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JULY 2025

e-Mobility
Plastic Gears
Data-Driven Manufacturing

TECHNICAL

Experimental Study on the Performance of Plastic Worm Gears

Electric vs. Combustion: A Comparative Analysis of Gear Design for Commercial Vehicle Applications

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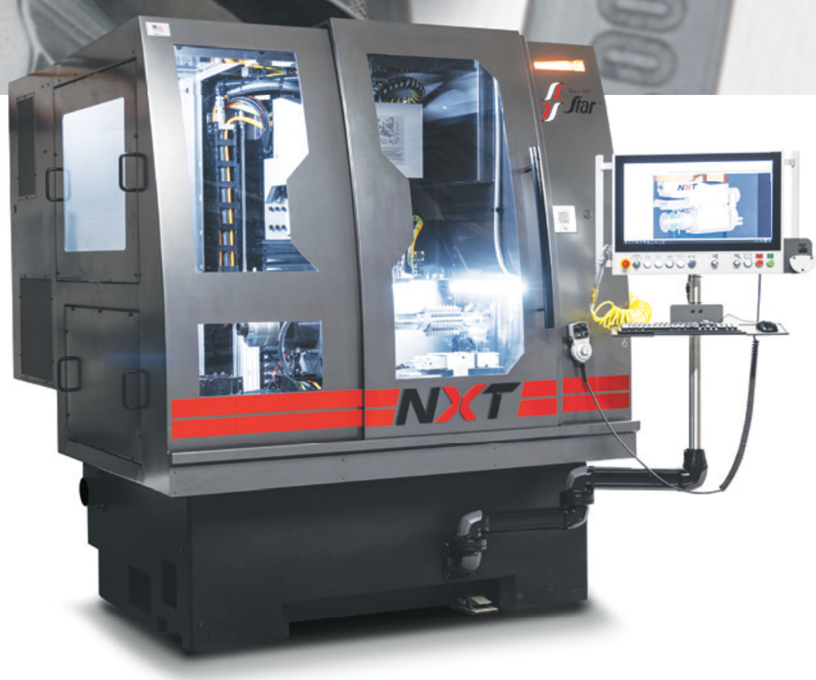
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Vol. 42. No.5 GEAR TECHNOLOGY. The Journal of Gear Manufacturing (ISSN 0743-6858) is published monthly, except in February, April, October and December by The Motion + Power Manufacturers Alliance, 1001 N Fairfax Street, Suite 500, Alexandria, VA 22314, (847) 437-6604. Periodical postage paid at Arlington Heights, IL, and at additional mailing office (USPS No. 749-290). The Motion + Power Manufacturers Alliance makes every effort to ensure that the processes described in GEAR TECHNOLOGY conform to sound engineering practice. Neither the authors nor the publisher can be held responsible for injuries sustained while following the procedures described. Postmaster: Send address changes to GEAR TECHNOLOGY. The Journal of Gear Manufacturing. 1001 N Fairfax Street, Suite 500, Alexandria, VA 22314.

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Vol. 42. No. 5

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GT VIDEOS

Forest City Gear Knows Robots

Forest City Gear manufactures extremely high-precision gears made for the most advanced robotics, right in Roscoe, IL. This family-owned team of gearheads specialize in high-precision gears engineered to handle the most demanding robotic applications—on Earth, and way beyond.

geartechnology.com/videos/forest-city-gear-knows-robots

GT REVOLUTIONS

Zoller Celebrates 80 Years of Innovation

Zoller celebrated its 80th anniversary recently at its North American headquarters located in Ann Arbor, MI, with a three-day open house. The celebration brought together manufacturers, partners, industry leaders, as well as members of the media, to explore the future of smart manufacturing while honoring the company's legacy of innovation, precision, and customer-driven solutions.

geartechnology.com/zoller-celebrates-80-years-of-innovation

AS SEEN IN *PTE*

Powerful by Design

Speed is a key factor for success. It is as important as cost, value, uniqueness, vision, user acceptance. This holds true for processes, goods and services. And for tools, including the one presented here. A tool that is intuitive to use requires little time to learn. A versatile tool is quickly accepted by a team dealing with many projects or concepts simultaneously. A tool that adapts to the users' workflow and integrates seamlessly maintains these processes speed. Introducing the *KISSsoft System Module*.

powertransmission.com/powerful-by-design

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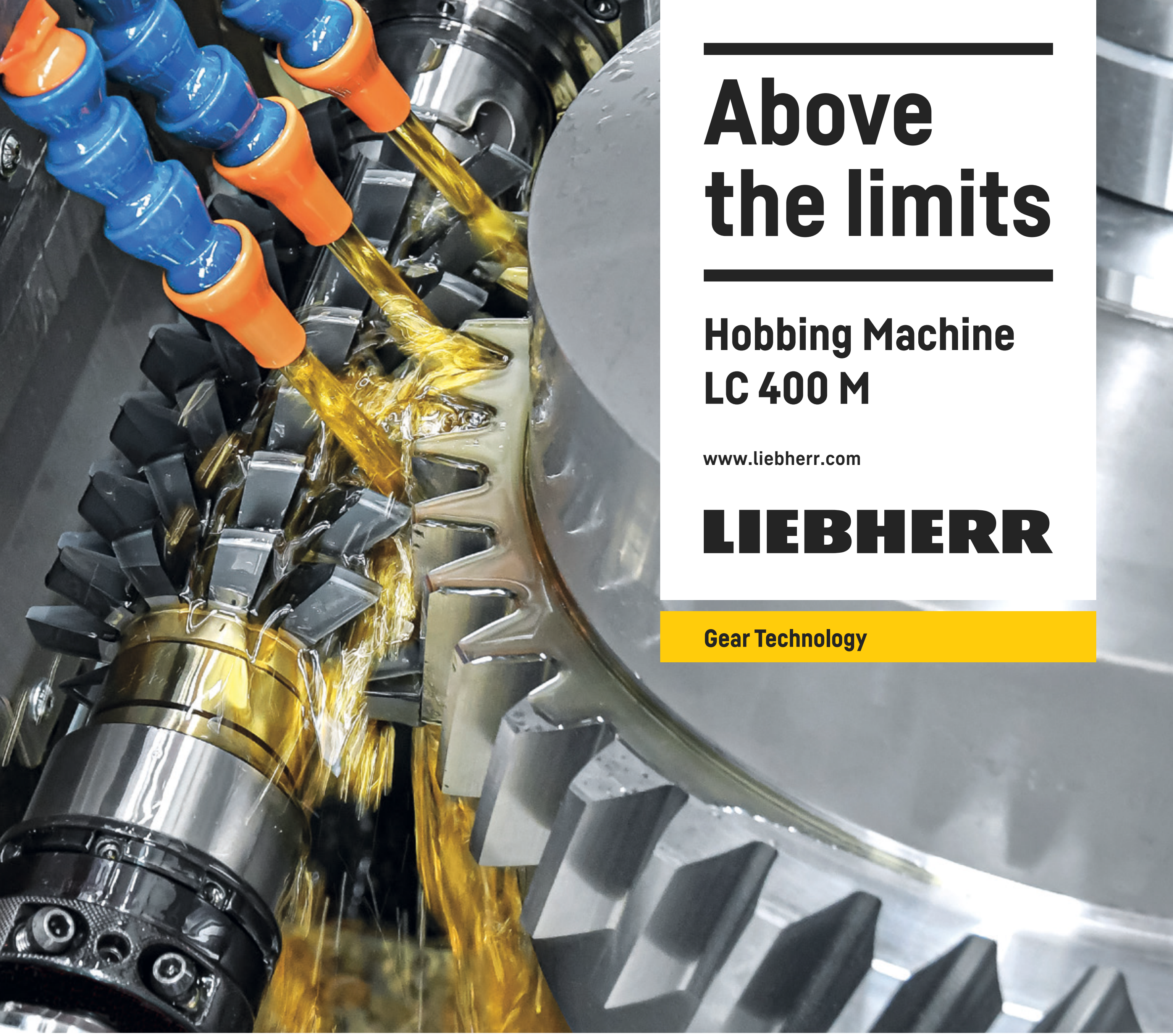
Michael Goldstein founded *Gear Technology* in 1984 and served as Publisher and Editor-in-Chief from 1984 through 2019. Thanks to his efforts, *the Michael Goldstein Gear Technology Library,* the largest collection of gear knowledge available anywhere, will remain a free and open resource for the gear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

Plug it In

I drive a plug-in hybrid electric vehicle, which my wife and I bought two years ago. At the time, we weren't quite ready to go full electric. We definitely wanted the smooth, quiet ride that an electric vehicle can provide. We wanted the convenience and ease of being able to "fill up" by simply plugging in at home. But like many American consumers, we also had range anxiety and doubts about the infrastructure's ability to provide charging on a road trip, for example.

So we bought the hybrid. It only has about 30-35 miles of range on a full electric charge. But for day-to-day driving, that's enough. When we need it, we've got the gas, which has allowed us to take the car on multiple long-range road trips. We even towed a boat across country. For us, the plug-in electric hybrid has been the right choice.

Of course, it hasn't been without its hiccups. We got a nice letter from the NTSB telling us not to plug it in, because it could blow up, or start a fire, or stop suddenly while driving. There was a safety recall on the charging port that required a software update, which, by the way, wasn't available yet.

During the couple of months we had to wait for the fix to become available, we had to drive on gas. While it was a blessing our car could just switch functions without missing a beat, it was also a curse, because every time we got into the car, we could hear it. And we missed that smooth, quiet ride.

Thankfully, we're back to normal now.

My experience gives me good perspective on the overall EV market, and a solid understanding on why the automotive manufacturers have stepped back from "all-in" on EVs to a hybrid strategy. But also, why electric vehicles are here to stay.

Because no matter the current political climate or the debate over whether EVs are environmentally better or worse, car manufacturers are still extremely busy converting factories and production lines over to build these new styles of vehicles.

Which brings us to this issue of *Gear Technology*. We have four significant articles this issue that touch on the EV space. Liebherr's automation systems have helped Ford convert a factory from internal combustion to EV production (p. 20). Romax and Hexagon present an article about NVH analysis and prediction in EV drivetrains (p. 22). Senior Editor Matt Jaster dives into the trends surrounding e-mobility and electrification with Drive System Design (p. 26). And the engineering team from Eaton Mobility have provided a technical overview of the differences in transmission design between internal combustion and electric vehicles (p. 34).

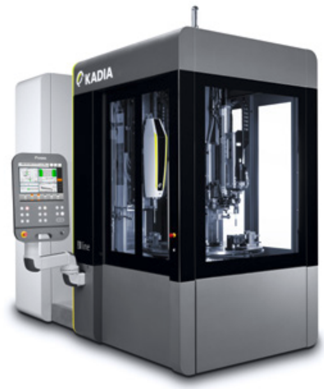
Transmissions for electric vehicles will continue to be a significant part of the discussion in the gear industry for the foreseeable future. If you read through this issue and decide you still need more, you should consider attending the upcoming AGMA class on "EV Automotive Transmission Design." This is a newly developed course offered by the Motion + Power Manufacturers Alliance, drawing on resources from the AGMA, ABMA and the AGMA Foundation to bring you the most up-to-date developments in EV transmission design. The course takes place August 19-21 in Rosemont, IL. For more information, visit *www.agma.org/events-education/*.

Hopefully all this information will keep you "plugged in" to the current trends and technologies revolving around electric vehicles.

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

Kadia

DEVELOPS COMPACT, RELIABLE HONING MACHINE



With the third generation of its successful U line, Kadia introduces a state-of-the-art honing machine that redefines standards in precision, productivity and serviceability—while maintaining full versatility.

"The U line combines what has always been at the core of Kadia: ultimate machining accuracy and maximum cost-efficiency through short cycle times, high machine availability and outstanding process reliability," explains Henning Klein, managing director of Kadia.

The U line is designed as a compact rotary indexing machine with six stations: two honing stations for rough and finish honing, two measuring stations, a loading/unloading station and an optional integrated brush-deburring station. Key maintenance components such as pumps, pneumatic systems and lubrication units are centralized and easily accessible in a dedicated service compartment.

Based on the experience gained from over 50 delivered systems from previous U line generations, the new machine lives up to its name—the "U" stands for "Universal." It covers a wide machining range from 1.5 mm to 40 mm bore diameters, making it ideal for both small parts like gears and larger components such as those used in the hydraulics sector.

A standout feature of the new U line is its significantly enlarged working area. The diameter of the rotary table has been increased by 30 percent, resulting in 60 percent more table surface—enabling the use of larger fixtures and significantly expanding the machine's application range. A smart feature: the transport speed of the rotary table automatically adjusts to the workpiece weight, minimizing mechanical wear and extending the drive's service life.

While the machine's footprint remains a compact 4.5 m^2, its mass has been increased by 20 percent, improving vibration damping. This allows the new highly dynamic honing spindles to operate more effectively—a key factor in reducing cycle times and maintaining process stability even at high material removal volumes.

User comfort and fast changeovers were top priorities in the development of the new U line. A walk-in side niche allows rear access to the work area for the first time—ideal for quick gauge changes at the rear measuring station. The front-loading door has been widened by 10 percent, improving manual part loading and enhancing overall workstation ergonomics.

"Today, our customers expect not only precision machines but also smart operating concepts that directly contribute to overall equipment effectiveness," emphasizes Klein. "With the new U line, we significantly reduce setup times and boost machine availability."

At the heart of the new U line is the newly developed LH2x honing spindle—the next evolutionary step in the successful "Lean Highspeed" series. Featuring three integrated direct drives for oscillation, rotation and tool expansion, the spindle introduces a completely new concept. It delivers higher cutting speeds, broader versatility, and easier maintenance compared to its predecessor. Four new patents underline the innovative strength of this development.

Together with the LH2x spindle, the HMC100 control unit forms the technological backbone of the U line. It enables scanning of the honed bore in axial direction, significantly improving in-process measurement quality. Even complex geometries can be analyzed precisely and consistently—a major advantage for high-end, reliable honing processes.

The HMC100 also supports multistage honing within a single cycle, with each stage individually programmable, e.g., in terms of cutting speed. This improves both cycle time and bore quality. A new feature, Form Honing, allows precise machining of tapered or barrel-shaped bores.

The measuring stations have also been technologically refined. Thanks to a rotary drive, workpieces can be inserted in any orientation, while the measuring axis automatically detects the correct position. The new measuring axis design also allows the use of shorter probes, enabling faster and more precise measurement—reducing cycle time and enhancing quality.

In the deburring unit, a new motor with 40 percent higher rotational speed significantly improves performance, especially for small-diameter bores. The automatic brush changer has been redesigned for higher robustness and now features new magazines that hold up to eleven spare brushes per diameter. This further automates the deburring process and minimizes downtime.

Whether for mixed-model production or high-volume manufacturing, manual or automated loading—the U line is the universal honing machine for highest quality and maximum productivity in bore finishing.

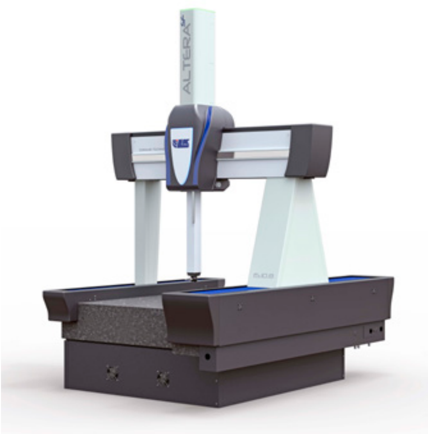
The new U line brings together over a decade of U line expertise with Kadia's decades-long honing expertise and enhances it with innovative technical advancements. It is a well-conceived, high-performance solution for manufacturers who demand precision, flexibility, and peak economic efficiency.

kadia.com/us

LK Metrology

OFFERS LABORATORY-GRADE INSPECTION

Inspection using a coordinate measuring machine (CMM) in a production environment brings enormous advantages compared with transporting components, sometimes considerable distances to a separate quality control (QC) room. Benefits include faster inspection, quicker reporting, reduced lead-times, rapid feedback on part conformity for prompt adjustment of manufacturing processes, increased output, reduced scrap and raised efficiency. Eliminating the need to transfer parts to another location saves labor costs and time, reducing the risk of damaging the parts being handled. It also allows the QC function to be closely integrated with production and automated if desired.



To meet such high precision inspection requirements in the rugged environment of the shop floor, CMM manufacturer LK Metrology, whose manufacturing facility is in Castle Donington, Derbyshire, has introduced eight bridge-type Altera SF models having laboratory-grade accuracy. These CMMS were launched at Control 2025, the annual international trade fair for quality assurance held at the Messe Stuttgart, Germany.

Normally, industrially hardened CMMs with the necessary temperature compensation and vibration isolation tend to be small to fit into confined spaces, but these new models have generous nominal axis travels ranging from 1,000 x 1,000 x 800 mm up to 4,000 x 1,500 x 1,500 mm. The large measuring volumes mean that bulky workpieces can be inspected near where they are produced, while the extra capacity affords more operational flexibility by allowing QC requirements to be met across a wider variety of component sizes.

All SF-series CMMs have a ceramic bridge and spindle with outstanding stiffness-to-weight ratio, thermal characteristics, dimensional stability and longevity. Friction drives with air bearings provide smooth axis movements, leading to high accuracy laser or analogue scanning, or touch-trigger probing. Either a Renishaw PH10MQ PLUS indexing probe head may be used, or a REVO2 head which converts the CMM into a 5-axis Scantek model. Both heads support multi-sensor technology.

Covers protect the guideways from thermal influence, accidental damage and contamination, aided by positive internal air pressure to prevent the ingress of dust and vapor particles. Fans under the granite table ensure a continuous flow of ambient air to avoid thermal imbalance in environments where there is no temperature control, as is the case on most shop floors. Temperature sensors embedded in each axis of the CMM monitor heat fluctuations within the structure and compensate all measurements to a 20°C reference. Optionally, thermistors can be clamped or attached magnetically to a workpiece or integrated into its fixture.

In a notable departure from the construction of LK's other ceramic-type CMMs, which use stainless steel linear encoders, Altera SF machines incorporate glass-ceramic optical scales that have zero thermal expansion as well as superior immunity to contamination,

minimizing potential sources of measurement error. The low-maintenance scales have excellent long-term stability, while signal stabilization results in low and predictable interpolation error.

Elastomer anti-vibration and shock-absorbing mounts isolate the CMM from sources of mechanical disturbance, such as machine tools. Passive anti-vibration may be specified, but to ensure maximum measurement accuracy, active intelligent anti-vibration is recommended. It involves built-in magnetic field sensors that detect the load on the table and monitor its height and level, enabling them to be automatically adjusted electro-pneumatically to within ±0.1 mm and 0.9 mm respectively. As the sensors are non-contact, they remove the disadvantage in traditional mechanical-pneumatic compensation systems of having an integrated tappet, or plunger, which is exposed to contamination and is a potential conduit for vibration transfer.

Altera SF machines, with their proprietary LK NMC300 multipurpose controller and *CAMIO* software suite, are ready for in-line or line-side automation to suit large volume production.

lkmetrology.com

Seco Tools

LAUNCHES WEB-BASED TOOL FOR CUTTING DATA

Seco has launched an innovative web-based tool that provides customers with product-specific, instant, high-quality cutting data recommendations based on their machine information. The Seco Machine Library simplifies the process of identifying, purchasing and optimizing tools that are appropriate for specific machines.

"Machine Library is the latest addition to the Seco My Pages portal that supports customers with a personalized digital experience on secotools.com," said Seco Product Lead Simon Karlström. "Customers can quickly access detailed cutting data for a particular tool based on their specific machine characteristics in addition to quickly getting product information. Machine Library closes the loop with all the information an operator needs to get the machine specific cutting data straight away."

Customers can easily add, edit and delete machines along with characteristics such as manufacturer, model, CNC, coolant, rpm, torque and power by simply logging in to their secure My Pages portal on *secotools.com* and navigating to Machine Library. Once the library is populated with machine information, customers simply add their machine in the cutting data tab on the product details page to obtain machine specific cutting data recommendations. Additionally, customers will be able to adjust machining parameters like cutting methods and number of passes to optimize their processes.

Configuring and saving their individual machines in Machine Library enables customers to easily integrate into future Seco digital products. Calculating cutting data on their unique machine settings will give operators quicker and more accurate recommendations to avoid costly trial and error. Machine-specific cutting data will help shops be more productive with increased throughput and decreased scrap.

Seco Machine Library recommends cutting data for any combination of machine and tool. It can also supply the appropriate cutting data for new tools or existing tools moved to a new or different machine. The Machine Library allows users to easily save and edit data on each of their machines.

secotools.com

SMW Autoblok

INTRODUCES AUTOMATIC QUICK JAW CHANGE WITH KNCS-MATIC

SMW Autoblok now also enables automatic quick jaw change for power chucks. The KNCS-matic chuck can be converted quickly and precisely by a loading robot using a release pin. The automated power chuck ensures that SMW Autoblok meets the current clamping technology requirements, ensuring readiness for the digital factory.

The KNCS-matic is the latest clamping system in the KNCS power chuck family from SMW Autoblok. It allows automatic quick jaw change by a conventional industrial robot. This releases the base jaws with a release pin, replaces them and then fixes the next jaws with the pin. Interaction with industrial robots enables the KNCS-matic to achieve short setup times ensuring reliable workpiece clamping with self-centering and repeat accuracy. Operators can work economically with the increasing variations within components, without having to compromise on precision and production quality.

The KNCS-matic 3-jaw power chuck is available in six sizes, achieving a total clamping force of 100 to 250 kN depending on the size. The chuck can be used for a wide range of machining operations, since its jaws can be displaced or turned, and each jaw can be moved from 7 to 10 mm. In addition, KNCS-matic has a large passage of 52 to 165 mm typical of the KNCS series. With speeds of 1,700 to 6,000 min^{-1}, the KNCS-matic ensures high machining speeds with consistently high precision. The proven Proofline seal from SMW Autoblok makes the chuck low-maintenance. It can be individually adapted to the relevant machining requirements with an extensive range of accessories such as different jaws, an axial stop and a water flush.

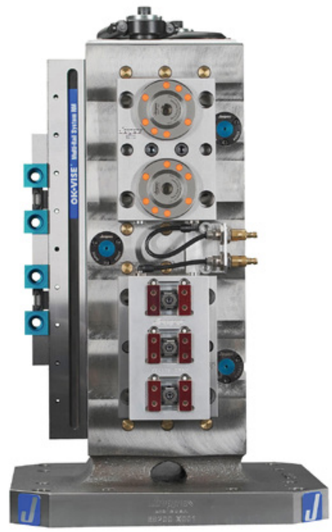
SMW-AUTOBLOK supports workpiece processing on the way to the digital factory with automated clamping devices. Together with SMW-Electronics, the company can outfit the process for a fully automated quick jaw change. The jaws of the KNCS-matic can then be replaced with the MX-S mechatronic gripper from the MOTIACT product range. An inductive coupling system such as the F100 enables contactless transmission of energy and signals between the robot arm and gripper, realizing its rotation by 360 degrees in both directions for easy jaw change.

smwautoblok.com

Jergens

OFFERS SIX STEPS TO CUSTOM DESIGN AND BUILD WORKHOLDING SOLUTIONS

Jergens Custom Design and Build workholding solutions are engineered around part configurations using standard products and a six-step process to reduce cost and lead time for customers. The advancements in the program are proven to guide customer decisions regarding the use of a dedicated solution versus standard off-the-shelf products, pinpointing Return on Investment (ROI) and productivity calculations.



The six steps to Jergens' Custom Design and Build program begin with the decision, or need, for a custom solution and proceed to concept, cost and timing, customer approval, initiation of manufacturing, and ultimately delivery. The process presents clear steps and milestones for both parties to reduce development time.

"There are a number of key objectives we focus on when recommending these solutions to a customer; they include achieving the greatest machining access, maximized number of fixtured parts, and minimal changeover for the shortest cycle times possible," said Omar Andino, Jergens national sales manager for the workholding solutions group. "Our six steps simplify and clarify the process, providing a streamline collaboration between our folks and customer stakeholders," Andino continued.

Adding quick-change to production boosts customer performance by minimizing change-over and setup time. Additionally, building a solution tailored to the exact needs of the component helps customers increase machining access, meet tight tolerances, shorten cycle times, achieve the lowest cost per part, and free up additional capacity. All of which supports high productivity as well as predictable and fast ROI.

Among the many Jergens products used are Ball-Lock mounting systems, QLS tooling columns, OK-Vise low profile edge clamps, and Zero Point System (ZPS). To produce the solution, Jergens relies on its decades of experience in engineering and manufacturing quick-change workholding systems.

