rate of dissipation?

Maybe what I've been reading as a rotating shaft with torque-transmission features is just the geometric solution to maximizing surface area for heat exchange while maintaining structural integrity. Or maybe it does rotate, and it's part of some kind of compression or pumping mechanism within the combustion booster assembly.

Does the form follow its function? But I don't understand the function; the form remains a puzzle. *Star Wars* has always excelled at creating technology that *looks* used and mechanically plausible without necessarily explaining exactly how it works, and the cryogenic density combustion booster is a prime example.

So, I'm throwing it open to you: What do you think this thing did in operation? How would it cryogenically boost combustion? And what role do those machined sections play? How would you manufacture it?

Whatever it is, it certainly did not withstand the compressive load of the compactor. Maybe there's no single right answer. Maybe that's part of what makes it fascinating. But if you've got theories about *Star Wars* engineering—I'm open. In the meantime, may the force be with you.