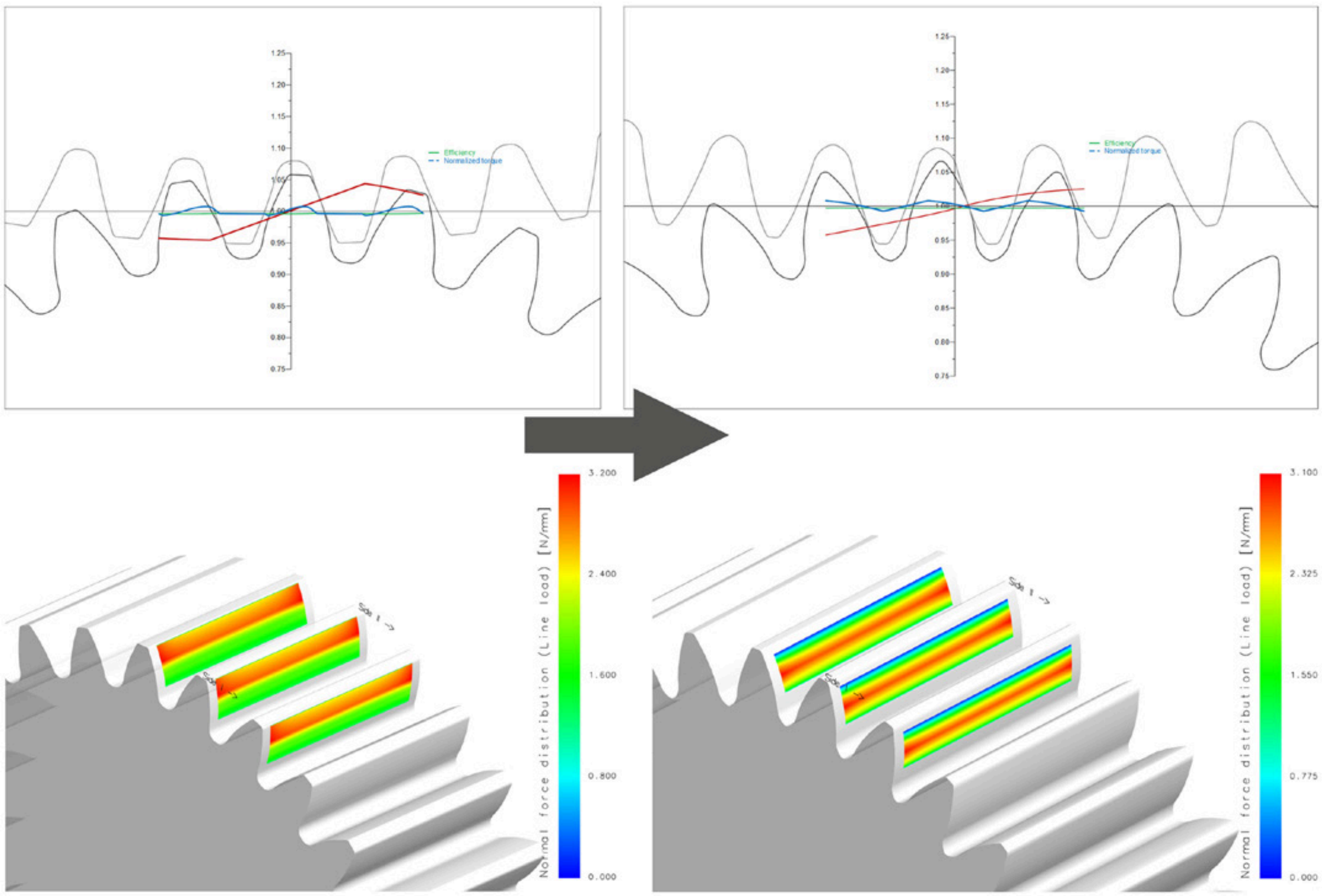
Successes with these unique solutions can be quite substantial. One such example with an automotive component manufacturer involved changing the machine tool from a vertical machining center with a 4th axis rotary table to a horizontal machining center using a tombstone fixture. A second change was to replace manual clamping with a hydraulic system. Finally, an all-new fixture was created to make full use of the alternate machine and workholding. The results were a reduction of setup from four hours (on the high end) to just 25 seconds, in total taking 61 percent out of the overall cost to produce each part.

jergensinc.com

Improving Power-Density and Efficiency of Plastic Gears

Applying non-standard design techniques to plastic gear geometry will significantly improve power density and efficiency

Swapnil Bhattacharya, Gear Design Engineer, Gleason Corporation



Contact pattern optimization and smoother meshing with the* KISSsoft *Contact Analysis tool.

It has been known that plastic gears have seen a rise in demand due to their inherent quietness, ability to run without lubricants, and low cost in high volume production. Due to the injection molding process, complex shapes and geometries can also be integrated into a single part, and the tooth form can be optimized free of traditional metal gear manufacturing process limitations.

Standard Tooth Form Design

Initial gear design was done on *KISSsoft* gear design software, using the Macro Geometry Rough Sizing Module. A 3.13 to 1 ratio was roughly sized using the VDI 2736:2013-modified (YF Method B) calculation method, considering the selected materials, required loads, and required minimum safety factors (amongst other considerations).

Table 1 details the initial design made for this purpose. This design uses a standard tooth profile, which will later be compared to an optimized plastic gear design that does not use a standard tooth form. Other geometry considerations, such as a minimum tooth tip thickness, tolerances, and tip rounding based on the EDM wire diameter, were also considered. Gleason Plastic Gears assumed an ISO 1328:2013 A8 Gear Quality using their proprietary No-Weldline Technology. Table 1 summarizes the gear pair data.

Figure 1 shows the meshing between the initial design of the polymer gear and pinion under load. This gives us a starting point only, with plenty of room for optimization. The dotted line represents the contact path with sharp transitions during tooth engagement and disengagement. This represents shocks that occur during the functioning of the gear pair due to high tooth deflection and unmodified profiles.

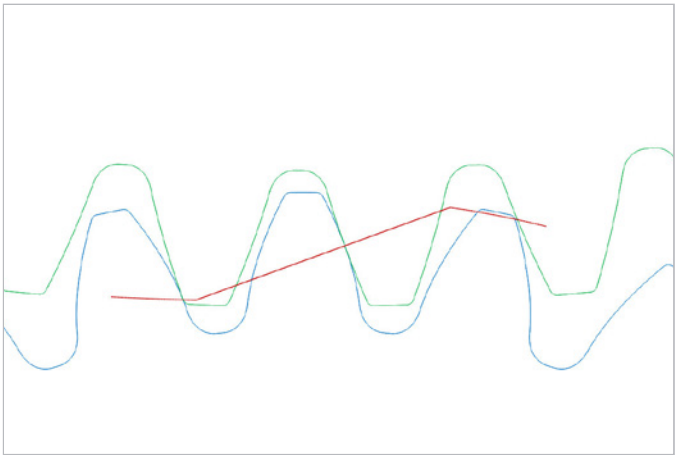


Figure 1—Gear meshing under load, along with the path of contact, shows some contact shocks and higher transmission errors when the gear pair rotates.

Gear data		Gear 1	Gear 2
Number of teeth		31	97
Normal module	mm	0.5	0.5
Facewidth	mm	5	4.5
Normal pressure angle	°	20	20
Addendum coefficient		1	1
Root radius coefficient		0.38	0.38
Dedendum coefficient		1.25	1.25
Profile shift coefficient		0.1946	-0.1946
Reference diameter	mm	15.5	48.5
Base diameter	mm	14.565	45.575
Tip diameter	mm	16.694	49.305
Root diameter	mm	14.444	47.055
Tip form diameter	mm	16.628	49.223
Root form diameter	mm	14.860	47.419
Tooth thickness tolerance	mm	-0.0381/-0.0508	-0.0381/ -0.0508
Quality (ISO 1328:2013)		8	8
Materials		POM	PA 66

Table 1—Gear data of the initial design.

Gear Stress Calculation

The initial design was sized based on the required load and minimum required safety factor under a given temperature using the VDI 2736 guideline and the Macro Geometry Rough Sizing Module in *KISSsoft* 2024. The calculation uses the input geometry and the material properties to determine the load-bearing capacity for a certain safety factor to be achieved on the gear pair. According to VDI 2736, the tooth root stress is calculated as:

$$\sigma_F = K_F \cdot Y_F \cdot Y_S \cdot Y_\varepsilon \cdot Y_\beta \frac{F_t}{b \cdot m_n} \leq \sigma_{FP} = \frac{Y_{St} \cdot \sigma_{FlimN}}{S_{Fmin}}$$

Investigation of the initial design yielded the following results:

Results	Gear 1	Gear 2
Root safety	2.093	1.493
Flank safety	1.832	2.283

Table 2—Root and flank safety as calculated according to VDI 2736 by KISSsoft.

The safety factors meet our minimum requirements, and now we also have some idea of the approximate center distance and face width needed to achieve the ratio and torque transfer required.

After further macro- and microgeometry optimization of the tooth form in later steps, the root stresses will be calculated and compared using the following methods:

- Analytical Method (Stress as calculated by VDI 2736)
- Loaded Tooth Contact Analysis (LTCA)
- FEM

Macrogeometry Optimization

Applying *KISSsoft*'s Macro Geometry Fine Sizing Module, the gear tooth profiles can be further optimized. Parameters such as tooth proportions, module, pressure angle, etc., can be varied and cross-calculated. The idea is to achieve an optimized macrogeometry solution that meets the design targets. In this design, the targets are:

- **High contact ratio tooth profile:** The gear tooth height can be increased by extending the gear tooth addendum and dedendum to target higher transverse contact ratios (2.0 and above). We must consider the effects of the stresses on the gear tooth flank and root, as well as specific sliding with higher contact ratio designs. In addition, tooth tip thickness needs to be considered here, as these types of designs can sometimes lead to pointed teeth.

- **Maximized root fillet:** With an extended dedendum and sufficient clearance to the mating gear tooth, a full root fillet can be used. Further steps to optimize this non-standard root geometry can be taken later.
- **Low/Balanced Specific Sliding (sizing of profile shift coefficients):** Specific sliding is the ratio of sliding velocity to the rolling velocity for a gear tooth. It is recommended by AGMA 917-B97 Ref. 1 to keep this balanced from the start of contact to the end of path to reduce tooth wear.

Table 3 presents the gear information after optimization of the pair. The module is slightly lowered to increase the number of teeth. This is done to increase the contact ratio.

Gear data		Gear 1	Gear 2
Number of teeth		34	109
Normal module	mm	0.45	0.45
Face Width	mm	5	4.5
Normal pressure angle	°	20	20
Addendum coefficient		1.11	1.31
Root radius coefficient		0.31	0.41
Dedendum coefficient		1.56	1.36
Profile shift coefficient		0.2961	-0.6768
Reference diameter	mm	15.300	49.050
Base diameter	mm	14.377	46.091
Tip diameter	mm	16.565	49.619
Root diameter	mm	14.162	47.216
Tip form diameter	mm	16.500	49.539
Root form diameter	mm	14.583	47.662
Tooth thickness tolerance	mm	-0.039 /-0.051	-0.039 /-0.051
Quality (ISO 1328:2013)		8	8
Materials		POM	PA 66

Table 3—Gear data of the optimized design.

Operating Backlash

Plastic gears typically are less accurate than metal gears and are highly sensitive to thermal and moisture effects. *KISSsoft*'s Operating Backlash Module was therefore used to consider not only tooth thickness and center distance tolerances, but also temperature and thermal expansion of the gears and housing, gear runout, manufacturing errors, and any potential misalignment. Tooth thickness tolerances, tip/root diameters, and/or center distance tolerances were then adjusted to ensure adequate backlash and tip clearance at all operating conditions.

Root Optimization

Once the macrogeometry is optimized, there might be a further need to examine the root, as modifications to the profile can often result in undesirable stress concentrations in the tooth fillet. It is an additional opportunity to also increase the strength of the root with non-standard geometry, and often high-contact ratio designs can lead to higher root stresses due to the cantilever effect of a tall tooth. Once again, this is a benefit of designing plastic gears manufactured by the molding process—the tooth and root shape can essentially be made to any shape required, within the limitations of manufacturing and injection molding tooling requirements. Elliptical root modification is one useful option to reduce stress concentration even more, as the stress can be lowered since it increases the material and reduces stress lines through the root. This might need to be followed with a radius at the root of the gear to reduce the sharp corners produced by the elliptical root modification, but not always.

A final verification using LTCA is performed after final microgeometry optimization to analyze the root stresses, contact, sliding, and transmission error.

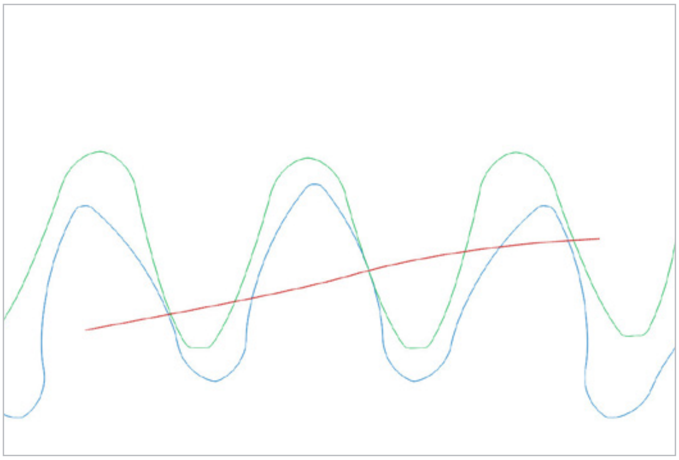


Figure 2—Meshing of the optimized gear pair under load, with the path of contact this time being free of any sharp points, indicating negligible contact shocks and lower transmission error.

Microgeometry Modifications

Profile modifications were sized and optimized in *KISSsoft* using the Modification Sizing Module. Flank line modifications were not considered due to the injection molding process. This can often be the most time-consuming part of the entire design process. Here we initially size some profile modifications such as tip relief, pressure angle modification, and/or profile crowning for a single load case. Then we vary the value and roll angle of the modifications on the active tooth profile across a range of operating loads for a single temperature case. Using Loaded Tooth Contact Analysis (LTCA), we can verify gear excitation, stresses, contact, and sliding in a loaded state, considering the microgeometry (which is not considered in the initial sizing using VDI 2736). Figure 3 shows the profile diagrams; no lead modifications were added due to the moldability of the part. Figure 4 compares the contact patches with the standard tooth profiles and optimized tooth and the presence of the highest contact on the center of the active profile and gradual changes are desirable outcomes of microgeometry addition.

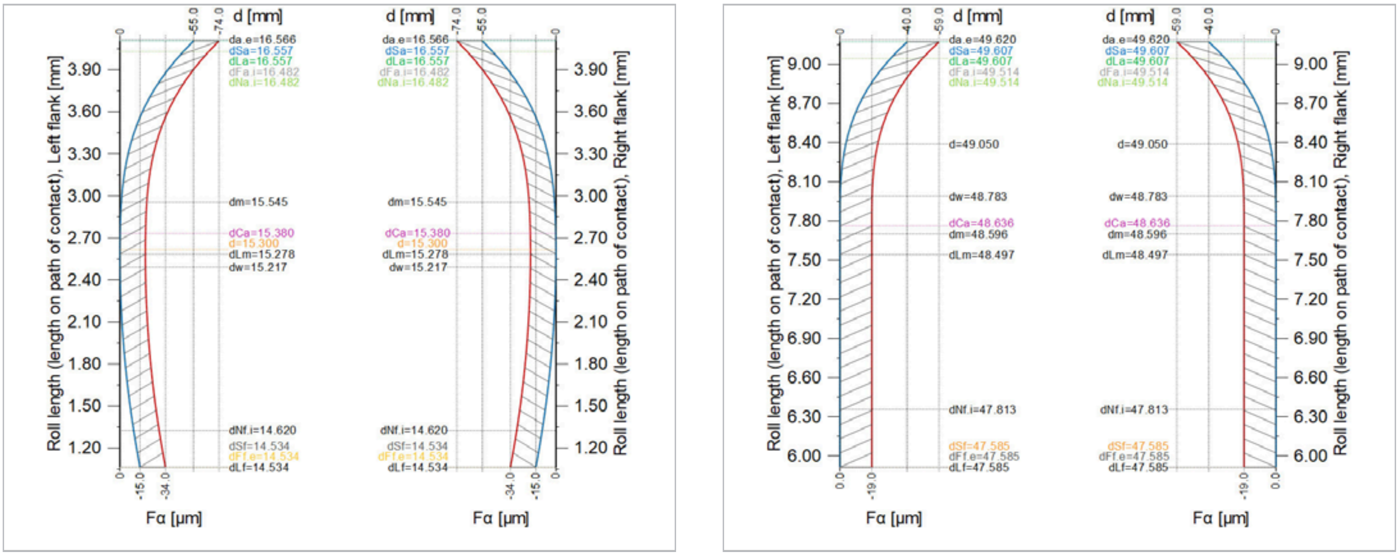


Figure 3—Profile diagrams for Gear 1 (left) and Gear 2 (right) with applied microgeometry corrections.

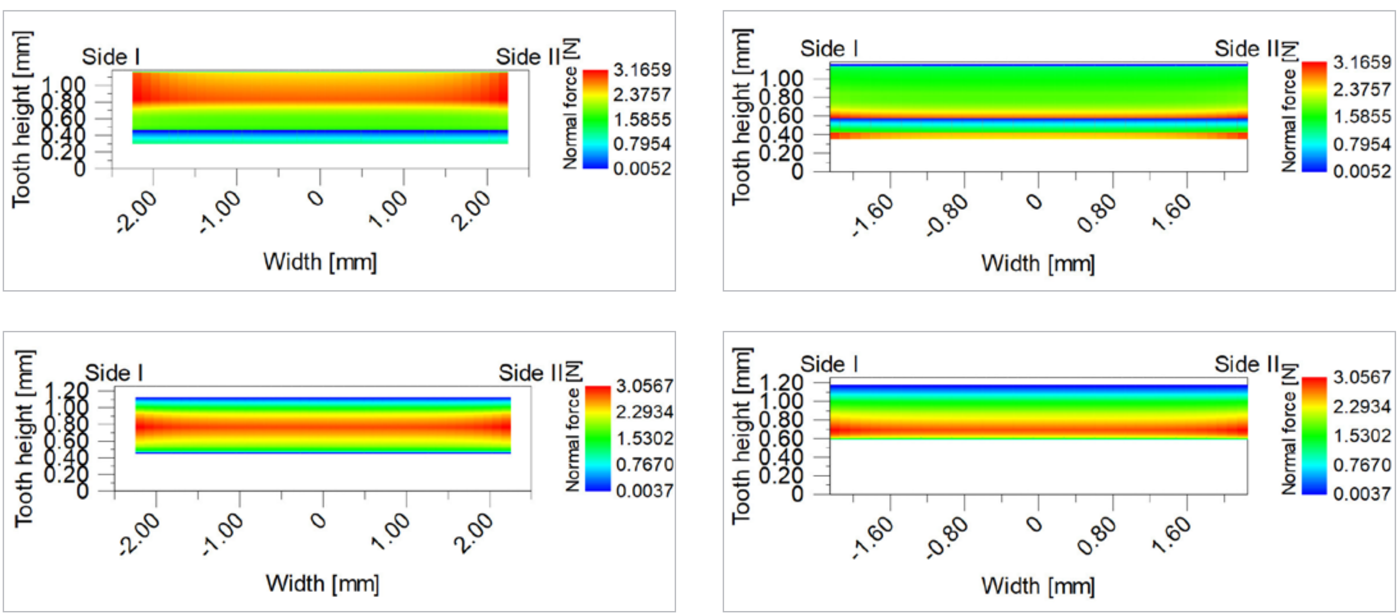


Figure 4—Contact pattern under load for Pinion (left) and Gear (right) shows contrasting pattern and non-uniform patches for standard geometry (top) and central contact zone and uniform transition for the optimized gear pair (bottom).

Stress Calculations After Optimization

Final stress calculations are shown in Table 4. It could be seen that the standard calculation results in ~42 percent and ~30 percent higher root stresses in Gear 1 and Gear 2, respectively. This calculation, according to VDI 2736 Method B, does not account for tooth deformation and load sharing. Thus, additional tools such as loaded tooth contact analysis show ~20 percent lower root stress for Gear 1 and ~13 percent higher for Gear 2, but overall, much better contact and lower transmission error, with sufficient safety factors. Figure 5 shows the FEM results for the gear pair stresses under load. In this, the Loaded Tooth Contact Analysis (LTCA) is used to simulate and does not show any major differences in the root stress.

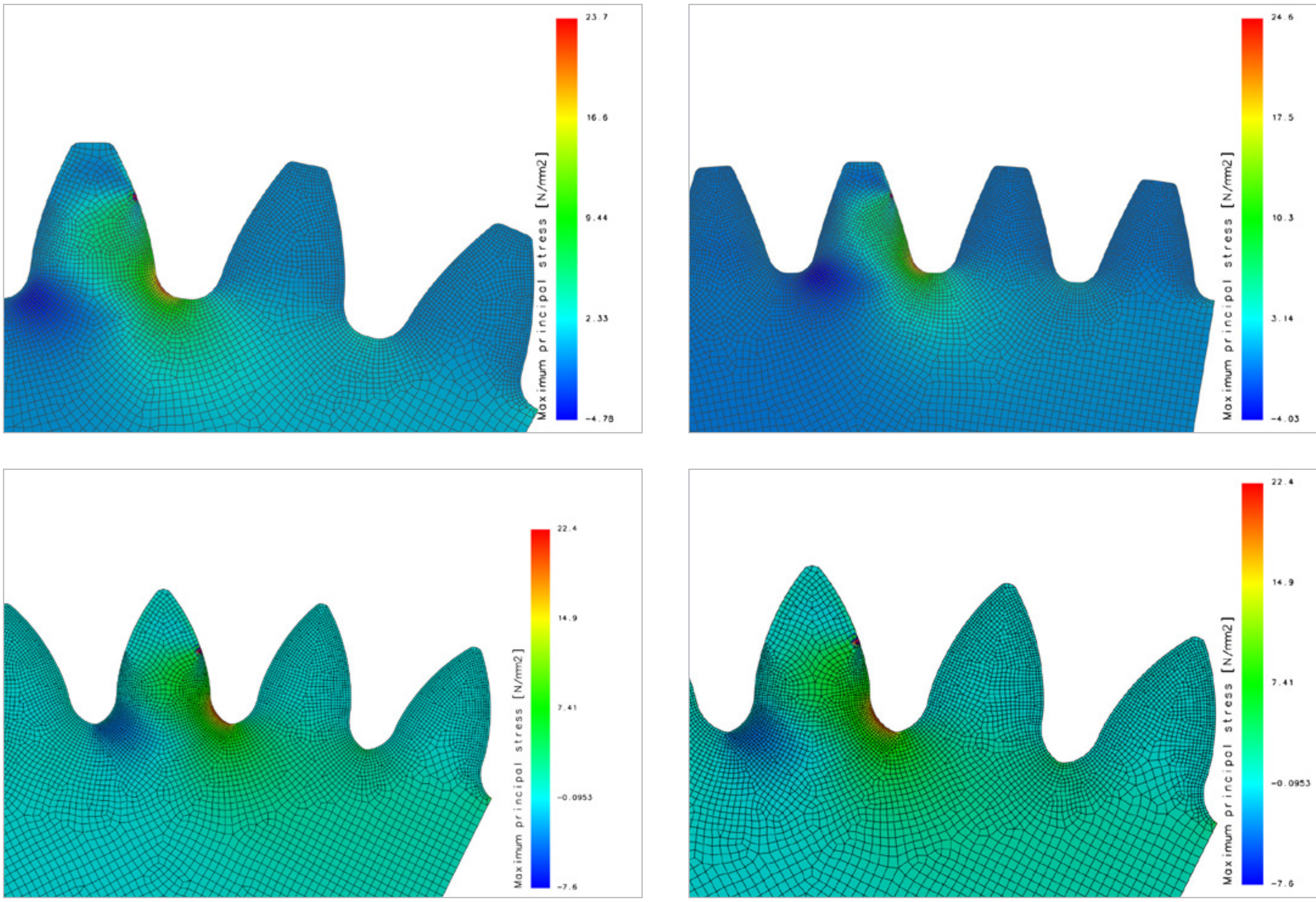


Figure 5—FEM results of the gear pair under load.

Standard Tooth Profile															
Gear #	*Teeth*	*Module*	*Face Width (mm)*	*Temp (deg C)*	*RPM*	*Torque (Nm)*	*Material*	*KISSsoft Tooth Root Stress (MPa)*	*LTCA Root Stress (MPa)*	*FEA Max Root Stress (MPa)*	*Allowable Bending Stress for Material (MPa)*	*Safety According to VDI2736*	*LTCA Root Safety Factor*	*FEA Safety Factor*	*Δ Transmission Error*
Z1	31	0.50	5.0	25	2500	0.1450	POM	21.69	18.19	24.80	45.40	2.09	2.50	1.83	7.78
Z2	97		4.5	25	799	0.4520	PA66	24.78	12.73	23.40	37.00	1.49	2.91	1.58	
Optimized Tooth Profile															
Z1	34	0.45	5.0	25	2561	0.1410	POM	32.23	14.57	24.30	45.40	1.41	3.12	1.87	3.14
Z2	109		4.5	25	799	0.4520	PA66	35.60	14.48	23.40	37.00	1.04	2.55	1.58	

Table 4—Summary of the results before and after optimization.

Conclusion

In this article, we explored plastic gear geometry optimizations that could be carried out using *KISSsoft*. It is encouraged to not stick with standard root shapes for polymer gears unless they are being hobbed which is a less desired process for plastic gearing. Injection molded plastic gears with optimized tooth shape were studied and compared to standard tooth shapes. It is concluded that even with a smaller tooth size, stresses are comparable or even lower on non-standard gear pairs.

The higher contact ratio achieved due to increased tooth count helps with load distribution and reduces transmission error, which leads to better acoustics of the gearset. While there may be more solutions and different designs that may satisfy the particular load case, this article emphasizes the need to use non-standard design techniques for plastic gearing, making polymer gears more power-dense and highly efficient.

kisssoft.com

Modernizing with Purpose

Liebherr gantry systems fuel Ford's EV ambitions in Europe

Photograph courtesy of Ford.

E-mobility is taking hold around the world, and the automotive industry is changing. Many manufacturers are shifting from internal combustion engines to electric powertrains. The Ford Motor Company—a long-term partner of Liebherr-Verzahntechnik GmbH—will be making most of the electric drive units for its European production at its UK transmission plant at Halewood near Liverpool. As before, Ford will be using Liebherr gantry technology, but for electric drive units rather than transmissions for internal combustion engines.

The world's sixth-largest car manufacturer aims to electrify its portfolio in Europe. The switch to producing electrical components in Halewood plays a crucial part in this. At this plant, Ford has invested for the first time in Europe in the production of components for all-electric vehicles, producing power units consisting of an electric motor and a single-speed transmission. 420,000 units will come off the production line annually instead of the previous 250,000 units, enough for 70 percent of the 600,000 electric vehicles Ford plans to sell in Europe each year.

The friction roller outfeed conveyor with the interface for unloading the good parts, behind it, the gantry system with the telescopic axes.

There are two reasons why Halewood was chosen. Firstly, it has enough space to expand production, and secondly, it is very close to the Liverpool City Region Freeport. This is a special economic zone created following Brexit, which offers special economic regulations, as well as customs and tax incentives.

Using Existing Technology Differently

Ford and Liebherr have been working together for 30 years, implementing numerous projects, including retooling projects. However, this was the first one to involve moving existing equipment to another location. “We took equipment from lines that were no longer producing internal combustion engines from Dagenham to Halewood, then upgraded and modernized them,” reports project manager Steve Treweek, senior process engineer at Ford Motor Company. “This saved us a lot of money—buying the lines brand new would have cost an additional 30–40 million euros.” The converted equipment was built in 2010 and is thus still relatively new. Retooling it is cost-effective, and the result is production lines that look—and run—like new.

Gantry Technology and e-Mobility

“If the project shows one thing, it’s that gantry technology is alive and well,” says Roman Buhmann, key account manager and Liebherr’s project manager for Halewood. “Anyone who thinks that gantry systems will die out along with combustion engines has got it wrong. Gantry technology is still needed—for producing gearboxes for electric drives just as much as for traditional engine blocks.”

Gantry Technology for the Entire Material Flow

The converted plant uses four lines to produce electric motor housings, gearboxes and covers and for assembling the transmission. Liebherr technology plays a leading role everywhere, including gantry robots for tooling the CNC machines (LP 200), gripper systems, connecting belts between gantry lines and maintenance areas, a tower storage system, state-of-the-art part tracking, and SPC stations for removing workpieces for quality assurance.

“Liebherr technology handles the entire material flow of transport, temporary storage, control and tracking—including process reliability, material flow optimization to guarantee cycle times on the production lines, as well as removal and data evaluation,” says Uwe Radigk, powertrain manufacturing sales manager at Liebherr-Verzahntechnik GmbH. “Only the control technology is completely new; 90 percent of the hardware is reused and upgraded. The energy supply chains have also been retrofitted, and the safety systems have been brought up to date to ensure the maximum possible occupational safety.”

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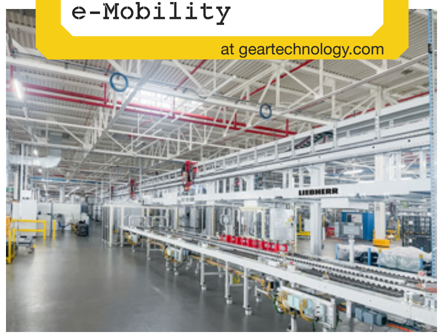

The friction roller outfeed conveyor for unloading the reject parts, in the background, the gantry system with the telescopic axes.

Productivity, Quality and Flexibility

The new plant offers a significant increase in productivity: availability will increase from 80–87.5 percent in the first step and up to 90 percent in the future. In terms of the gantry technology alone, it is no less than 98 percent. “The advantages of Liebherr gantry technology are clearly productivity, quality and flexibility in equipment and engineering—and also tidiness,” says Treweek. “Looking around the factory, you can’t tell that it’s used equipment. Everything looks brand new.”

Challenges During the Conversion

The change from producing heavy cast iron parts for diesel engines in commercial vehicles to the much lighter, more delicate parts for electric powertrains was one of the key characteristics of the project. The engine block for which the lines were originally designed weighed 120 kg, while the new electric motor block is about the same size but is made of aluminum and weighs only 13 kg. This meant all the axes and grippers of the gantry robots had to be replaced.

Another particular challenge was adapting the equipment to the low roof height in Halewood. The halls here are only 5.2 m high, while the standard height of Ford production halls is 6.4 m. Liebherr-Verzahntechnik GmbH specially converted the entire gantry system for the 1.2 m lower height.

The IT system was also changed: part tracking no longer takes place by reading data tags but using a cloud system. This means Liebherr not only moves the parts but also transfers the associated data.

On top of this, it was all done in a very short space of time, made more difficult by the coronavirus pandemic. Normally, a timeframe of 18–24 months is estimated for installing a new gantry system—without transferring all the equipment. This time, though, it only took eight months from the installation of the first beam to the initial test runs in production.

Seamless Collaboration

Treweek knew from the start that he would carry out this project with Liebherr. The decisive factors for him were not just the quality of the equipment, but also the know-how, comprehensive expertise in Ford projects and the reliability of the Liebherr engineering team. “Over the last 15 years, I have had all my gantry technology supplied by Liebherr,” he says. “I’m very experienced and know exactly what I need—but even with less experienced Ford project managers, the Liebherr team would have mastered the task. I know what the teams, assembly crews and project managers can do. When it comes to the whole system, there’s no one comparable.”

The excellent collaboration between the Ford and Liebherr teams was crucial in ensuring that the Halewood project ran smoothly despite all the challenges. “This kind of thing is only possible with Liebherr,” Treweek emphasizes. “We have a deep mutual understanding and both teams complement each other perfectly. I would always argue for Liebherr as a supplier. As a Ford project manager, I need quality, reliable project partners and a good team on my side—and this is exactly what they give me. It’s a pleasure to work with Liebherr.”

liebherr.com

From Gear Mesh to System: Advanced Prediction of Transmission Error

Eliminating common assumptions of single gear mesh calculations by considering the full system for higher-fidelity gear transmission error prediction and gearbox NVH analysis

Kristian Kouumdjieff, Product Manager–Romax Enduro & Romax Spin, Design & Engineering BU, Hexagon; Shantono Biswas, Aerospace Applications Engineer, Design & Engineering BU, Hexagon; and Annabel Shahaj, Global Engineering Manager–System Dynamics, Design & Engineering BU, Hexagon

The demand for lower emissions and greater electrification is intensifying in the realm of transmission applications, especially within the automotive industry. At the same time, there is a push to enhance performance and quality. This evolving landscape necessitates sophisticated structural design strategies, focusing on lightweighting, durability, and the optimization of noise, vibration, and harshness (NVH). Fortunately, engineers now have access to ever-advancing tools that facilitate a CAE-led design approach, offering valuable insights at each stage of development with the appropriate level of detail. This approach minimizes design iterations and reduces the reliance on physical testing, ultimately saving both time and costs.

In a multi-fidelity modelling process, simpler and faster models are invaluable for early design exploration, such as assessing the impact of different tooth geometries on robustness. As development progresses, higher-fidelity models become crucial. Though they demand more detailed design inputs and are computationally intensive, their true value lies in the later stages of development, where they validate a select few, more refined design choices.

This paper delves into the analysis of gearbox transmission error and the resultant vibrations within a representative electric vehicle (EV) powertrain model. Transmission error (TE) quantifies the displacement of the gear mesh induced by the combination of varying tooth contact force, mesh stiffness, and flexibility of the system. Two levels of fidelity of TE analysis are considered in this paper: single mesh loaded tooth contact analysis (LTCA) and gearbox transmission error (GBTE) analysis. In addition, these approaches are combined in turn with two distinct tooth contact models—a Basic uncoupled 2D finite element model, and an Advanced coupled 3D finite element model. This gives us four different combinations to compare and contrast.

GBTE analysis, see Figure 1, is a quasi-static phased system analysis that evaluates the gearbox at multiple rotational angles. It performs an LTCA at each angle, accurately phasing all gear meshes. By considering system coupling and the phasing of all gears, GBTE analysis captures the complex interactions within the system, such as those occurring in planetary gearsets. It facilitates the calculation of the overall gearbox transmission error.

This analysis adopts less restrictive assumptions than single mesh calculations, allowing for variations in misalignment and torque through the gear meshes and system deflections during the meshing cycle. It considers changes in stiffness experienced by the gear mesh as the system rotates and recognizes that forces in one gear mesh can affect forces in others. Additionally, this approach allows the gear mesh to transfer moments in the misalignment direction, in addition to forces along the line of action, providing a fuller picture of the gear excitations, resulting in predictions of linear TE and tilt TE.

Linear or transverse TE is widely recognized as one of the main sources of gear whine noise. In contrast, tilt TE is less frequently discussed and is referred to by different terms, such as force axial shuttling, so it is worth clarifying, see Figure 2. Tilt TE results from the slight axial movement of the centroid of the gear mesh force as the gears rotate through the mesh. This axial shift arises from the varying load distribution along the lines of contact and is also influenced by the rest of the system, such as other gear meshes and bearing stiffnesses. By solving the entire system in the gearbox transmission error (GBTE) analysis at each rotational step, with all components accurately phased, these variations and interactions are effectively captured.

The GBTE analysis provides critical parameters for NVH analysis, including linear TE, tilt TE, and linear, tilt and cross-term mesh stiffness. These calculated values can be integrated into the NVH model. By coupling and solving the entire system with correct mesh phasing and accommodating variations and interactions, the analysis achieves much higher fidelity than single mesh LTCA.

Similarly, the Advanced tooth stiffness model captures more effects than the Basic model, see Figure 3. Specifically,

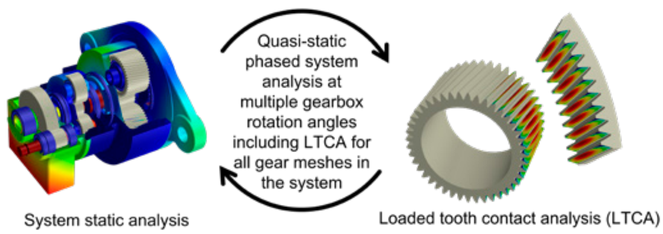

Figure 1—Gearbox transmission error (GBTE) analysis.

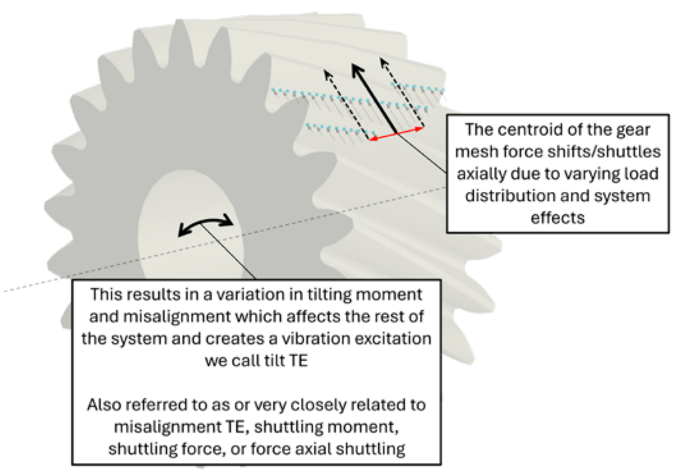

Figure 2—Tilt transmission error (TE).

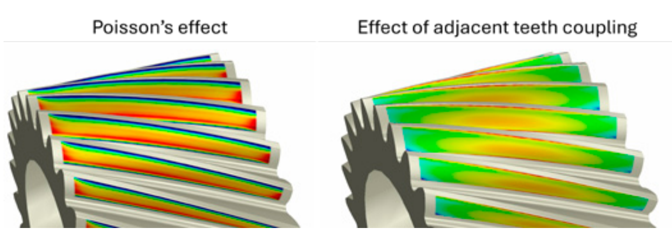

Figure 3—Additional effects captured by the Advanced tooth stiffness model.

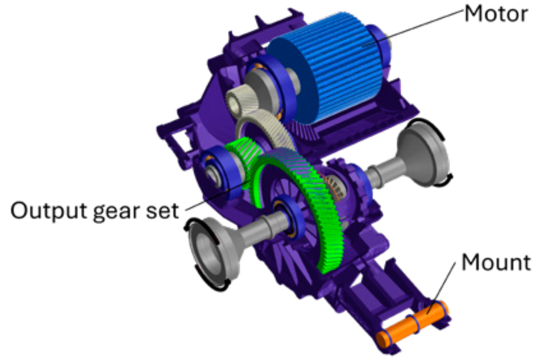

Figure 5—Example electric powertrain model.

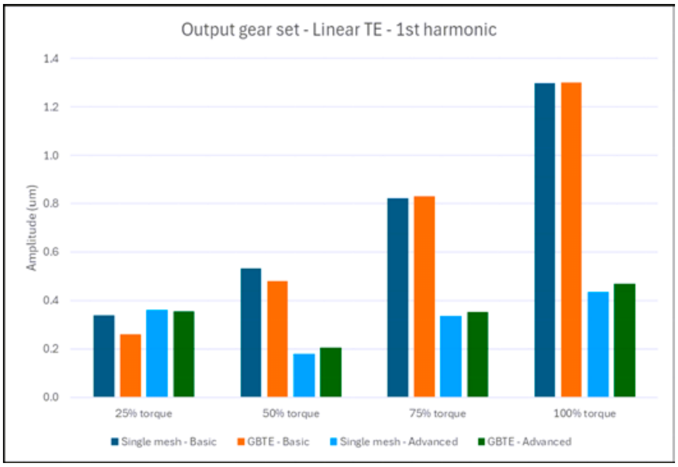

Figure 6—Linear TE comparison.

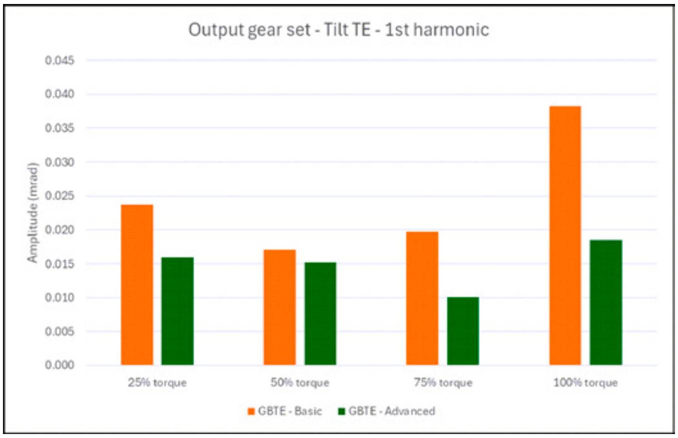

Figure 7—Tilt TE comparison.

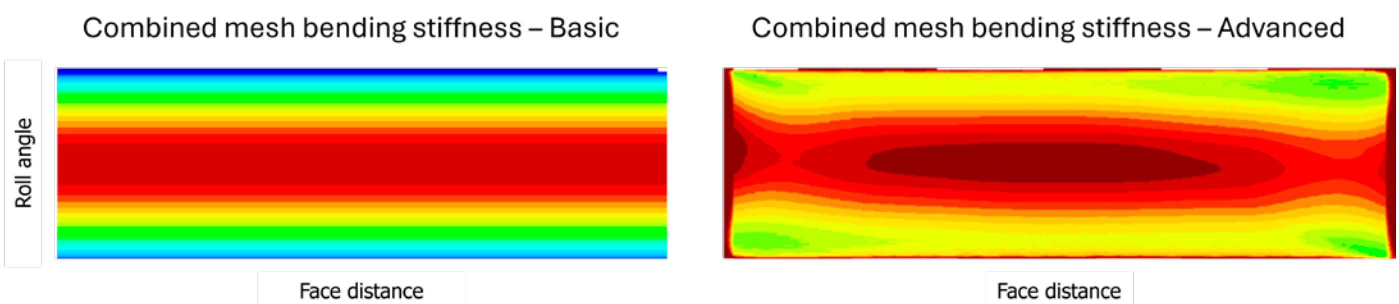

Figure 4—Combined mesh bending stiffness comparison between Basic and Advanced.

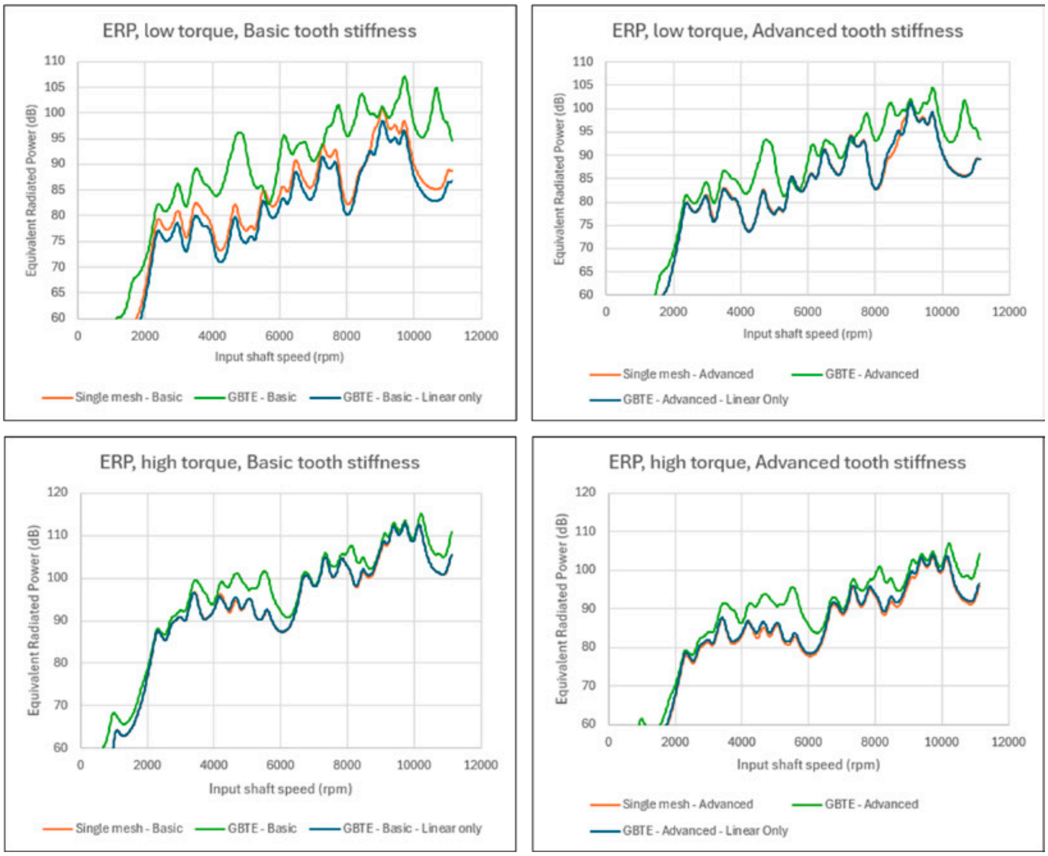

Figure 8—ERP comparisons with and without tilt TE included.

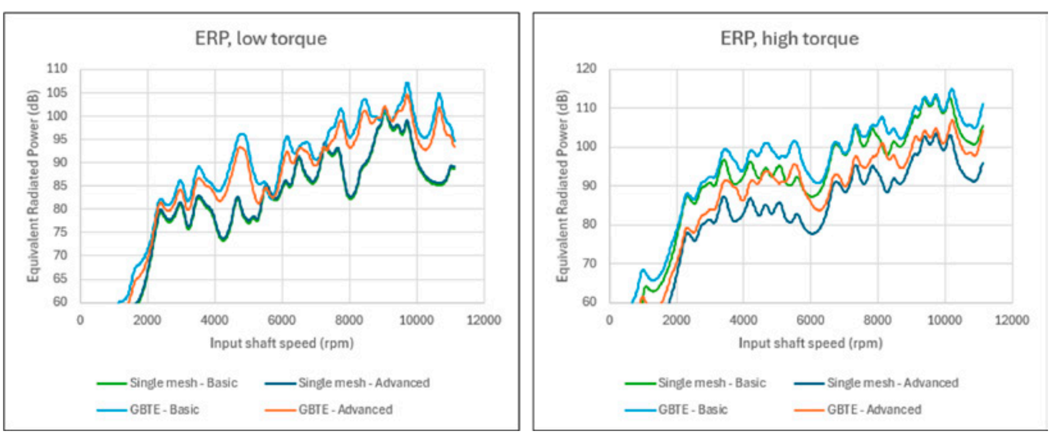

Figure 9—ERP comparisons of all 4 combinations for low and high torque.

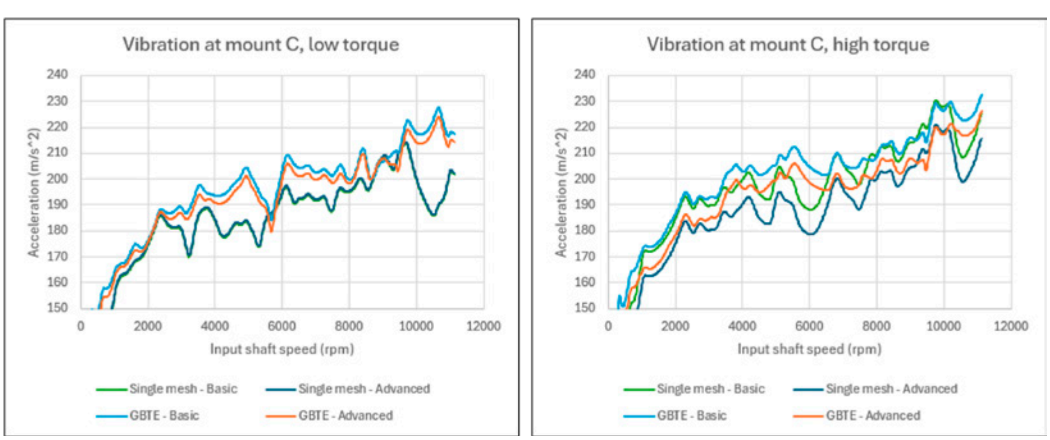

Figure 10—Comparison of vibration at one of the housing mounts for low and high torque.

the material coupling within a single tooth captures Poisson's effect, which causes the tooth to assume an anticlastic curvature that alters the load distribution and can result in peaks towards the side edges if insufficient lead crowning or end relief is applied. Coupling between adjacent teeth can cause peaks near the tip and root due to the highest-loaded teeth deflecting more, increasing the load on the teeth that are just coming into or out of contact, especially at the corners where contact starts or ends.

Considering these effects not only impacts the load and stress distribution, but also influences the mesh stiffness, which is a crucial part of the TE calculation. The combined mesh bending stiffness from the Basic model is a relatively simple curve that is constant across the gear face width. In contrast, the combined mesh bending stiffness from the Advanced model is more complex and varies with face width, see Figure 4.

A comparison is presented of the results of different fidelity methods to demonstrate how the latest advancement in GBTE analysis—incorporating the Advanced tooth stiffness model—stacks up against single mesh LTCA analysis and Basic tooth stiffness within a unified modeling environment.

The following case study was conducted using an EV powertrain simulation model, which includes representations of bearings, an electric motor, input and output gearsets, shaft assemblies, finite element (FE) internal components and housing, and housing mounts, see Figure 5. Gear excitations are calculated using both single mesh LTCA and GBTE analysis, each utilizing Basic or Advanced tooth stiffness. These excitations are then applied to vibration and acoustic analysis to assess their impact on NVH performance.

The initial results compare the first harmonic of linear TE from the output gear set across a range of torque levels, see Figure 6. These results highlight the difference in linear TE between the Basic and Advanced tooth stiffness models. At low torque, the differences are small, while at higher torque, the Advanced model predicts significantly lower linear TE. Further investigations, not shown here, indicate that this discrepancy largely stems from the variations in combined mesh bending stiffness mentioned earlier.

While the difference in linear TE between single mesh LTCA and GBTE analysis is relatively minor, the GBTE analysis uniquely predicts tilt TE, which the single mesh analysis does not account for and is therefore effectively zero. Similar to linear TE, tilt TE predicted by the Advanced tooth stiffness model is lower than that predicted by the Basic model, as illustrated in Figure 7.

To assess the significance of these differences and the impact of considering tilt TE, the vibration and acoustic response can be studied. The subsequent results compare the housing equivalent radiated power (ERP) at high and low torque levels, which indicates the acoustic radiation from the gearbox housing. In addition, a comparison is made between GBTE analysis, with and without tilt TE, and single mesh LTCA, see Figure 8.

GBTE analysis with only linear TE and single mesh LTCA yields very similar ERP at both low and high torque, using both the Basic and the Advanced tooth stiffness models. However, the full GBTE analysis, incorporating both linear and tilt TE, consistently shows higher ERP. This suggests that the main difference in ERP between single mesh LTCA and GBTE analysis is due to the inclusion of tilt TE excitation. In regions with larger discrepancies between the two methods, certain modes are more easily excited by tilt excitation, which can be analyzed further and mitigated if needed.

A comparison of ERP for the four combinations of types of analysis and tooth stiffness models is presented in Figure 9.

The single mesh LTCA with the Advanced tooth stiffness model yields the lowest ERP, while the GBTE with the Basic tooth stiffness model results in the highest ERP. The most accurate combination, the GBTE analysis using the Advanced tooth stiffness model, falls between these two extremes. Additionally, it is worth noting that at low torque levels, the difference between Basic and Advanced tooth stiffness is relatively minor, corresponding with earlier observations from the TE comparisons.

Structure-borne vibration can also be evaluated by analyzing the vibration at one of the housing mounts, as depicted in Figure 10. The trends mirror those observed in ERP. Comparisons including GBTE analysis without tilt TE excitation (not shown) show that the vibration when tilt TE is included is noticeably higher. When the four combinations of types of analysis and tooth stiffness models are examined, once again, the single mesh—Advanced case shows the lowest vibration, the GBTE analysis—Basic shows the highest vibration, and the highest fidelity case of GBTE analysis with Advanced tooth stiffness predicts vibration somewhere in between. Once again, at low torque, the differences between Basic and Advanced tooth stiffness are small, while much more pronounced at high torque.

Automotive customers have made similar observations in their analyses and specific applications. One customer noted that using the Advanced tooth stiffness model correctly predicted that a modification to the design resulted in improved NVH performance as observed in physical tests, while a competitor tool predicted the opposite. Another customer shared that, in some of their applications, the tilt TE has a relatively small impact, while in other projects, they have observed extreme sensitivity in sound power with changes to tilt TE.

Although reduced fidelity modelling lends itself to fast assessment of the design space for making early design decisions, the full system approach to TE calculation, i.e., the GBTE analysis, combined with Advanced LTCA, captures more effects and eliminates some underlying assumptions such as fixed load sharing and misalignment. Therefore, the TE predictions and subsequent NVH analysis from the higher-fidelity approach include more physics and produce results that allow more insight into the expected behavior of the final produced component. By taking a multi-fidelity CAE-led approach to design, the analyst can evaluate where additional detail makes a difference to the results and, as such, can judge how, when and where the highest fidelity is needed.

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Industrial Flexibility

Drive System Design Examines Electrification and e-Mobility Markets

Matthew Jaster, Senior Editor

Hybrids, range extenders, electric vehicles, ICE vehicles and autonomous driving: There's a little bit of everything in the automotive market today. Electrification and e-Mobility remain the end game, but politics, global policies, tariffs, and infrastructure challenges have put the "all-in on BEVs" on hold for the moment here in North America. The biggest question is how long will the electrification and e-Mobility markets fluctuate?

ICE-related technologies remain strong here in the United States while China remains steadfast on its mission to provide plug-in hybrid vehicles to its consumers. Tesla has its own unique set of challenges. So how does a company like Drive System Design respond during periods of market uncertainty? They adapt, evolve and diversify.

David Hind, principal engineer, Drive System Design (DSD), recently shared his insights on the state of electrification and e-Mobility today.

"I think the overriding feeling is that things will still go electric eventually, but maybe not when we first thought. There's a resurgence of some things like range extenders, hybrids, etc., and DSD is well positioned to cater to all these technologies. We have an extensive background in hybrids and range extenders as well as internal combustion engines, so we're in a great position to meet the evolving needs of the automotive market," Hind said.

DSD is a leading engineering and mobility consultancy within the Hinduja Tech group specializing in the development of next-generation electric and hybrid powertrains, internal combustion engines, and associated technologies. The company offers test facilities in the UK, United States and India with a presence in Australia, Japan and South Korea.

Electrification Trends

Size, speed and efficiency continue to play an impactful role in components for electric vehicles and e-Mobility applications.

"We're seeing a number of trends in this space today," Hind said. "Motors going to higher speeds, unlocking the benefits of size reduction and increased power density. On the inverter side, Silicon carbide is already a mainstay, but we're seeing people moving toward GaN technologies and more complex architectures as well." (GaN stands for gallium nitride, which is a crystal-like semiconductor material. GaN chargers can deliver power more quickly, charging up to three times faster than standard chargers).

"We're also seeing a big uptick in multilevel inverters, not just for the inverter itself, but also for motor size reduction as the lower harmonic content from the inverter can allow a reduced thermal size of the motor. This translates into massive savings. In terms of electrified EDUs, we see this trend towards what we call "X-in-1" essentially taking more functions that would have previously been separate boxes all around the vehicle and then putting them into one box and trying to make the design as compact as possible. This is a great fit for DSD with our transmission and control expertise," Hind said.

The transition from aerospace technologies being implemented into automotive applications has been noteworthy for many years, but Hind is seeing some of these developments go from automotive to aerospace—and branch off into several additional markets.

"We're seeing big safety considerations taking place currently in aerospace as well as automotive. Sensor technology, for example, continues to offer accuracy, quick response times and invaluable data for monitoring and controlling performance. These aren't new ideas but they're being implemented in other areas such as oil and gas, off-highway, marine and defense applications. Now that electrification is happening across the board, there are huge growth opportunities in electric vehicles in these areas," Hind added.

North American Outlook

A new technology for the next generation of high-speed, high power density traction and propulsion systems has been jointly developed by DSD and Transense Technologies. Hind recently presented this topic "Unlocking Powertrain Power Density with Innovative Motor Control," during the CTI USA Symposium. The visit gave him a unique opportunity to look at some of the key electrification developments taking place currently in North America.

Editor's Note: An article on this subject and some talking points from Hind will be included in the next issue of *Power Transmission Engineering*.

"There's plenty of question marks in North America right now," Hind said. "We mentioned earlier about the shift to multilevel inverters so we're seeing more and more people working on those. Tier One manufacturers are developing devices specifically to support that. It's not just about R&D anymore, you're starting to see a shift in manufacturing. OEMs can't go away and just do whatever they like. They need support there from the industry manufacturing parts underneath."

Another obstacle continues to be infrastructure. The ability to put charging systems in place across the United States will determine how quickly the industry will evolve.

"Particularly regarding large commercial vehicles traveling across state lines. There's talk of putting this megawatt charging capability in for those guys to be able to charge up. And, yeah, I think getting a system like this in place is going to be the key to unlocking electrification here down the road," Hind said.

Preparing for the Future

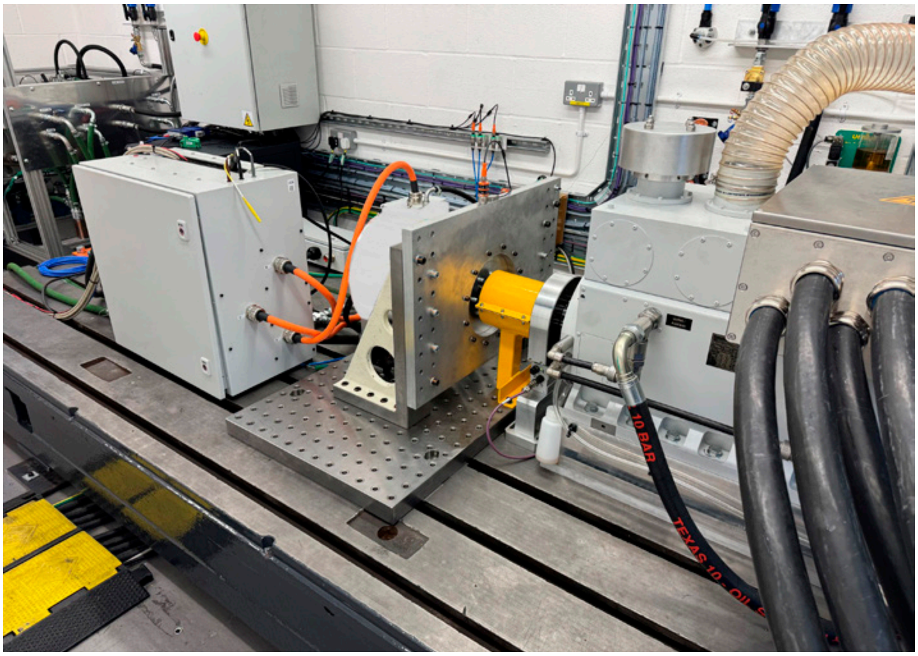
How does one navigate the electrification and e-Mobility markets in 2025?

Experience helps and according to Hind DSD attracts some of the best and brightest engineers in the industry. "I think that's partly because of the varied and interesting engineering work we do here. When it comes to designing EDUs, we've got everything we need in terms of people and facilities to perform these tests in a controlled environment."

DSD has been at the forefront of the electric vehicle sector since 2010. They offer increased capability in power conversion, including the development of DC-DC converters, onboard chargers and PDUs, as well as broadening their "X-in-1" design capabilities as full system developers.

OEMs and manufacturers in automotive, aerospace, defense, commercial vehicles, off-highway, and marine sectors will benefit from these advanced skills and integrated solutions. DSD consults on detail design and optimization of driveline systems including "X in 1" EDUs, transmissions, geartrains and ancillary systems.

"I was at the Farmington Hills, MI, test facility last year and the company



Drive System Design offers in-house design, development and testing for the rapid development of systems and components.

Drive System Design provides independent testing for powertrain systems including EV propulsion and transmissions, motors, electronics and more.

has invested a lot of money to provide our North American customers with the same testing and development technologies we provide in the UK," Hind said.

The Michigan facility features high-speed motor dynos and high-power drive unit test rigs—capabilities in high demand from customers in the region. With the fluctuations in automotive, DSD has transitioned and expanded its expertise in off-highway and defense propulsion systems.

Additional capability offered by the facility includes the support of hydraulic system development and loaded testing. The company has commissioned a 3E rig and has installed a battery emulator, for electric and hybrid vehicle development and hardware in the loop (HIL) testing. Existing driveline test equipment includes a transmission efficiency test rig that is suitable for all transmission types, including engine accessory drives, such as supercharger and CVT drives.

The latest UK facility—opened in May 2023—built on the success of DSD's first high-speed eMachine test cell and supports a variety of development tests including calibration and control optimization projects and meets escalating customer demand for more powerful, efficient, and compact electric machines.

The facility is equipped with a 600 kW dyno, supporting eMachine and inverter development and validation. With up to 24,000-rpm, the rig offers a highly flexible, automated testing approach that shortens development cycles and accelerates time-to-market for DSD's customers. Combined with the company's proprietary motor testing power analysis routines and deep engineering expertise, DSD can deliver a comprehensive eMachine calibration loop, which gives customers rapid, actionable insights for advanced development.

And this flexibility is why DSD can provide consistent testing protocols and quality data for its global customer base—allowing DSD to efficiently balance workloads across regions, minimize bottlenecks and offer localized support.

With the volatile electrification outlook, especially in North America, Hind believes DSD is still prepared to keep up with trends and market demands in automotive applications.

"I think this comes back to providing a diversity of the solutions we see people developing right now," Hind said. "I don't think it's probably a good idea to hedge all your bets on one thing. Certainly, in terms of electrification in converters and motors, there's several competing technologies which are still good, strong candidates in the right application. Overall, automotive suppliers need to pay attention to the many competing technologies to understand which ones are going to be leading contenders down the road."

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Four Bonus Reasons to Join an Emerging Technology Committee

Mary Ellen Doran, AGMA Vice President, Emerging Technology

In today's rapidly evolving manufacturing landscape, keeping up with emerging technologies isn't optional; it's essential. That's why AGMA launched its Emerging Technology Committees eight years ago: to help member companies stay informed and future-ready.

At the time, I understood the need for this effort, but what I didn't anticipate were the unexpected bonuses committee members have uncovered by participating in this free, accessible resource. While our standards development committees benefit from a century of bringing together specialists—bevel, worm, precision, you name it—the Emerging Technology Committees offer something different. They're a cross-section of the industry: executives, machinists, salespeople, engineers, Gen Z to Baby Boomers—all coming together to explore the unknown.

This unique mix leads to surprising discoveries and unexpected benefits. Here are four ways committee members have found added value from being involved:

1. Find Your Inner Geek—In Unexpected Places

The topics we explore—blockchain, artificial intelligence, powder bed fusion, and more—are novel for almost everyone in the room. That's the point. Rather than leaning solely on deep expertise, members draw on curiosity, backed by a strong knowledge base.

The result? Fascinating, cross-disciplinary conversations. When tech entrepreneurs who've created new machines sit down with gear veterans, the knowledge exchange can lead to streamlined processes, problem-solving breakthroughs, shortened lead times, or even new products.

2. Get Your Hands Dirty

These aren't passive discussions. Committee members shape the direction of research and conversation. Interested in how 3D printing could repair gears? Say the word. Want to explore AI-driven tools for your documentation process? We'll get the right people in the room. Curious about robotics, cybersecurity, or additive manufacturing for cutting tools? Let's go there together.

Discussions evolve to meet the specific needs of the gear industry. Whether it's tackling long lead times for castings or navigating CMMC 2.0, these committees are places where pain points are addressed—and possibilities uncovered.

3. Feel Like You've Won a Golden Ticket

Committee participation connects you with forward-thinking professionals and opens doors to exclusive opportunities. From early access to emerging trends to curated events, the benefits are real.

We've partnered with AMT and NTMA to host in-person think tanks. We've led guided tours at RAPID since 2019, invited more than 100 outside experts into our discussions, and hosted nearly 50 webinars. Our work has led to meetups, facility tours, collaborations, and even white papers. This isn't just a seat at the table, it's a front-row seat to what's next.

4. Discover Something That Helps Your Business

Ultimately, what you gain here isn't just knowledge—it's impact. Many members leave with something they can use immediately: a faster way to print fixtures, a predictive maintenance idea, a new contact who can solve a tough technical challenge.

These committees are idea incubators. The ROI isn't hypothetical; it's in your shop floor improvements, your process optimizations, and your strategic pivots. It's professional development with a real-world payoff.

The Future Is Being Built—Join Us

Joining an Emerging Technology Committee won't just keep you current—it will change how you think, work, and lead in this industry. Whether you're an engineer, a manager, or simply curious about what's next, there's a place for you here.

Jump in. The future is already taking shape—and we want you to help shape it.

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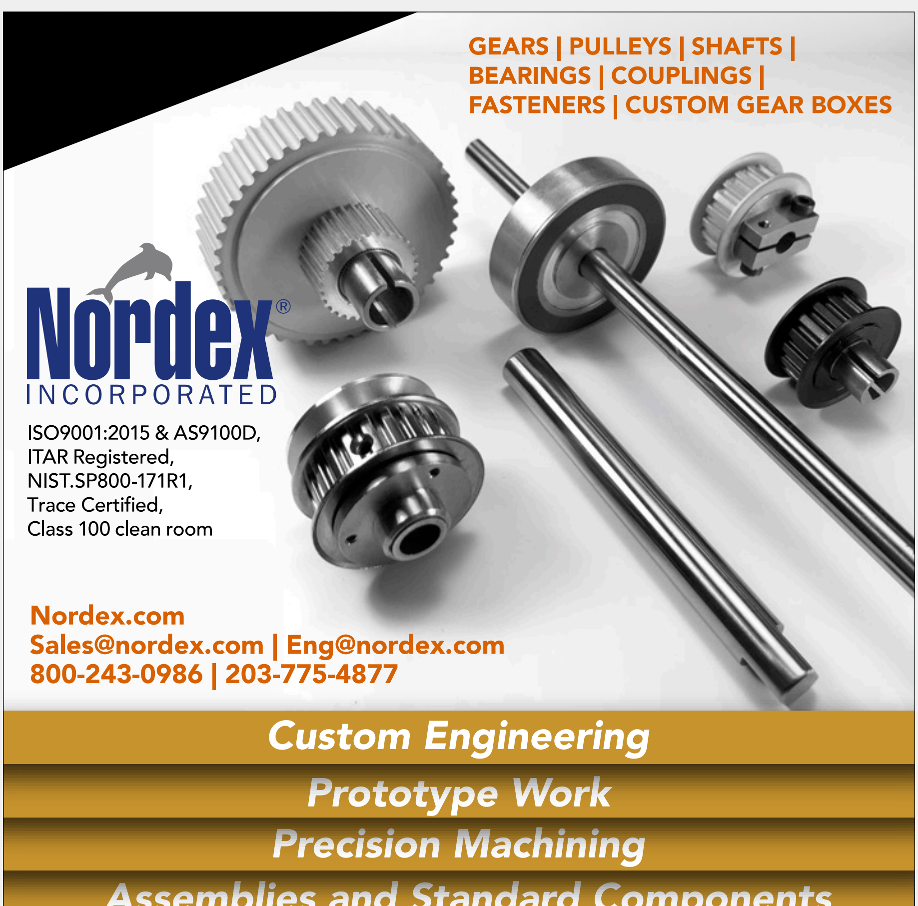

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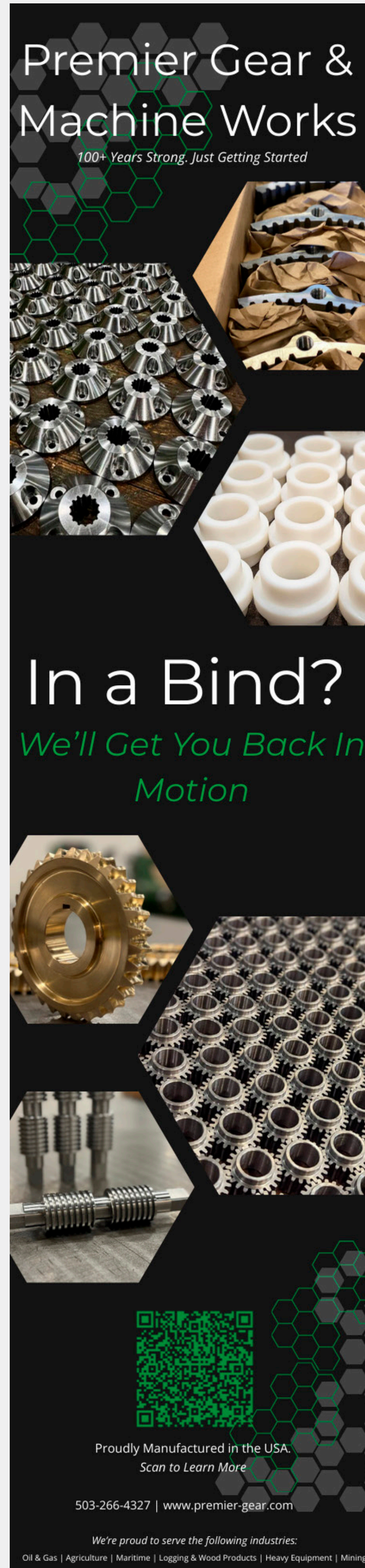

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Decades in the Making: ANSI/AGMA 2101-E25

Frank Uherek, Principal Engineer–Gear Engineering Software Development, Regal Rexnord Corporation and Courtney Carroll, AGMA Senior Manager, Technical Services

Publishing technical standards is a lengthy process that takes place over several years. After the process of the working group writing the document, AGMA staff making changes from the General Ballot, and completing all associated ANSI documents, it is finally time for the working group to turn the document over to AGMA staff for publication. These final publication tasks are to:

- Create publication draft and final formatting to AGMA style guide requirements.
- Go through the publication checklist.
- Final review by the working group leader/volunteers to make sure all final changes from the General Ballot are correctly incorporated.
- File the ANSI BSR 9 form to report the voting summary and register the project as complete with ANSI.
- Final AGMA publication actions:
  - Send the new publication to online resellers.
  - Add a new publication to the online store.
  - Announce the publication via AGMA newsletter, press release, *Gear Technology* and other AGMA media, etc.
  - Notify the technical representative at each AGMA member company of the new publication and how to obtain it.

Sometimes the process can be extra complicated. This leads us to the case of ANSI/AGMA 2101-E25.

Work on the new edition began soon after the publication of the 2004 edition. The committee set out with the goal of using ISO 6336 as the base document and incorporating the unique features of ANSI/AGMA 2001. As this process continued, many in the gear community felt the need to maintain ANSI/AGMA 2101 for use as a fundamental standard and in various application standards derived from it. This resulted in a major course correction back to the basis of the 2101-D04 document and improvement to rating methods and specifications. Having reached the final agreement on the draft, two committee ballots and a general ballot were held to confirm that we had reached consensus.

And without further ado, AGMA is pleased to announce the publication of: ANSI/AGMA 2101-E25, *Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth,* written by the AGMA Cylindrical Gear Rating Committee.

ANSI/AGMA 2101-E25 provides a choice of methods by which different gear designs can be theoretically rated and compared.

ANSI/AGMA 2101-E25 added an extensive discussion of safety and service factors, and removal of the unity factors for size and surface condition. New factors added to the standard were Y_I reverse bending factor and K_γ mesh load factor. The grade requirements for non-metallic inclusion, ultrasonic, and microstructure characteristics apply only to those portions of the gear material where the teeth will be located to a depth below the finished tooth tip of at least 1.5 times the tooth height, was 1.2 times the tooth height. The term pitting was replaced with macropitting to match the usage in ANSI/AGMA 1010. Maximum case depth is now measured at the tooth tip rather than on the flank.

On behalf of the gearing industry, AGMA would like to extend a sincere appreciation for the participation and the valuable contributions of the listed experts. In addition, AGMA would like to thank the companies of these experts during their time of contribution whose foresight and generosity made their participation possible.

ANSI/AGMA 2101-E25—AGMA Cylindrical Gear Rating Committee

Chair: Frank C. Uherek, Regal Rexnord Corporation

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Walt Weber, Flender

Electric vs. Combustion: A Comparative Analysis of Gear Design for Commercial Vehicle Applications

Soniya Lahoti, Sahil Chawla, Hareesh Kurup and Carlos H. Wink

The evolution of automotive technology has ushered in a new era where the traditional internal combustion engine (ICE) is gradually giving way to electric vehicles (EVs). This transition is not without its engineering challenges, particularly in the domain of gear design. ICEs and EVs have fundamentally different requirements for gearboxes, which are pivotal in translating engine power into motion. ICE vehicles require complex multi-speed transmissions to accommodate a narrow band of optimal engine speeds, while EVs benefit from simpler, fewer number of speeds gearboxes due to the electric motor's ability to deliver consistent torque across a wide range of RPMs (Ref. 1). Firstly, we would shed some light on how ICE vehicles transitioned to EVs in the commercial segment, discussing various powertrain layouts and potential gearbox configurations. Then we will present a comparative study of different gear parameters between ICE and EV gear design and explore the impact of EV gear design on manufacturing processes. Finally, we will present a case study focusing on a 14-ton commercial vehicle (Class 7), comparing a multi-speed ICE gearbox to an EV central drive single-speed reduction gearbox. For this comparison, we assume the vehicle operates at the same output speed and torque requirements. The case study aims to provide practical insights into the application of EV gear design in real-world scenarios.

General Architecture Comparison of an ICE and EV Gearbox

A typical ICE powertrain layout, as illustrated by the block diagram of Figure 1a, is comprised of an engine, a gearbox, and a rear drive axle. For a 14-ton vehicle, a multi-speed (5 or 6 speed) gearbox is generally necessary. Some commercial vehicle manufacturers have initiated the transition to Electric Vehicles, adopting a retrofit approach. This involves replacing the ICE with an electric motor while keeping the rest of the powertrain the same (Ref. 2) as illustrated in Figure 1b. While this approach could potentially reduce initial costs and prolong the lifespan of the existing fleet, it may not yield the most efficient solution, even with adjustments to the gearbox (Ref. 2) An alternative approach would be to replace both the ICE and the multi-speed gearbox with a high-torque, low-speed electric motor to directly drive the rear axle as illustrated in Figure 1c.

Building on the concept of optimizing electric powertrain layouts, a more effective solution for an 8–14-ton central drive layout emerges. This solution, as shown in Figure 2, uses a power-dense, high-speed (>10,000 rpm) motor coupled with a single-speed reduction gearbox. System analysis shows that a single gear ratio is sufficient to meet the startability, gradeability and top speed requirements of 8–14-ton vehicles. Because of a single reduction ratio gearbox and a high-speed motor, the overall powertrain becomes power-dense. A comparative study between the direct drive layout and a motor with a single reduction ratio gearbox showed a 300 percent weight improvement in the powertrain. Now this single-speed gearbox can further have different configurations as shown in Figure 2.

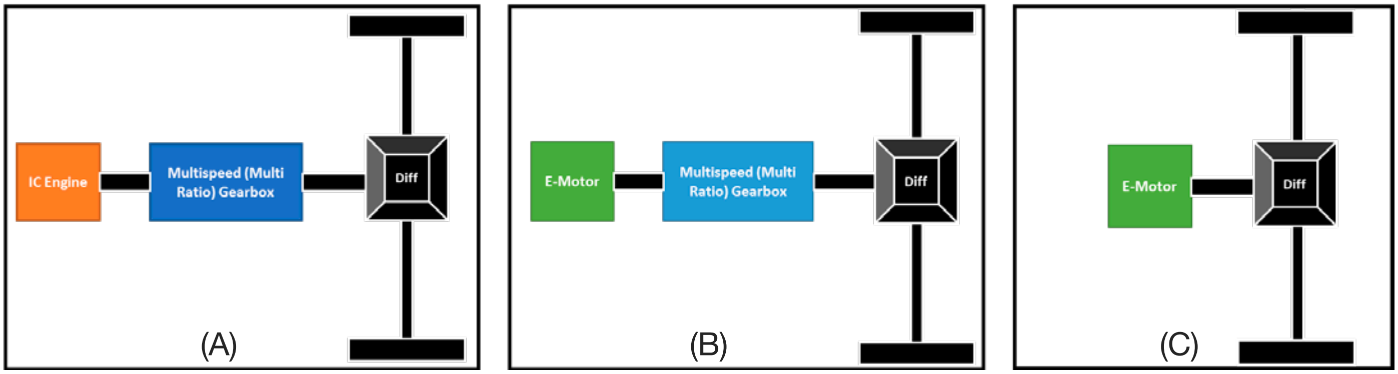

Figure 1—Powertrain layouts.

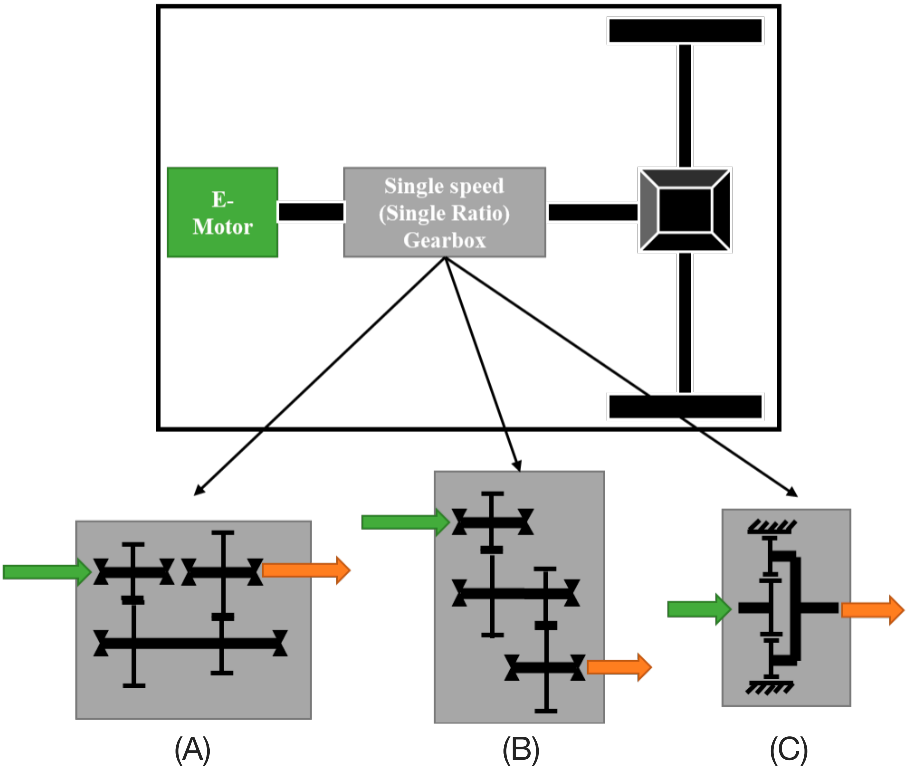

Figure 2—Central drive system with different gearbox configurations: (a) Coaxial input/output with offset gear layout; (b) Offset input/output with countershaft layout; and (c) Coaxial input/output with planetary layout.

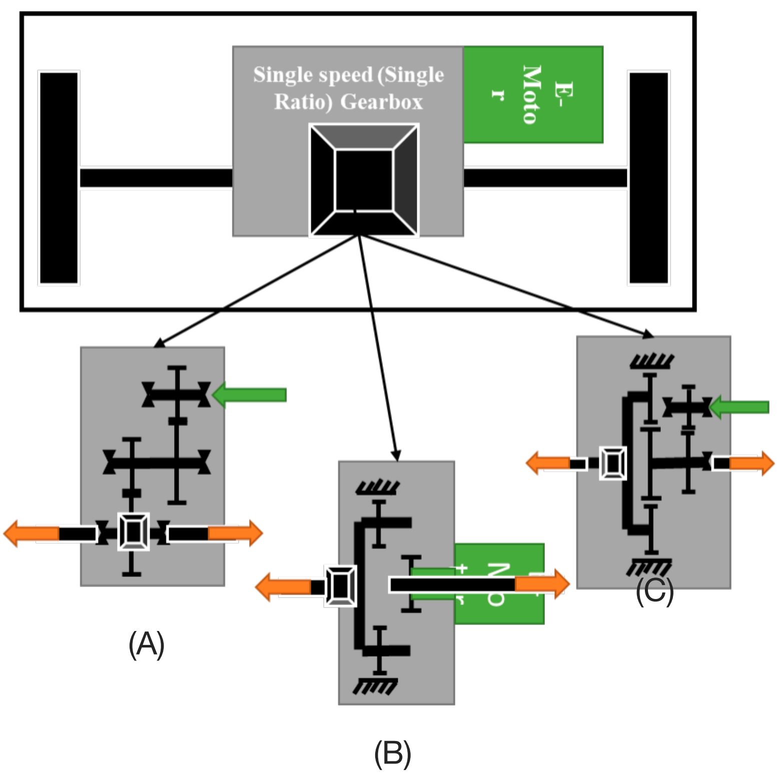

Figure 3—E-beam layout with different gearbox layout: (a) Offset input motor with countershaft layout; (b) Coaxial input output Layout with planetary gear reduction; and (c) Offset input motor with planetary layout.

In addition to the aforementioned powertrain layouts, another viable option is the e-beam layout. In this configuration, the motor and the reduction gearbox are integrated into the vehicle axle as shown in Figure 3. This design eliminates the need for a propeller shaft and the final drive ratio becomes a part of the overall gearbox ratio. There are several ways to achieve this configuration. One possibility is a parallel axis offset reduction gearbox. where the ratio can be achieved in stages. Another option is a compound planetary system, where the ring is fixed, and the carrier is integrated into the differential case. A third option could be a combination of a parallel axis gear set with a planetary reduction set. There are numerous other configurations that can achieve the same ratio. Each of these configurations has its own advantages and disadvantages. The optimal layout can be selected based on a variety of factors, including available space, target volume and weight, cost, efficiency, and complexity.

Gear Design Comparison for ICE and EV

The primary objective of the transmission gear design is to meet the durability as per the transmission product life requirement. This is achieved by ensuring sufficient safety factors against potential failure modes. The major failure modes in transmission gears, bending and pitting, are fatigue failures that develop over time due to repeated cyclic loadings on the gear teeth during the service life of the transmission. Industrial standards like ISO 6336 (Ref. 3), AGMA 2001-D04 (Ref. 4) are generally used for the rating of gears at the design phase, so that the designed gears would have sufficient life to meet the product requirement. These rating standards estimate the safety factors by comparing the life requirement from the application to the available life calculated from the stresses under operating loads using a defined S-N curve of the gear material used. The gear's loading pattern changes when the power source shifts from an internal combustion Engine to an electric motor. Although electric motors can provide a more stable torque input to the transmission compared to ICEs, certain characteristics of electric motors, such as bidirectional operation and regeneration, influence the loading pattern on gears. These characteristics require special attention from gear engineers to achieve the desired gear performance.

In conventional ICE transmissions, the gears rotate only in one direction, as the engine rotation direction cannot be reversed. Therefore, the primary design focus is mainly on the drive flank, which bears the load when the engine propels the vehicle. The coast flanks of the gears are loaded only when the vehicle is coasting, and these loads are typically smaller than drive loads. Exceptions to this include reverse idler gears and planet gears of planetary systems. In these cases, both flanks are loaded during normal operation as they are engaged in multiple gear meshes simultaneously. Splitter gears in certain transmission architectures are special cases where the drive and coast flank get interchanged depending on the gear selection. One of the most important features of electric vehicles over ICE vehicles is regenerative braking. During this process, the motor operates as a generator to recover the braking energy. As power flows in the opposite direction during regeneration, while the driveline rotation direction remains the same, the coast flank of the gears transmits the load. This makes the design of both drive and coast flanks equally important in EV gear design. Therefore, the overall gear reliability is the product of drive flank reliability and the coast flank reliability. Since the motor can operate in both rotational directions, reverse gear is achieved just by reversing the motor direction. This is another case where both the gear flanks transmit load in EV gearboxes.

For cases like reverse idler or planet gears where the gear teeth are loaded in both directions in every rotation, the gear rating standards (Refs. 3, 4) recommend a 70 percent reduction in bending safety factor. ISO 6336-3 Annex B calls it the mean stress correction factor Y_m, which considers the influence of working stress conditions other than pure pulsations. An electric vehicle gear gets a fully reverse loading in instances when the motor switches between motoring and regeneration. The loading of EV gear teeth with regeneration is given in Figure 4. The Y_m factor for periodic load reversals, as in electric vehicles, should be between 1 and 0.7, depending on the number of load reversals. Turci (Ref. 5) investigated various methods to account for similar loading patterns of hybrid vehicles in bending calculation and gives reference calculations from the gear design book (Ref. 6) for estimating Y_m from the number of load reversals.

Considering that, Y_m for no load reversal is 1 and full load reversal is 0.7, the Y_m factor for periodic load reversals with the number of load reversals as N_{rev} is given by:

$$Y_m = 0.85 - 0.15\frac{\log N_{rev}}{6}$$

For, $1 \leqq N_{rev} \leqq 10^6$ and

$$Y_m = 0.70$$

For, $N_{rev} \geq 10^6$

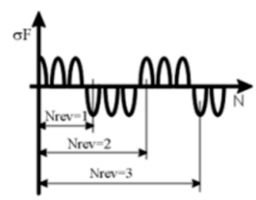

Figure 4—Gear tooth loading pattern with periodic load reversals (Ref. 6).

The loading pattern considered for the calculation, as per Ref. 6, is given in Figure 4. The number of load reversals needs to be estimated from detailed duty cycle data. This data can be derived from data collection on a similar application or from a simulation performed with appropriate driving cycle and vehicle parameters. It is important to note that the equation takes into account a full reversal load, which means the magnitude of the loading is identical in both directions.

Consideration of reverse loading in bending safety factor calculations using the appropriate Y_m factor ultimately results in lower allowable bending stress levels in EV gears compared to ICE transmission gears with similar bending life requirements. The active use of both the flanks of the gear teeth during operation in an EV transmission demands higher quality levels and good manufacturing control on both gear flanks of EV gears compared to ICE transmission gears.

Gear Microgeometry Comparison for ICE and EV

In an ICE vehicle that has a multi-speed gearbox, each gear stage has a range of torque at which it operates, so each gear pair can have optimized microgeometry for that torque range. For gears that operate at high torque, larger microgeometry modifications, such as tip relief and profile crown, are typically needed to compensate for the tooth deflection, whereas for low torque, higher speed gear pairs, the modifications are relatively smaller. The below figure illustrates the microgeometry comparison of gears of different ranges from a multi-speed gearbox. The first gear operates at high output torque and low speed and as the gear number progresses, the output torque reduces and the speed increases. With decreasing torque, the amount of involute modification decreases. In an EV single-speed gearbox, the same gear pair takes the complete range of torque from the electric motor. So, one approach could be to optimize the microgeometry modification for the torque range in which the vehicle operates for the longest duration. Generally, this maximum operation occurs at torque levels close to or less than the continuous torque of the electric motor. In this case, smaller microgeometry modifications may be required for the EV gears. Along with this, the tolerance band applied to the microgeometry is also higher for ICE gears, whereas it is tightly controlled for EVs to reduce the effect of manufacturing variation on noise.

Comparison of Gear Performance

In this section, we would like to compare various gear parameters like efficiency, NVH, micropitting and scuffing, and how the results compare for an ICE and EV gear design. Efficiency and NVH are two contradictory critical quality parameters of gears, and the design must maintain a balance between both. The design cannot be optimized for efficiency and

NVH independently; it must be done conjointly. The high-speed operation of gears in EVs has increased the risk of micropitting and scuffing, so we have discussed what can be done to minimize this risk.

Efficiency

Efficiency is one of the most important parameters in EVs as it directly influences the vehicle's range, which is a critical factor in product marketability. The overall powertrain efficiency is driven by efficiencies of various components, including the motor, inverter, gears, bearings, seals and auxiliary components like the pump and heat exchanger. Every component should operate at its optimum efficiency to improve the overall vehicle performance. Thus, it is important to design gears for high efficiency. Gears with shorter tooth height typically exhibit higher efficiency; however, they tend to perform poorly in terms of NVH. Therefore, gear design involves a tradeoff between maximizing efficiency and minimizing NVH. Figure 6 compares the calculated efficiency of an ICE drivetrain and an EV drivetrain across a range of operating speeds. Efficiency values are determined per ISO 14179-2 (Ref. 7).

Figure 6 compares total power loss, which is the sum of load-dependent and speed-dependent losses. The ICE gearbox has splash lubrication and uses high viscosity oil, whereas the EV has forced lubrication and uses lower viscosity oil. In EV, it is preferred to have forced lubrication to avoid churning loss and have baffles around gears to ensure mesh lubrication. At lower speed in an EV, the total loss is less than in an ICE because of lower module and lower surface roughness of gears. As speed increases, the difference in loss between ICE and EV increases further because of more churning or speed losses in ICE as it uses high viscosity oil and has many components dipped into the lubricant.

NVH

While striving to maximize efficiency, it is equally important to evaluate NVH concurrently. The contact ratio is one of the most important parameters determining gear tooth excitation and, thus,

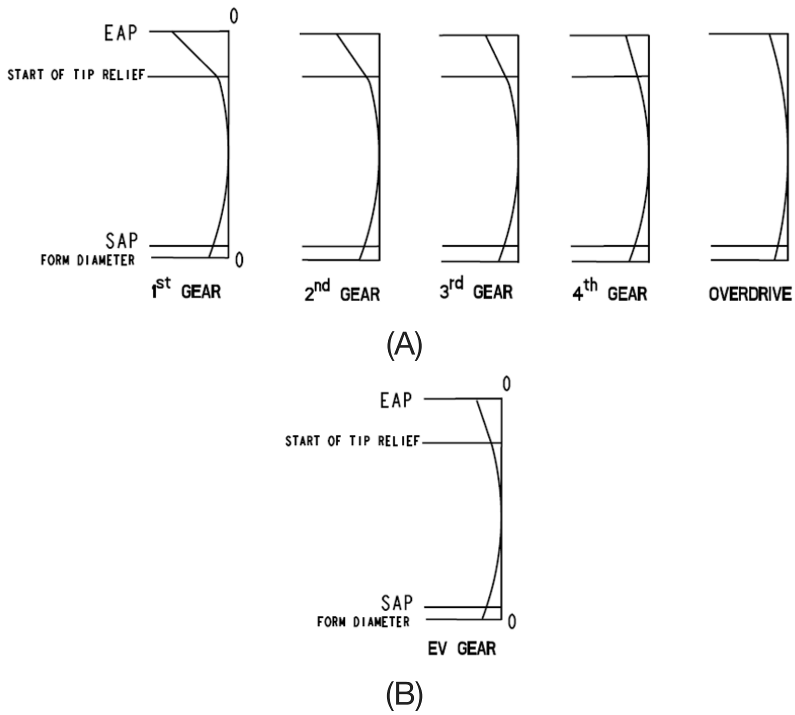

Figure 5—Illustration of Involute modifications of: (a) different gears of a multi-speed gearbox and (b) gear of a single-speed gearbox.

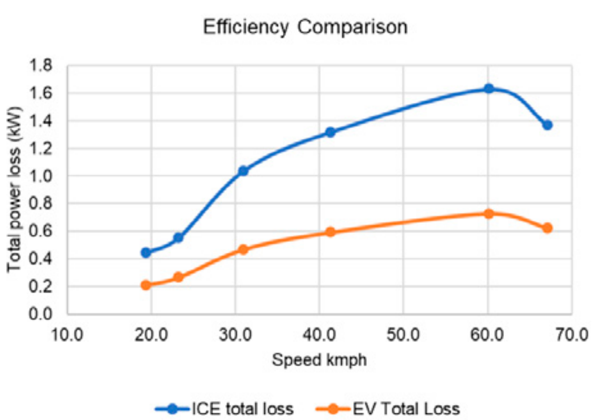

Figure 6—Efficiency comparison for ICE and EV.

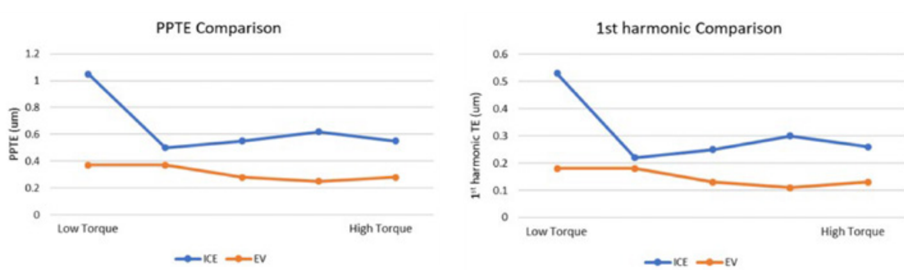

Figure 7—PPTE and 1st Harmonic comparison for ICE and EV.

gearbox noise level. The primary source of gear noise, often referred to as whine noise, in a gearbox is the peak-to-peak transmission error and its harmonics (Ref. 8). In ICE vehicles, the engine noise would mask most of the other noises coming from the gearbox and thus gear noise is not as critical as it is with EVs (Ref. 2). In EVs, the motor operates quietly, allowing other noises to become more noticeable, making NVH a significant challenge. A comparison of the PPTE, in a quasi-static condition and over the operating torque range in Figure 7, shows that the values are reduced to less than half for EV gears compared to ICE gears. The reduction is different for different torque values, as the microgeometry is optimized for torques that operate for the maximum duration of operation. If we convert the improvement to a dB level with ICE as baseline, an average of 6dB of improvement can be achieved with this reduction (Ref. 9). This can be achieved by designing higher contact ratio gears while maintaining efficiency targets. The contact ratio should be such that it minimizes the variation of mesh stiffness over the meshing cycle. Reducing gear mesh stiffness variation ultimately reduces the peak-to-peak transmission error and, in turn, the TE harmonics.

As EV operates at higher input rpm, to quantify the effect of speed on noise, we have compared the dynamic TE over a vehicle speed of 0–60 kmph and its combined effect on the resultant dynamic forces acting at the bearings. Figure 8 shows that the dynamic TE in EV is maintained to less than one-third of that in ICE, thus significantly lower resultant dynamic forces are observed at the bearings. At higher frequencies, the first harmonics of the resultant dynamic forces are a bit higher, but still, the peaks of EV are much smaller in magnitude than the ICE. So, in EV, it is important to minimize static as well as dynamic transmission error, as the input speeds in EV are much higher compared to ICE. As the nominal value for TE reduces, even small variation in TE leads to higher variations in sound pressure level (SPL). So, the gear design should be robust enough that the TE is least sensitive to manufacturing errors to minimize variation in SPL.

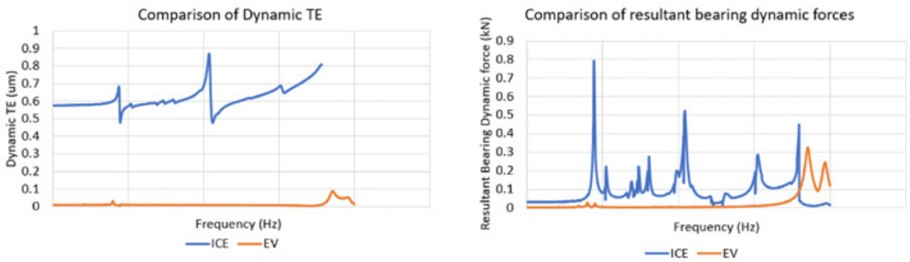

Figure 8—Dynamic TE and Resultant Dynamic Force comparison for ICE and EV.

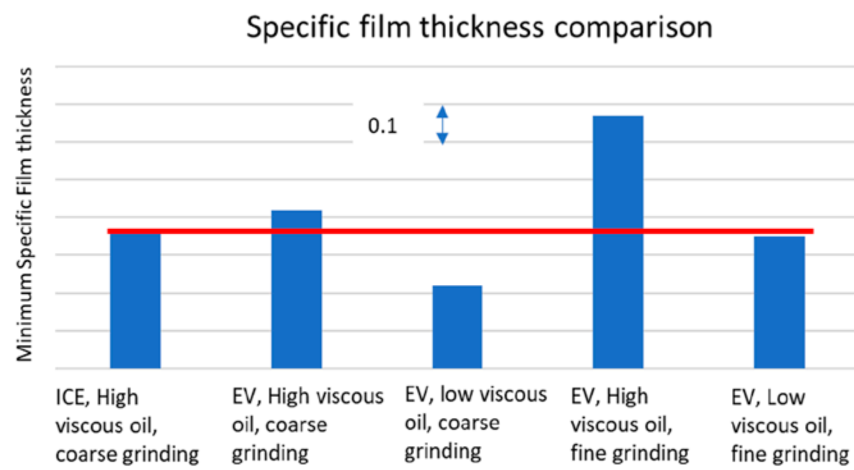

Figure 9—Comparison of the risk of micropitting.

Micropitting and Scuffing

Micropitting occurs when the lubricant film thickness is insufficient relative to the surface roughness of the gears. Factors such as high temperatures, low oil viscosity, and excess load can lead to reduced film thickness. The smaller the ratio of surface roughness to lubricant film thickness, the greater the likelihood of micropitting. Increasing the ratio of surface roughness to lubricant film thickness is one of the most effective preventative measures against micropitting (Ref. 10). The following analysis shows the effect of oil viscosity and surface roughness on lubricant specific film thickness.

In ICE transmissions, high-viscosity oil is typically used, and surface roughness is higher compared to EVs. Figure 9 shows a comparison of the minimum specific film thickness in ICE and EV gears at a vehicle speed of 60 km/h. In EVs, low viscosity oil is commonly used to improve efficiency, but if the same level of surface roughness is maintained in EVs as in ICE, then the specific film thickness degrades, increasing the risk of micropitting. To maintain the same level of specific film thickness in EV as in ICE, an improvement in gear surface roughness is necessary to help lower the risk of micropitting issues. Therefore, to improve the gear mesh efficiency and prevent micropitting with low viscosity oil, a superior surface roughness should be maintained in EV gears.

Scuffing is a localized damage to the gear teeth resulting in matte and rough finishes of the contacting surfaces, along with changes in tooth form. This type of damage generally occurs in the tooth contact zone, where contact pressure and sliding velocity are high, far from the pitch line. In EVs, gears are designed for a higher contact ratio, resulting in high sliding velocities, which can increase the risk of scuffing. As a severe adhesive wear phenomenon, scuffing occurs when the oil film thickness between the tooth contacting surfaces is not enough to prevent metal-to-metal contact, which causes local welding and subsequent tearing (Ref. 11). So, to avoid the risk of scuffing in EV gears, lubrication design should ensure sufficient lube flow, cooling, and film thickness formation at the contact location.

Effect on the Manufacturing Process and Gear Inspection

ICE gearboxes, with their more complex designs, typically involve more components and assembly processes, which can increase manufacturing complexity and cost. On the other hand, required gear tolerances are not as stringent as in EV applications. Whereas manufacturing the simpler design of EV gearboxes can lead to overall reduced production costs, although the materials used must be carefully selected to withstand the high number of load cycles. Also, the surface roughness on EV gears is much less than ICE gears, which calls for polishing after grinding. This impacts tooling cost and manufacturing cycle time. Planetary gear reductions, and more specifically compound planetary gears, are used in EV applications to reduce the gearbox volume and best fit the vehicle's powertrain envelope. The machining of such gears is difficult and needs operations like skiving and honing. Since NVH is a critical requirement, a single-flank roll test is recommended at the end of line testing to maintain product quality. All these machining requirements require significant initial investment and know-how. So, even though the gearbox complexity has reduced, component design has become complex, which could lead to increased manufacturing costs.

Conclusion

Designing gears for electric vehicles requires a delicate balance between achieving high efficiency and maintaining low NVH. To attain high mesh efficiency, gears should be fine ground or even polished, depending on surface roughness requirements. This approach also helps mitigate the risk of micropitting. With the use of low viscosity oil, the risk of micropitting and scuffing increases, requiring a lubrication design that ensures sufficient oil delivery to the gear mesh. For low NVH, the transmission error (TE) values should be minimized, and the design should be robust to manufacturing variations. From the manufacturing perspective, existing machines and tooling may require updates and enhanced process control will be required to minimize variations.

Overall, the transition to electric mobility is driving innovation in gear design, with a focus on optimizing efficiency, reducing weight, and minimizing noise and vibration. As the automotive industry continues to evolve, the gear design for both ICE and EVs will undoubtedly continue to adapt to meet the unique requirements of each powertrain technology.

In summary, the design of gears for high-speed electric motors is a complex endeavor that requires a careful balance of material science, mechanical engineering, and precision manufacturing. As electric vehicles continue to gain popularity, the demand for high-performance, reliable, quiet and efficient gear systems will only increase, presenting ongoing challenges and opportunities for innovation in this field.

Acknowledgement

The authors thank Eaton–Mobility Group for their support in the development of this paper.

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Experimental Study on the Performance of Plastic Worm Gears

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

Plastic worm and crossed helical gears are increasingly utilized in various applications due to their distinct advantages over traditional metal worm gear drives. These advantages include lower weight, reduced noise, and corrosion resistance, making them ideal for automotive, consumer electronics, and medical devices. However, plastic gears also come with limitations such as lower load-bearing capacity and higher susceptibility to temperature variations and wear. The design and calculation of plastic crossed-helical gears (often referred to simply as worm gears) are defined in guidelines like VDI 2736, which provides comprehensive methods for material selection, dimensioning, and performance prediction. Experimental testing, also thoroughly described in VDI 2736, includes procedures to evaluate the durability and efficiency of these drives under realistic operating conditions.

In most applications, plastic worm gear pairs are composed of a metal worm paired with a polymer worm wheel. In terms of load-carrying capacity, several types of failure modes typically determine the service life of a plastic worm gear pair. Out of these, fatigue is one of the most detrimental and often exhibited failure modes in worm gear drives. Polymer worm wheel fatigue was studied by Nomura et al. (Ref. 1), who tested polymer worm wheels in pairs with various metal worm geometries. Kim et al. (Ref. 2) additionally tested the durability of a glass fiber-reinforced polyamide polymer worm wheel used in a car steering system. They identified root fatigue with cracks forming slightly above the root to be the driving failure mode.

Marshek et al. (Ref. 3) noted that polymer worm gear drives can fail due to multiple failure modes simultaneously, e.g., fatigue combined with wear. Wear was studied in more detail using SEM microscopy by the same author (Ref. 4), who noted that pitting and ridge formation are two types of flank damage phenomena often related to wear on polymer worm wheels. In the already noted study by Kim et al. (Ref. 2), wear, as a function of running cycles, was also studied. Wear was measured as a function of angle loss during meshing.

Additionally, the NVH (noise vibration and harshness) behavior of polymer gears is often of interest, since one of the key goals of polymer gear drives is to reduce the noise level in a gear transmission. Chakroun et al (Ref. 5) presented a numerical model, based on the Generalized Maxwell Model (GMM), a widely adopted type of viscoelastic constitutive mechanical model, to analyze the influence of the non-elastic mechanical characteristics of the polymer wheel on the frequency-spectrum vibration response of the meshing gear drive.

Despite these advancements, achieving higher performance in plastic worm gear drives remains challenging. Current research is focused on enhancing material properties, improving manufacturing precision, and developing more robust predictive models to bridge the performance gap compared to their metal counterparts. The study presented focuses on the implementation of the state-of-the-art worm gear calculation methods, exemplified by the VDI 2736 guideline and the experimental testing aspects correlated with this implementation. Via an executed case study, the work outlines suitable testing methodologies for the characterization of worm wheel limiting strength parameters. These parameters are essential for the implementation of the calculation methods defined in the guideline. Additionally, practical aspects related to the implemented testing procedures are discussed.

Worm Geometry Variants

Several variations of worm gear drives exist, each offering distinct advantages and disadvantages. The possible combinations are schematically shown in Figure 1 and include:

a. Cylindrical crossed-helical gear pair
b. Cylindrical worm paired with enveloping (globoid) worm wheel
c. Cylindrical worm paired with semi-enveloping (semi-globoid) worm wheel
d. Enveloping worm paired with cylindrical worm wheel
e. Enveloping worm paired with enveloping worm wheel

The most common type is the cylindrical crossed-helical gear pair, where both the "worm" and the "worm wheel" are cylindrical and hold a helical lead profile. This simple design is relatively straightforward to manufacture, also using plastic processing methods like injection molding. The main drawback of this gearing geometry is that it results in a theoretical point contact during meshing and consequently offers a lower load-carrying capacity due to a less favorable load distribution across a small contact area on the active flank.

For improved load-carrying capacity, durability and smoother operation, enveloping worm gears can be produced. This design offers an improved line-contact load distribution, potentially leading to reduced wear and a longer service life. Two main variations exist: cylindrical worm/enveloping (globoid) worm wheel and enveloping worm / cylindrical worm wheel. In the former, the worm wheel has a curved profile, matching the worm's curvature of the helix, which prolongs the path of contact. The

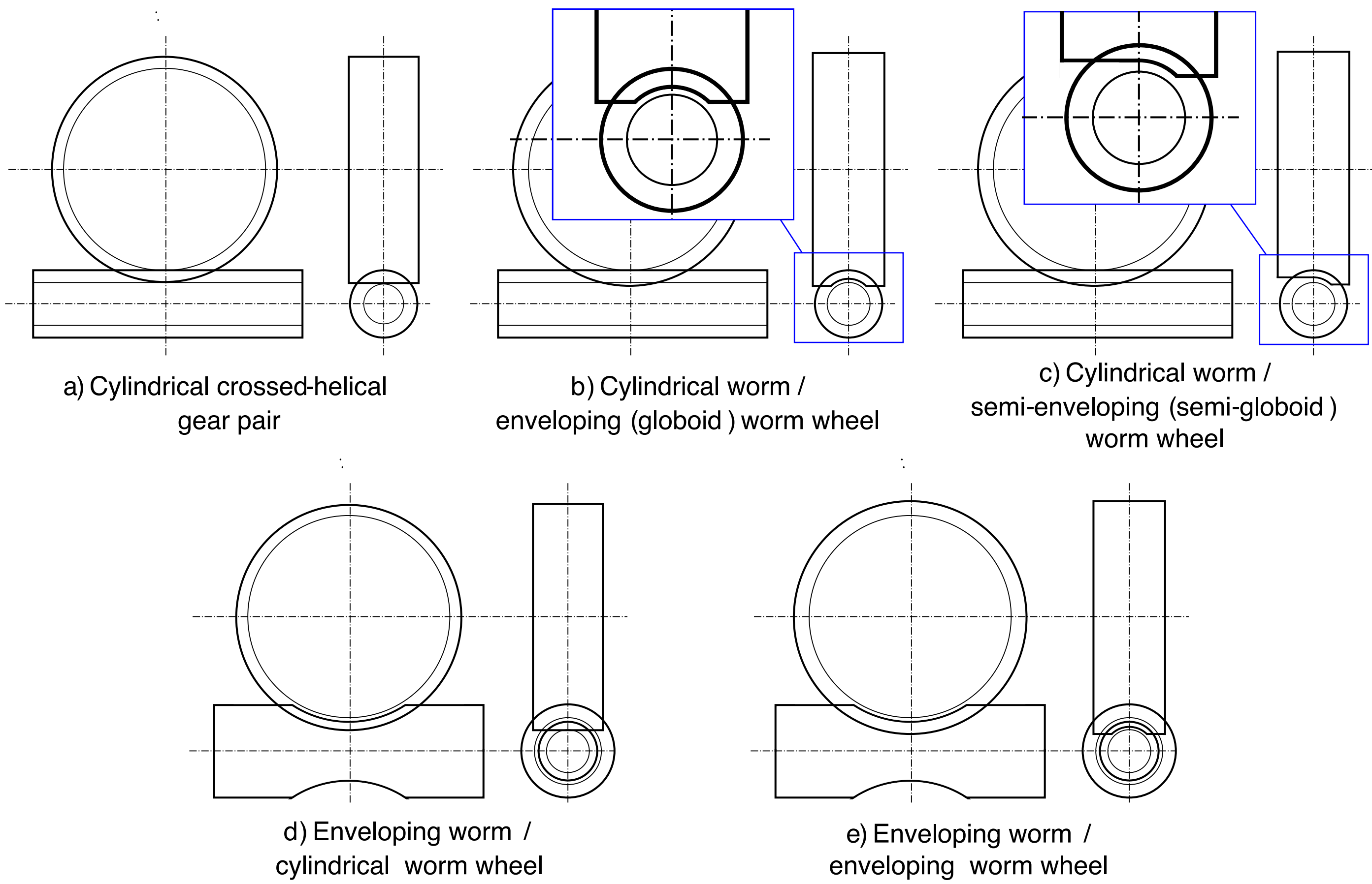


Figure 1—Available crossed helical and worm gear geometry configurations.

latter features a curved, hourglass-shaped worm gear meshing with a straight-toothed worm wheel. Both offer improvements over the basic cylindrical pair, but the cylindrical worm / globoid worm wheel generally boasts the highest efficiency due to its deeper tooth engagement. On the other hand, both geometries increase the complexity and cost of production. A globoid worm wheel is especially problematic for plastic injection molding since it exhibits negative draft angles, which hampers the possibility for part ejection from the molding tool. To amend this problem, a semi-enveloping (semi-globoid) worm wheel geometry can be introduced that provides partial line contact and avoids negative draft angles that undermine part ejection in the globoid geometry.

Finally, the least common variant is the enveloping worm / enveloping worm wheel. Both the worm and the worm wheel have curved profiles, maximized tooth contact and achieved the best load distribution among all these designs. However, these benefits come at the cost of increased manufacturing difficulty, as already discussed above. Our further analysis will entirely be based on cylindrical crossed-helical gear pairs, since this geometry is by far the most commonly used in plastic worm gear drives and the VDI 2736: Part 3 guideline also provides calculation methods for this type of gear pair. To simplify communication, in subsequent sections, the words "worm" and "worm wheel" will be used to denote the pinion and gear of the analyzed crossed-helical gear pair.

Failure Modes and Load Carrying Capacity Evaluation of Plastic Worm Gear Drives

Plastic worm gear drives are commonly designed by employing a metal worm in pair with a plastic worm wheel. Plastic worms, although viable, are used less often due to the complexities involved in injection molding and much lower achievable load carrying capacity and service life compared to metal variants. In this regard, available design guidelines and standards, like the VDI 2736: Part 3 (Ref. 6), further discussed in the following sections, also focus primarily on the evaluation of plastic worm wheels. The design of this type of worm wheels involves a durability control against the most commonly experienced failure modes during gear running (Fig. 2). In general, there are various failure modes that can, depending on the materials, loads, and lubrication conditions, occur on plastic worm wheels (Ref. 7), including:

- Thermal failure
- Root fatigue failure
- Flank fatigue failure
- Pitting
- Wear
- Viscoplastic tooth deformation

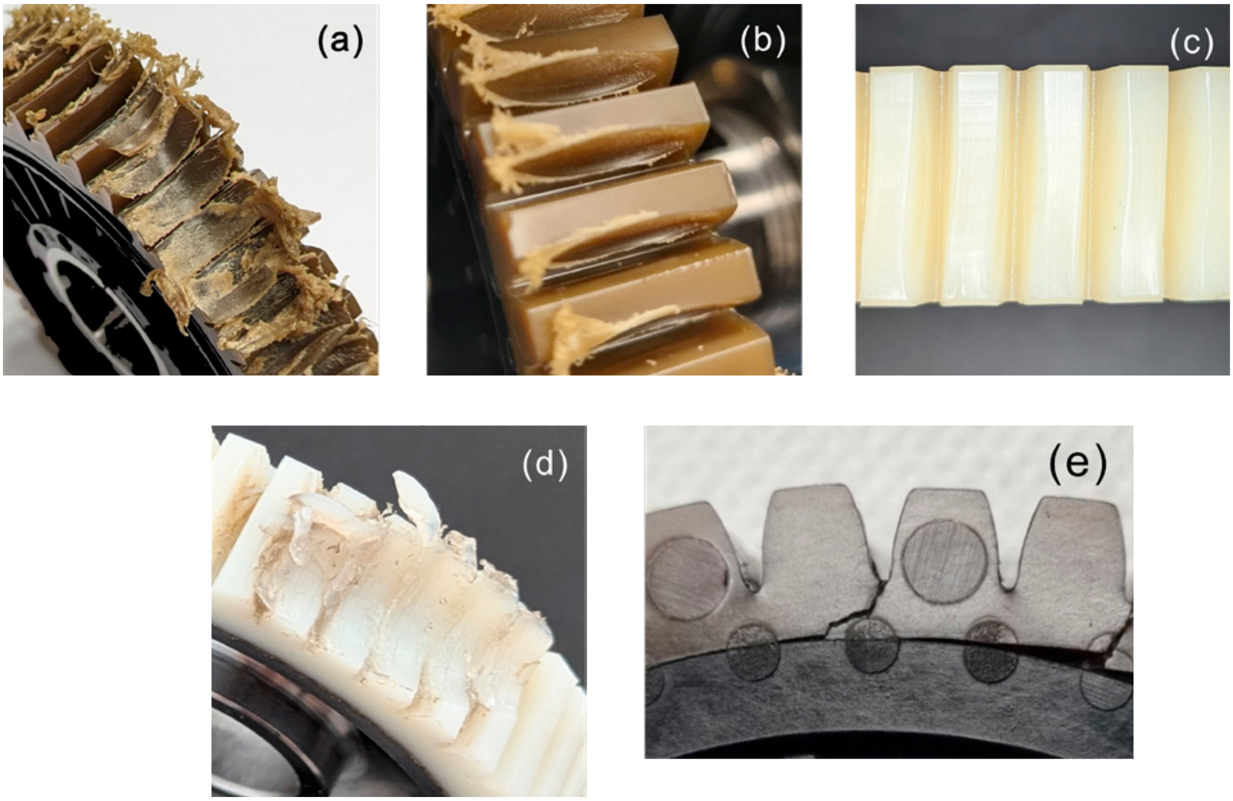


Figure 2—Examples of various failure and damage modes exhibited on polymer worm wheels- a) thermal overload, b) wear, c) tooth deformation, d) tooth fatigue fracture and e) root fatigue fracture.

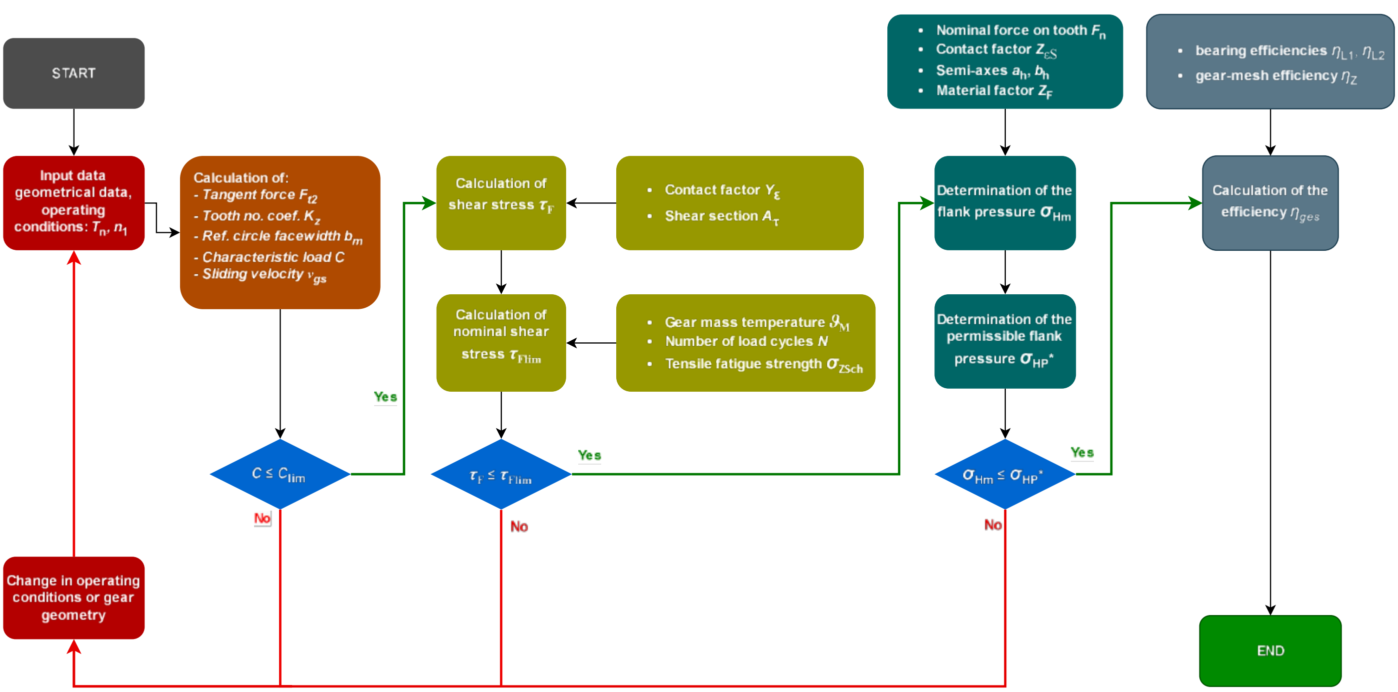


Figure 3—Overview of the worm gear rating workflow according to the VDI 2736: Part 3 guideline (reconstructed based on the flowchart defined in Ref. 6).

These are, in essence, the same types of failure modes exhibited by cylindrical (parallel axis) plastic gears. However, there are certain differences in the way these failure modes manifest and their probability of occurrence. In the following sections, the main failure modes will be presented in more detail, with methods of durability evaluation and experimental characterization further discussed.

Standards and Guidelines for Load-Carrying Capacity Evaluation

In the past few decades, there has been a gradual evolution in worm and crossed-helical gear design standards. The already noted VDI 2736: Part 3 guideline for plastic non-enveloping worm gears has its foundation in the DIN 3996 standard, which covers the calculation of load-carrying capacity of metal worm gears. The standard covers calculation methods for pitting resistance, wear load capacity, worm shaft deflections, tooth root strength, and thermal stability (Ref. 8). The standard has undergone revisions, with the 2012 and 2019 versions reflecting updates in calculation methods and material properties. Based on the DIN 3996 standard, the ISO/TR 14521:2010 (Ref. 9) standard was formed, which provides calculation methods for assessing wear, pitting, worm deflection, tooth breakage and temperature in metal cylindrical worm gears. The standard was withdrawn and replaced in 2020 by the ISO/TS 14521 (Refs. 10, 11), which covers the same failure modes but omits sections related to worm gear geometry and instead references the standard ISO 10828:2024 (Ref. 12) for geometry specifications.

In the field of non-metal gears, the precursor of the VDI 2736: Part 3 guideline is the VDI 2545 (Ref. 13), which was withdrawn in 1996. The 2545 version includes a root stress carrying capacity evaluation method, which was also deemed suitable for use in crossed-helical cylindrical gears and is still proposed in modern gear design software. In the VDI 2736: Part 3 guideline, no comparable root strength rating method is presented, and instead, a fatigue fracture model dependent on the nominal shear stress on the active flank is defined. Since the VDI 2736: Part 3 guideline currently constitutes the state of the art in plastic worm gear rating models, it will be considered in more detail in subsequent sections.

Worm Gear Load-Carrying Capacity Evaluation According to VDI 2736: Part 3

The guideline enables the evaluation of the load-carrying capacity of plastic worm wheels and durability against several key failure mechanisms, typically exhibited by these components during running. A schematic presentation of the complete worm wheel evaluation procedure per noted guideline is shown in Figure 3. As is visible, the complete evaluation procedure is composed of several steps and failure mode criteria, described in more detail in the following pages.

Tooth Root Load Carrying Capacity

The guideline presents a model for evaluating worm wheel tooth fracture load-carrying capacity. While the precursor guideline, the VDI 2545, considered bending root stress as the main fatigue failure criterion (leading to root crack induced failure), the updated 2736 guideline assumes that fracture predominantly occurs at the edge of the worm (i.e., at its addendum diameter, see Fig. 4) and considers instead the shear fatigue stress as being the one leading to this type of failure.

According to Wassermann (Ref. 14), a shear fatigue stress safety factor can be introduced as:

$$S_F = \frac{\tau_{Flim}}{\tau_F} \geq S_{Fmin} \tag{1}$$

Here τ_{Flim} is the shear fatigue strength of the used worm wheel material, while τ_F is the evaluated nominal shear stress. The guideline assumes that τ_{Flim} can be approximated as a fraction of the tensile fatigue strength at the specified operation temperature ϑ_M (of which data are more readily available) and recommends to multiply the tensile fatigue strength by a factor of 0.75 to obtain shear strength data. Alternatively, the data could be obtained directly from gear tests as discussed in Section 4.3.3. It is further recommended to consider a minimum safety factor of $S_{Fmin} \geq 1.3$. The nominal shear stress is calculated as:

$$\tau_F = \frac{F_{t2} \cdot K_A}{A_\tau} \cdot Y_\varepsilon \tag{2}$$

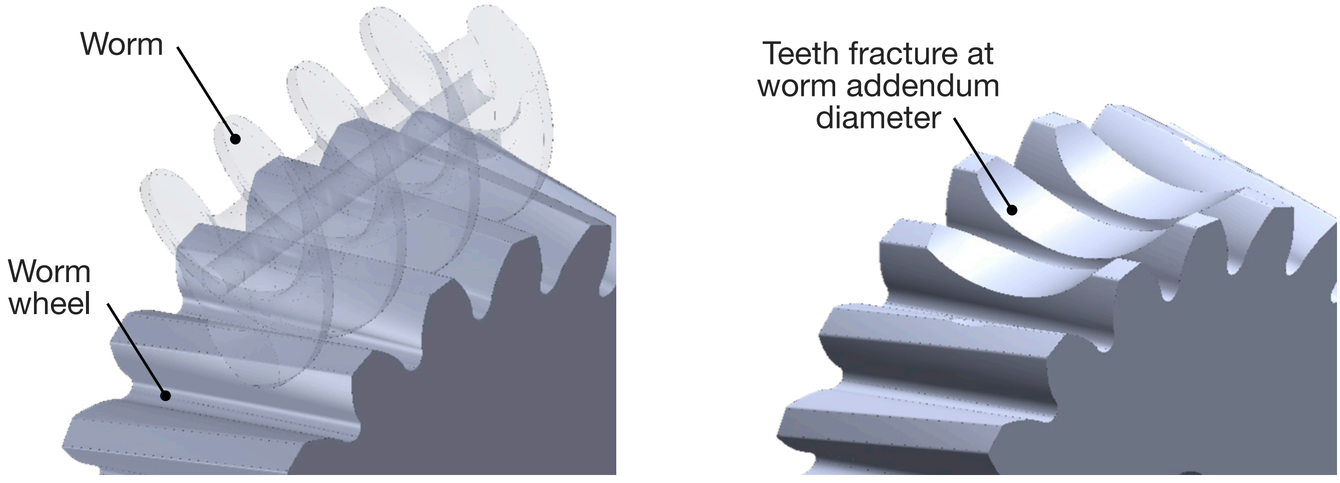


Figure 4—Worm wheel teeth fracture at the tip (addendum) diameter of the worm gear.

Here F_{t2}, K_A, Y_ϵ and A_τ, are the tangential force on the wheel, application factor, contact factor, and shear section area, respectively. A_τ is defined as a radial projection of the fracture area as depicted in Figure 5.

The fatigue fracture model assumes that there is no major wear involved throughout the worm wheel's life cycle, since wear would influence the shear section area. If measurable wear is identified, a reduced tooth thickness of the wheel should be considered in the calculation, in line with the expected wear rate.

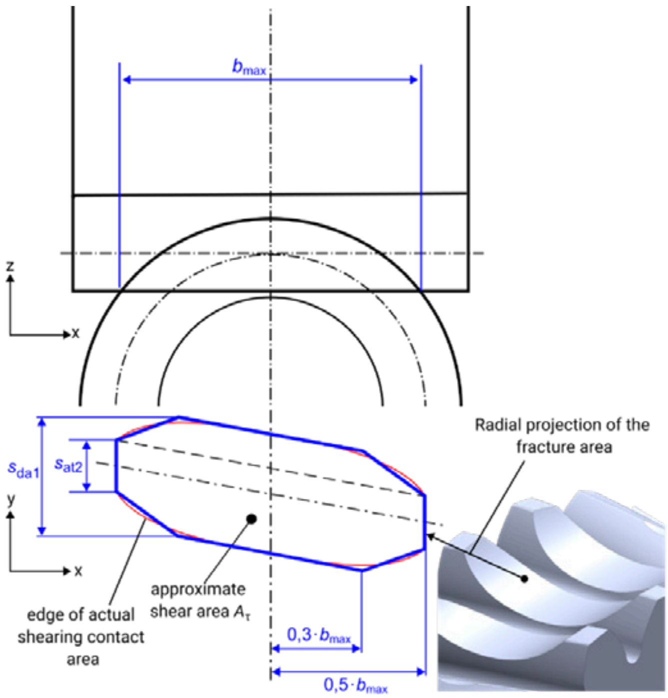


Figure 5—Shear section area A_τ used in the VDI 2736: Part 3 (Ref. 6) fatigue model for nominal shear stress evaluation.

Flank Load-Carrying Capacity

In worm gears, flank pressure is crucial for estimating the overall wheel load-carrying capacity. Hertzian theory is used to calculate this type of pressure, considering the elastic deformation of the contact area. This deformation creates an ellipsoid distribution of the compressive stress, with the maximum stress occurring approximately at the centroid of the contact area (Figure 6).

Here, the flank curvature near the contact zone and the material properties of the gears influences the reached flank pressure magnitudes significantly. In line with the above, the average or nominal flank pressure is defined as (Ref. 15):

$$\sigma_{Hm} = \frac{3}{2} \cdot \frac{F_n \cdot K_A \cdot Z_{\epsilon S}}{\pi \cdot a_h \cdot b_h} \leq \sigma_{HP} \quad (3)$$

where F_n, $Z_{\epsilon S}$, a_h, and b_h are the normal force, contact factor, major and minor semi-axes of the contact ellipse, respectively. The limit contact stress, σ_{HP}, is typically taken from available data in the VDI 2736: Part 2 (Ref. 16) guideline for cylindrical gears, which can however result in insufficient safety factors. In the subsequent section, methods for the characterization of σ_{HP} on worm gear pairs is discussed. The normal force can be calculated as follows:

$$F_n = \frac{F_{t2} \cdot \cos \rho_z}{\cos \alpha_{sn} \cdot \cos(\beta_{s2} + \rho_z)} \quad (4)$$

Here, F_{t2},ρ_z,α_{sn}, and β_{s2} are the tangential force on the wheel, the frictional angle, the normal pressure angle and the helix angle at the helix circle of the worm wheel. The contact factor is a function of the contact ratio in the normal direction:

$$Z_{\varepsilon S} = \frac{1}{\sqrt{\varepsilon_n}} \quad (5)$$

$$\rho_z = \arctan\left(\frac{\mu}{\cos \alpha_{sn}}\right) \quad (6)$$

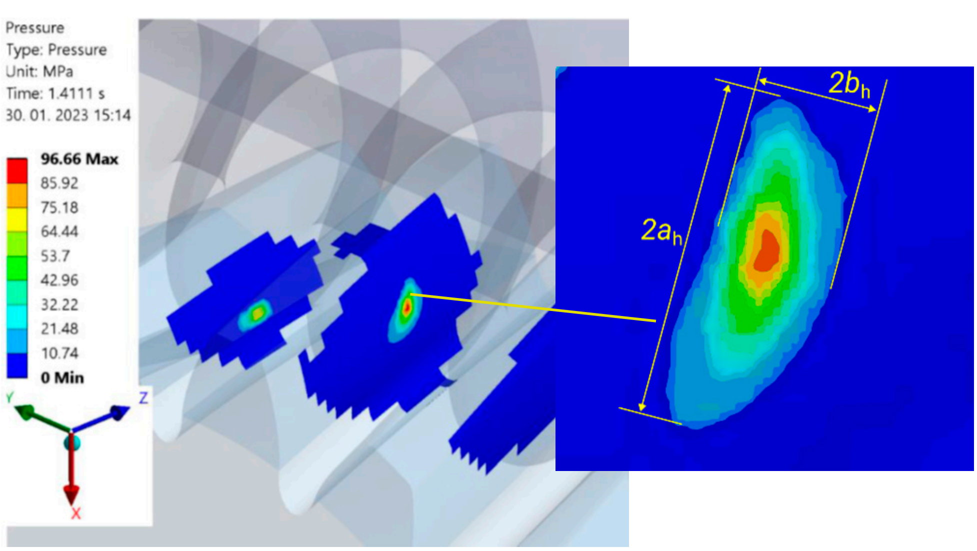


Figure 6—Ellipsoid shape of the tooth contact at the pitch circle area as calculated using FEA on a typical plastic worm wheel geometry (the simulation was performed for a complete tooth meshing cycle using a non-linear quasi-static time-dependent contact analysis model).

while the frictional angle is a function of the coefficient of friction μ and normal pressure angle:

$$a_h = Z_F \cdot \xi \cdot \sqrt[3]{K_A \cdot F_n \cdot \rho_n} \tag{7}$$

The semi-axes of the contact ellipse are further:

$$b_h = Z_F \cdot \eta \cdot \sqrt[3]{K_A \cdot F_n \cdot \rho_n} \tag{8}$$

and are both a function of the elastic properties of the selected material pair:

$$Z_F = \sqrt[3]{\frac{3}{2} \cdot \left(\frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2}\right)} \tag{9}$$

the equivalent radius of curvature at helix point, ρ_n, and empirically defined coefficients η and ξ. ρ_n is calculated using:

$$\rho_{n1,2} = \frac{\sqrt{d_{s1,2}^2 - d_{b1,2}^2}}{2 \cdot \cos \beta_{b1,2}} \tag{10}$$

with $d_{s1,2}$, $d_{b1,2}$ and $\beta_{b1,2}$ being the helix and base circle diameters and the base circle helix angle of both gears in pair. ρ_n is then evaluated as:

$$\frac{1}{\rho_n} = \frac{1}{\rho_{n1}} + \frac{1}{\rho_{n2}} \tag{11}$$

Efficiency

Worm gear efficiency is, in general, much lower than that of cylindrical spur or helical gears. The efficiency is in effect a function of the coefficient of friction and the worm's helix angle β_{s1} (or its complement, the lead angle γ_{m1}. If the efficiency drops below 50 percent the worm gear drive is said to be self-locking, meaning that it cannot run if power is applied on the worm wheel to drive the worm. Per VDI guideline, if the input power is introduced on the worm, the efficiency is calculated as:

$$\eta_z = \frac{\tan \beta_{s2}}{\tan(\beta_{s2} + \rho_z)} \tag{12}$$

Alternatively, if the worm wheel is driving (assuming the pair is not self-locking), the efficiency is:

$$\eta_z = \frac{\tan(\beta_{s2} - \rho_z)}{\tan \beta_{s2}} \tag{13}$$

Experimental Methods for Material Data Characterization

As noted in the sections "Tooth Root Load Carrying Capacity" and "Flank Load-Carrying Capacity," the limit stress values τ_{Flim} and σ_{HP} used for gear rating are obtained based on simplified testing methods, like tensile fatigue data with a normalizing factor for τ_{Flim} and rolling contact fatigue data used for cylindrical gears for σ_{HP}. For the latter, contact fatigue failure is defined as when pits populate at least 30 percent of the flank contact area. Flank fatigue is generally controlled when designing Polyamide and PBT gears, but not for POM, where root fatigue is generally expected. While these methods offer a good approximation for defining limiting fatigue fracture and contact stresses of worm wheels, they do not accurately represent the phenomenological mechanical behavior of worm wheels during running. It is therefore more advisable to perform experimental characterization of these failure modes in actual gear running conditions. This type of methodology is presented in more detail in the subsequent sections.

Testing Methodologies and Test Rig Setups

There are hence several available methodologies for the characterization of worm wheel materials in terms of the failure mode of interest. The limiting fatigue strength of the material as a function of load and stress can, e.g., be obtained by performing pulsator or tensile fatigue tests on a rig setup as presented in Figure 7. The fatigue strength is characterized as a function of load and sample temperature, which is a highly important parameter also determining the material's service life. These tests are usually performed in a positive sinusoidal cyclic fatigue load regime defined by the fatigue factor R>0 (Figure 8). While these tests offer a fast and fairly reliable method of fatigue characterization, they can perhaps oversimplify the actual stress state occurring during gear running, which is a rather complex function of the gear geometry, meshing kinematics, contact ratio and load magnitude. Hence, it is advisable to perform tests on a suitable gear test rig, similar to the setup schematically presented in Figure 9. This type of setup applies to both cylindrical and crossed-helical gearings and provides the most realistic load conditions in comparison with actual gear applications.

Test Samples

For comparative tests of different material pairs and lubricants, it is required to employ the same gearing geometry. While no standard exists that would define a specific sample geometry for worm gear tests, the VDI 2736: Part 4 (Ref. 17) guideline recommends a sample geometry initially proposed at the Ruhr University Bochum, Chair of Industrial and Vehicle Drive Technology. The main parameters of this geometry are defined in Table 1.

Parameter	Sign	Unit	Worm	Worm wheel
Center distance	a	mm	29.98/30.02	
Axis angle	Σ	°	90	
Hand of gear		/	Right	
Number of teeth	$Z_{1,2}$	/	1	40
Pressure angle	α_n	°	20	
Helix angle	$\beta_{1,2}$	°	82,493	7,507
Pitch circle diameter	$d_{1,2}$	mm	9,568	50,432
Tooth width	$b_{1,2}$	mm	25	10

Table 1—Base geometry parameters for the testing sample worm gearing geometry defined in Ref. 17.

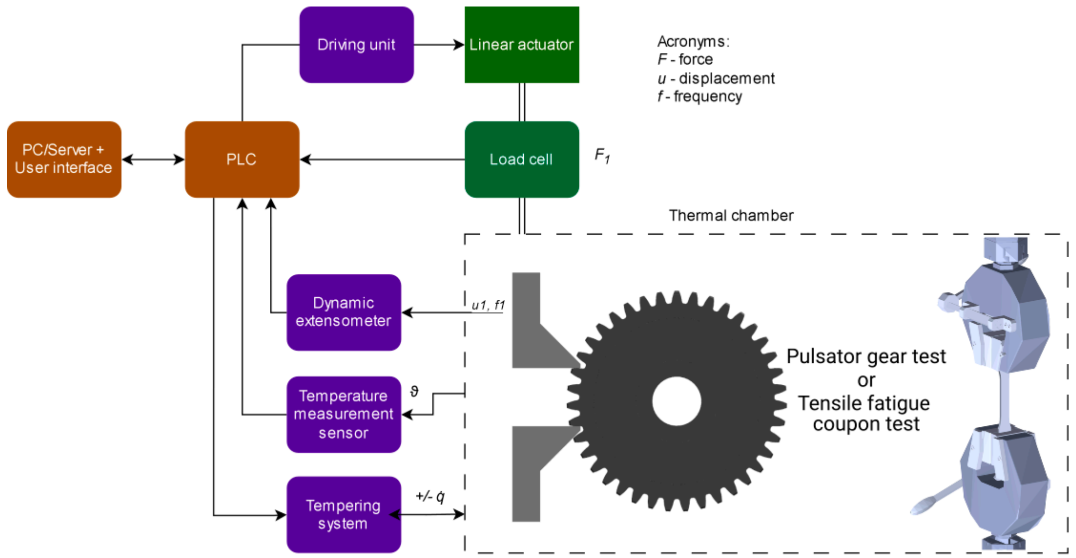


Figure 7—Pulsator and tensile fatigue test setup used for limit fatigue stress characterization of polymer materials used for worm wheels.

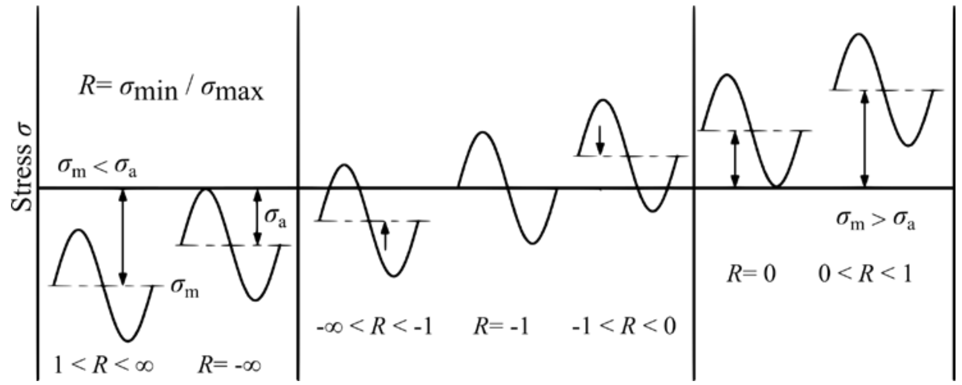


Figure 8—Fatigue testing R-factor determines the applied cyclic load regime.

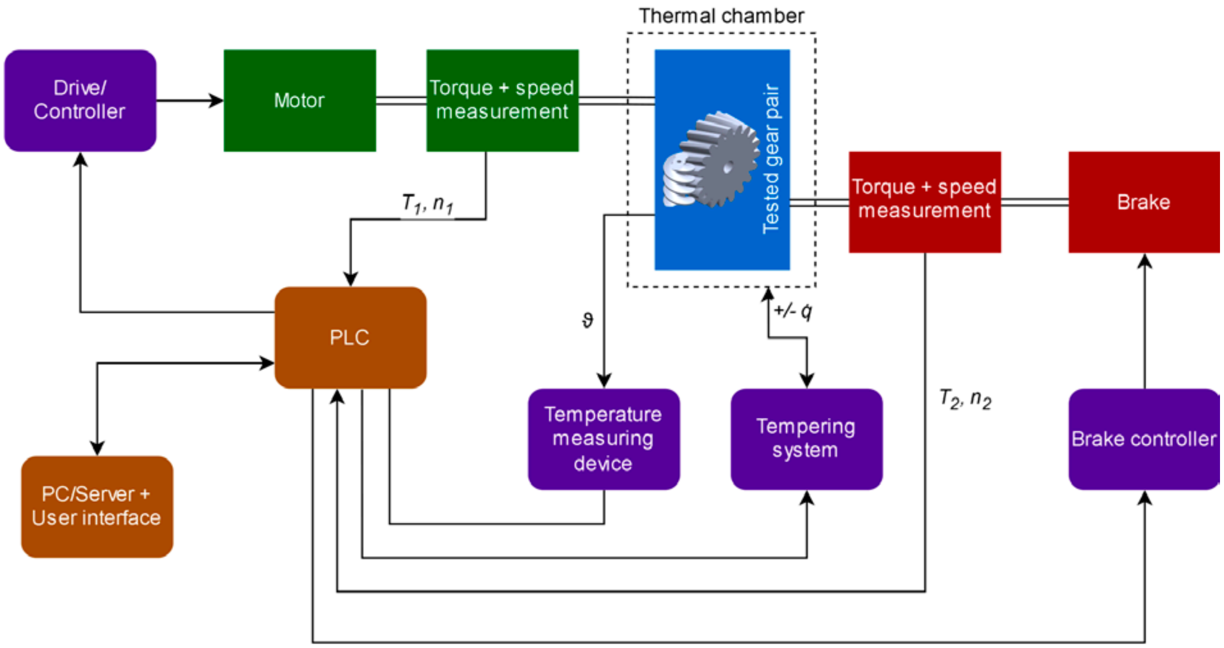


Figure 9—Schematic of a general test rig setup suitable for worm gear pair experimental characterization testing.

The defined geometry can be used as a basis for performing material characterization tests to obtain fatigue or flank strength data required for the gear rating calculations described in the previous sections. It is, however, always important to ensure that at the range of testing loads and temperature selected, the failure mode corresponds to the studied strength limit parameter. Different strategies can be introduced to achieve this, but apart from load and temperature, the failure mode is mainly a function of the used lubrication conditions. It is, e.g., possible to avoid unwanted thermal failure at higher loads by introducing a suitable grease for lubrication, which might suffice to reduce the temperature and avoid the material reaching the melting point. Flank fracture, on the other hand, is often exhibited in oil-lubrication conditions (although sometimes even in other lubrication regimes), which therefore requires the testing to be done in such conditions as well.

Case study—Experimental Characterization of a PA Compound Worm Wheel

Overview

A case study was performed to examine the viability of the material characterization procedures using worm gear tests and assess how variable failure modes can be analyzed using a selected gear pair geometry. In the presented case, a worm gear with a gear ratio of i=21 and module m=2 mm. Here, the worm wheel was produced using a specific type of polyamide (PA) compound in pair with a steel worm. The goal of the study was to characterize the fatigue and wear performance of the tested worm wheel material paired with the selected steel in both dry and grease-lubricated conditions.

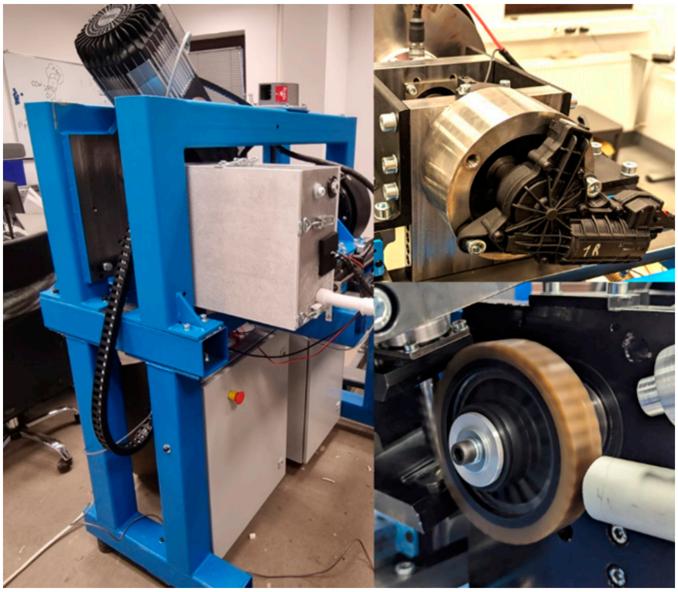


Figure 10—General-purpose worm gear test rig (GTR-170 model by RD Motion) used for the case study tests. The test rig is suitable for performing lifetime gear tests and failure mode-dependent limiting material strength characterization.

Thermal Failure

Initial tests were executed in dry running conditions with temperature control, at an output load on the wheel of 50 Nm and 100 rpm speed. Even at such moderate load conditions, the generated heat losses (combined with thermally induced wear) were exceedingly high, leading to imminent thermal failure (Figure 11). Based on these results, it was concluded that continuous running tests could only be executed in lubricated conditions and possibly at a lower running speed for thermal failure to be avoided and other failure mechanisms to develop.

Figure 11—Thermal failure on the worm wheel run in dry, non-lubricated conditions.

Fatigue Characterization

Tests in grease-lubricated conditions were subsequently carried out at an output speed of 60 rpm. A suitable grease for the used material pair can decrease the coefficient of friction to such a degree that thermal overload can be avoided and a quasi-steady thermal state at a selected temperature can be achieved. Combined with suitable active temperature control, which on the used rig is achieved by integrating a thermal spot sensor yielding the reference sample temperature, conditioned air inflow and an active PID-based control algorithm, it was possible to retain the worm wheel temperature at room level, i.e., 23 ± 4°C even at higher output torques. For accurate temperature measurements, it is important to account for any influence of the used lubricant on the surface emissivity. For the grease used, the emissivity was found to be very close to the emissivity of the polymer, i.e., approximately ε = 0.95. The results from the fatigue characterization testing presented in the form of an S-N curve as typically used in design and rating models as the one defined in the VDI 2736: Part 3 guideline, are shown in Figure 12 (plotted for 50 percent failure probability in line with Ref. 17). The observed failure mode throughout the range of testing loads was, rather surprisingly, root fatigue, where the location of fatigue crack nucleation was at the root below the active tooth flank (Figure 13). Since the worm wheel was composed of two polymers (i.e., it was a two-component injection-molded part), there could have been an influence of the transition between the two materials at the gear rim on the root fatigue failure. Due to this material configuration, the rim thickness of the first (gearing) material was reduced, which could have hastened the root crack nucleation at the root diameter.

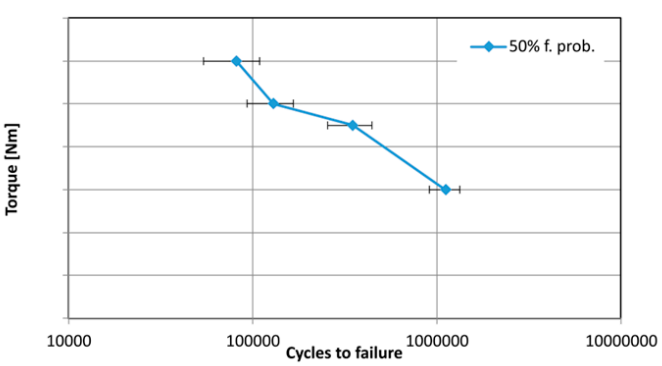


Figure 12—Generated S-N curve for the tested worm gear pair (torque data confidential and cannot be disclosed at the time of writing).

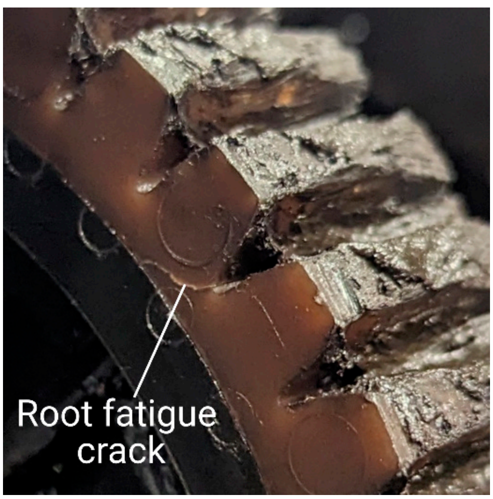


Figure 13—Fatigue crack nucleation location as commonly exhibited during the performed tests.

The exhibited failure mode falls outside of the assumptions laid out for the fatigue model described in the VDI guideline for worm wheels, where fracture at the flank as a function of shear stresses is predicted (see the section "Tooth Root Load Carrying Capacity"). The obtained results underline the necessity for a thorough revision and expansion of current state-of-the-art guidelines to account for and model other types of failure modes, which can indeed occur in certain material/lubrication/load configurations.

Wear Characterization

While wear rate prediction models are not presented in the VDI guideline for worm gears (even though such a model is defined for cylindrical gears), wear can, notwithstanding, be an important damage mode that can itself lead to failure or contribute to other failure modes like tooth fracture. In general, the same two categories of wear characterization methods could be used, i.e., the gravimetric (weight-loss) or geometric (tooth thickness reduction) types of methods. While wear can be described in terms of weight loss, due to a lack of suitable conversion models for evaluating the wear rate based on these measurements, currently, the thickness reduction method is preferred. An additional benefit of using the latter is that it enables measurements in any type of lubrication regime, while the gravimetric method is only valid for dry running conditions.

Still, the thickness reduction method poses several challenges, mostly in terms of reducing measurement uncertainty, which can result from:

- Location of measurement variation in the lead direction
- Angular deviations of the measurement tool relative to the tooth
- Variations in the diameter or height of measurement (in general measurements should be done at the reference circle diameter)
- Other operator-related errors

The noted sources of error can influence the measurements noticeably. It is therefore important to ensure repeatable measurement conditions and avoid any other external influences and decrease the measurement uncertainty to the highest degree possible. To achieve consistent results, the measurements should be executed on an appropriate bench with positioning tables, while the measurement tool should be suitably calibrated and with high enough resolution to allow for micron-level accuracy. In our example, a Mitutoyo GMA-25MX micrometer was used for the task. Figure 15 shows results obtained from three tests executed at 60 Nm in grease lubricated running conditions.

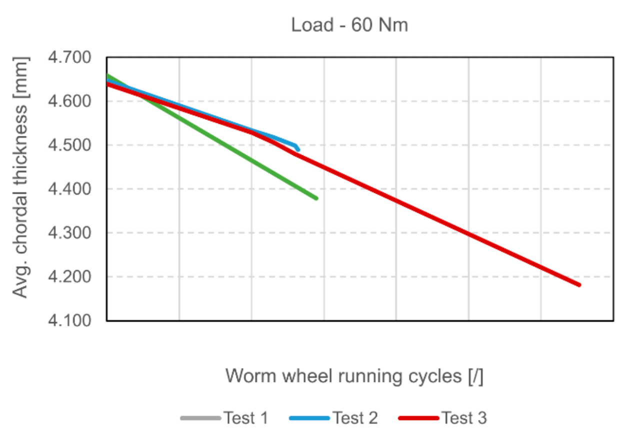


Figure 15—Tooth thickness reduction resulting from wear measured during three tests run in grease-lubricated conditions at 60 Nm. (Achieved running cycle data cannot be disclosed at the time of writing.)

Thermal Measurements

In lifetime gear tests carried out for root/flank fatigue or wear characterization, temperature is a key parameter that must be accounted for, since the mechanical properties and durability of polymers are highly dependent on it. These types of lifetime tests should, in most cases, be carried out at controlled temperatures to distinguish between the influence of the specified load and temperature on the service life of the gear pair. Temperature control (i.e., the retention of a gear sample at a selected temperature) can only be imposed if a suitable thermal measurement system is integrated into the test rig. To obtain consistent measurements, the sensors must be calibrated, the measured material emissivity correctly accounted for and the measurement position precisely specified. Per VDI (Ref. 17), the measurement location is defined to be at one quarter of the wheel's face width, on the active (i.e., meshing) flank side where the temperature is the highest (Figure 16a). IR thermal sensors, i.e., spot sensors or thermal cameras, are commonly used to measure the temperature as described. Figure 16b shows measurements

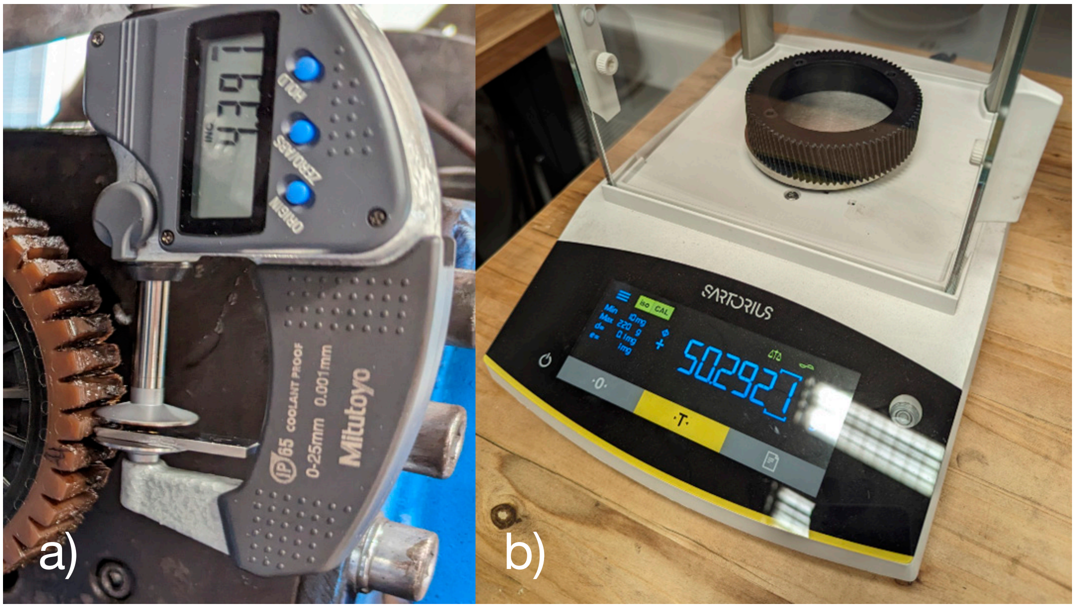
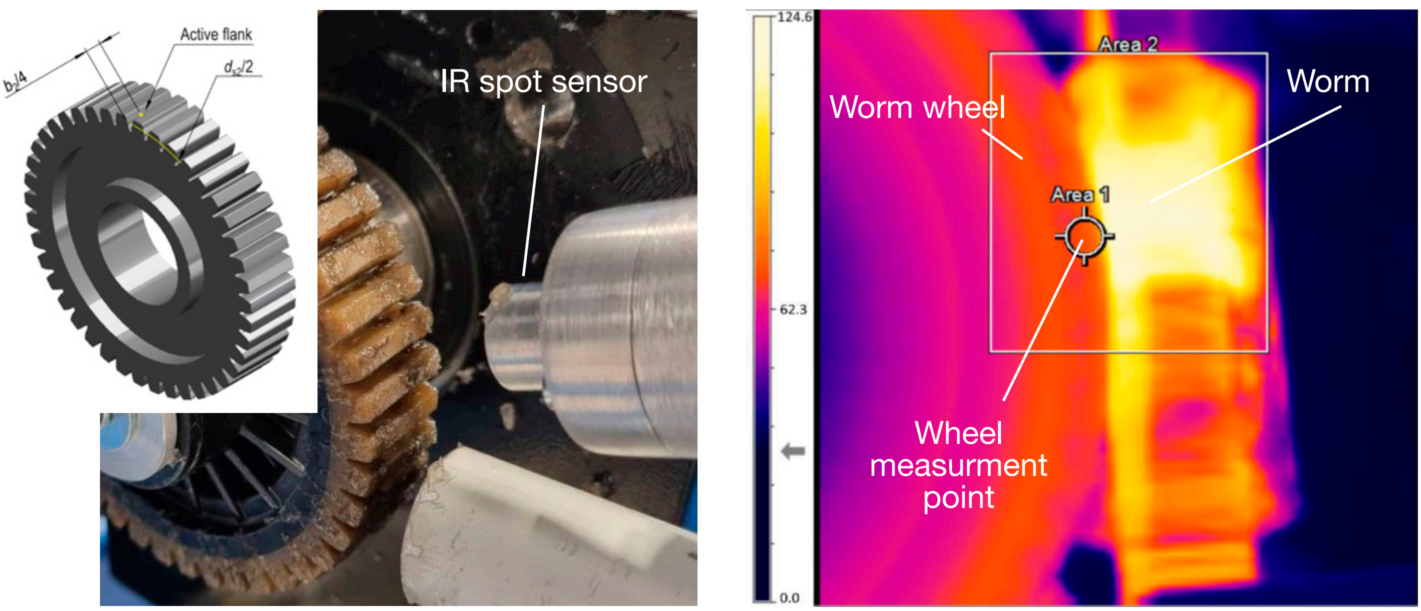


Figure 14—Geometric tooth thickness reduction (a) and gravimetric (b) wear measurement methods.



a) Measurement location

b) Measurement example using a thermographic camera

Figure 16—Thermal measurements executed on a worm wheel. a) VDI-specified measurement location and b) measurements executed on a worm wheel using a thermal camera.

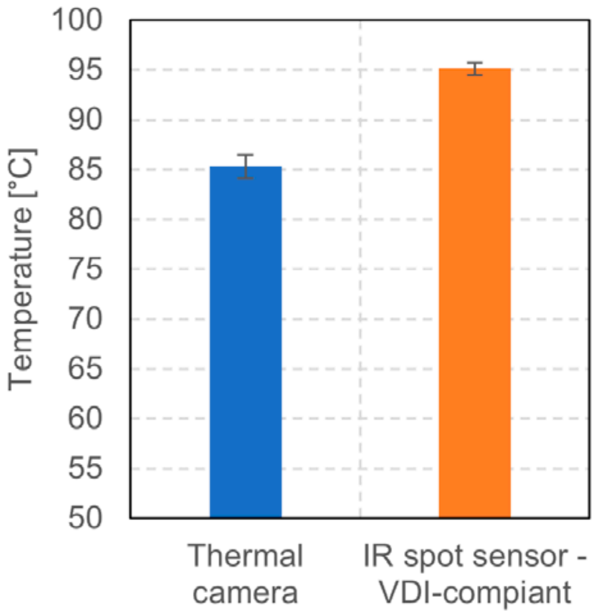


Figure 17—Difference in measured temperature between thermal camera positioned radially to the sample (Figure 16b) and a thermal spot sensor positioned as prescribed in the VDI guideline.

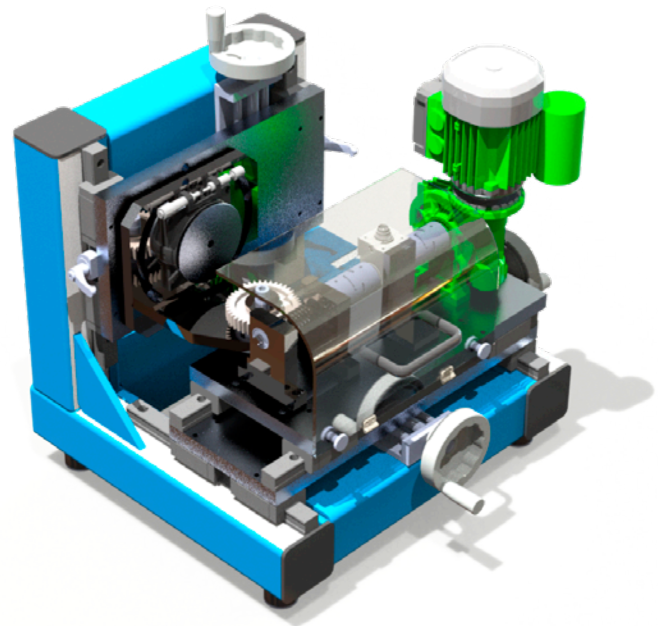


Figure 18—Ultimate-torque test rig (STR model by RD Motion).

obtained using an Optris Xi 80 thermal camera on a PA worm wheel run at 60 Nm in grease lubricated conditions without any active temperature control (i.e., the temperature is allowed to increase organically due to generated frictional/hysteresis heat losses). In this case, the camera was positioned almost perpendicularly to the wheel. An additional thermal sensor was positioned fully in line with the VDI specifications to measure the temperature on the active flank side. The difference in measured temperatures between both sensors is shown in Figure 17. The variation between VDI-specified measurement method and the thermal camera measurement was, in this case, a substantial 11 percent. The results underscore the importance of defining and adhering to measurement setup specifications to obtain compliant and comparable results in the type of tests described.

Ultimate Torque Fracture Testing

Worm gear drives are often required to withstand only short operation lifetimes, with cycle-to-failure numbers below N_L=10^3 (sometimes this number can be in the 10^1 range). In such cases, the ultimate (or peak) torque Tsp and correlated ultimate local root stress $\sigma_{FP,s}$ (Ref. 16) need to be evaluated. Here, $\sigma_{FP,s}$ is a function of the polymer's yield stress σ_S and is defined as:

$$\sigma_{FP,s} \leq 2,0 \cdot \frac{\sigma_S}{S_{Smin}} \tag{14}$$

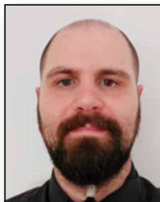
Here, the factor 2 accounts for an overstress capacity of the tooth relative to a tensile coupon due to a bending stress redistribution phenomenon (S_{Smin} is a safety factor; typically, 1.5.) $\sigma_{FP,s}$ is defined for cylindrical gears, however the same assumptions can be considered valid for worm wheels.

It is also possible to obtain experimental $\sigma_{FP,s}$ data directly on the gear geometry. To this end, universal mechanical testing devices with suitable mounting jigs for applying suitable loads on the worm wheel can be used. Alternatively, purpose-built test rigs can be employed. The test rig shown in Figure 18 provides the required torque overload via the worm, while the worm wheel is fully fixed. In this setup, the failure is achieved in one sweep of the worm tooth in contact with the tested tooth on the fixed wheel. The device therefore enables direct measurement of $\sigma_{FP,s}$ in realistic application load conditions. A similar testing method was used by Jiaxing et al. (Ref. 18). A slightly different variation of this testing approach, which instead uses a universal testing device for mounting the worm and applying a tangential force on the wheel, was presented by Shi et al. (Ref. 19).

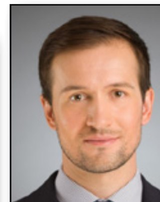
Conclusion

The paper presents the current state-of-the-art in plastic worm gear design and load-carrying capacity rating. The VDI 2736: Part 3 guideline is studied as a reference, since it provides the most comprehensive set of models and data for worm wheel calculations. Based on an executed case study, it was found that the guideline, while fairly comprehensive, lacks suitable models and methods for the characterization of root fatigue and wear as exhibited in the tested polymer worm wheel. Root fatigue was found to be a driving failure mode in the executed study, instead of tooth fracture across the worm's tip diameter as assumed in the VDI guideline. Furthermore, the results showed the necessity for a suitable wear rate model similar to the one presented for cylindrical gears in VDI 2736: Part 2, since significant wear was measured even in grease lubricated conditions. Overall, the study further attests to the fact that a more comprehensive worm gear standard would be required for the load-carrying capacity analysis that would take into consideration various material/lubrication/geometry/load configurations and would also provide more comprehensive material data for the wealth of available engineering polymers employed in such applications.

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



Rok Kalister is a VP of technology and product R&D at RD Motion. Holding a master's degree in Mechatronics Engineering at the University of Ljubljana, he has extensive knowledge in control systems design and product development, with a strong focus on polymer gear design and power transmission testing rig design.



Dr. Damijan Zorko is a Co-CEO at RD Motion. He studied Mechanical Engineering at the University of Ljubljana and received his Ph.D. in 2019. Having 15 years of experience in gear transmissions, he was deeply involved in developing RD Motion's modern test benches and testing methods for experimental research on gears.

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First presented at the 2024 Fall Technical Meeting (FTM), October 7–9, 2024, Rosemont, IL. Printed with permission of the author(s). Statements presented in this paper are those of the author(s) and may not represent the position or opinion of the American Gear Manufacturers Association.

ANCA and Zoller

DATA EXCHANGE HELPS FRAISA STREAMLINE REGRINDING PROCESS

It's the same old story every day and the pressure is constantly increasing: the first tool must be in quality and rework must be avoided. Scrap must be avoided at all costs, because it is one of the major cost drivers. This applies to both the production of new tools and to regrinding.

To achieve this, it is essential to have a perfect grinding program as well as valid information about grinding wheels and wheel packs. ANCA provides a standardized interface for this in the WheelEditor of ANCA's own ToolRoom grinding software, which enables both the export of wheel information and the import of measurement results. These measurement results are the basis for all calculations that lead to a perfect tool in the first run. It does not matter whether the wheel data is managed locally or across multiple machines using ANCA WheelServer. This interface can be used to exchange all wheel information, such as diameter, wheel radius, wheel angle, flange size and other relevant information. The interface also offers the option of exchanging only individual parameters, such as flange size or diameter, for wear control. In this case, only this data is transferred via the network and measured. The results are also provided and transferred via the network.

Fraisa, a precision tool company based in Willich, Germany, uses the Zoller Venturion to measure its grinding wheel packages. The data is sent directly to the ANCA WheelServer, which assigns the actual data of the physical package to the virtual package and in turn provides this to the grinding machine. "The transfer of actual data from Zoller to the ANCA software is a game changer for us. It saves us an enormous amount of time and effort," says Stefan Schaefers, head of technology at Fraisa.

Here, each package is measured before use, ensuring that only real data is used. Since its introduction in 2018, the system has been implemented on all Zoller devices and the 20 ANCA machines on site. "We are talking about 10 grinding wheel packages per day that are dressed by our external partners and then measured directly by the machine operators in our company," explains Schaefers. The results are impressive: "Particularly with regard to machine availability, external measurement and automated data transfer have brought huge improvements. We were quite amazed ourselves when we did the first evaluations in this regard and realized that we could save 20 percent in non-productive time and reduce the rework rate by 10 percent."

Fraisa GmbH in Willich is the main location for tool reconditioning. Around 350,000 tools are reground here every year. The ReTool concept uses the latest production control and automation solutions to offer customers cost savings of up to 70 percent compared to new tools, while also reducing CO_2 emissions by 50 percent. This is possible, among other things, due to a very high level of plant efficiency, which in turn is partly due to grinding wheel management.

"Our motto is 'first tool = good tool'," says Schaefers. "This only works if we do our homework in terms of data storage, measurement and handling. Thanks to the data transfer between Zoller and ANCA, we always have a ready-to-grind wheel package at hand. The error rate is practically zero due to the guaranteed repeatability and operator-independent measurement. If the wheel pack fits, the tool is as good as in the simulation after the first regrind."

Steffen Kluth, product manager for digital manufacturing at ANCA, adds: "The measurement on the Zoller and the data transfer to the ANCA machine can be carried out by the machine operators. These are value-adding tasks that have a significant influence on quality and thus also increase the value of daily work. In addition, data transfer eliminates the risk of typing errors."

The state-of-the-art production methods and control at Fraisa are success factors for ReTool. Schaefers sees this advantage and has already thought about further enhancements. "We are aware that the use of connectivity and automation must be continuously expanded. For example, we want to become even better at grinding wheel management. We have 250 different variants of grinding wheel packs in circulation. On the one hand, we have to maximize the efficiency of our workflows and, on the other hand, we have to ensure that we always have a duplicate wheel pack available when one is needed. That's another thing we're pushing."

"That's a further important step towards the integrated manufacturing of tools," says Kluth, "because the data format used for the transfer is based on the widely known XML format." This standard will also be incorporated into the future specification OPC UA for Cutting Tools, for example.

Since the introduction of its own modular automation system AIMS 2022, ANCA has developed its own portfolio for digital, automated tool production and is also contributing to various standardization projects, such as the GDX interface or Umati.

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JULY 9–10

Dritev 2025

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

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SEPTEMBER 10–12

11th International VDI Conference on Gears 2025

The 11th International VDI Conference on Gears 2025 will be held in Garching, Munich at the Gear Research Centre (FZG) of the Technical University of Munich. Supported by national and international associations, the conference brings together 500+ leading experts from the international gear and transmission industry. Visiting the conference gives attendees the opportunity to take part in this leading international forum and learn about the latest developments and research results in the powertrain industry and academia. The conference is a unique meeting point for propulsion system manufacturers and researchers of gear and transmission systems.

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SEPTEMBER 15–17

CAR Management Briefing Seminars 2025

The Center for Automotive Research (CAR) MBS leads the industry in providing a context for auto industry stakeholders to discuss critical issues and emerging trends while fostering new industry relationships in daily networking sessions. The CAR Management Briefing Seminars take place at Michigan Central Station in Detroit. Seminars include sessions on manufacturing strategy, connected and automated vehicles, advanced powertrain, supply chain, sales forecasting, purchasing, talent and designing for technology, future factories, design optimization, the mobility ecosystem and more. Roundtables will focus on cybersecurity, policy updates, sustainability, decarbonizing, electrification and more.

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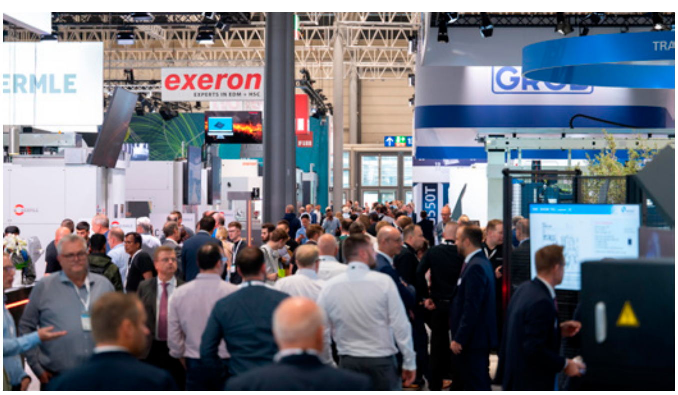
SEPTEMBER 22–26

EMO Hannover 2025



Founded in 1975, EMO Hannover has stood for innovation, internationality, inspiration and the future of metalworking worldwide. This trade fair for production technology offers a unique platform every two to four years in Hannover under the motto 'Innovate Manufacturing' to establish international contacts, tap into new business opportunities and gain a comprehensive overview of the industry's global offering. Most recently in 2023, over 92,000 visitors from 140 countries and around 1,850 exhibitors took part in the event. EMO showcases the entire metalworking value chain including cutting and forming machine tools, manufacturing systems, precision tools, automated material flow, computer technology, industrial electronics and accessories. Exhibitors and visitors with a high level of expertise discuss the megatrends in manufacturing, exchange ideas with representatives of international production research and develop solutions for existing challenges.

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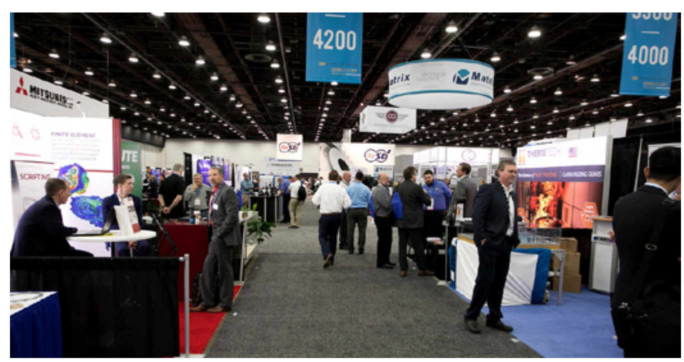
OCTOBER 21–23

Motion + Power Technology Expo 2025



Produced by AGMA, Motion + Power Technology Expo (Detroit) is a three-day show that connects professionals looking for motion power solutions with manufacturers, suppliers, and buyers. Attendees will find new power transmission parts, materials, and manufacturing processes. Buy, sell, and get business done with organizations in aerospace, automotive, agricultural, energy, construction and more. Forge partnerships at one of the largest gatherings of CEOs, owners, engineers, sales managers, and other professionals in the electric, fluid, mechanical and gear industries. End-users can shop the latest technology, gear products, and services from leading manufacturers. No matter your industry, you will find new ideas and solutions that can benefit your plant and company. Hundreds of exhibitors and attendees means MPT Expo is a unique opportunity to find partners that can help fulfill your specific production needs.

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ADDENDUM

The Anatomy of a Mecha Goat

Aaron Fagan, Senior Editor

At Expo 2025 Osaka, Kawasaki unveiled Corleo, a rideable four-legged robot designed for off-road terrain. It's not a motorcycle, ATV, or mule—but a hydrogen-powered quadruped that blends advanced robotics with a distinctly mechanical engineering mindset. And it's designed to go where wheels can't.

Corleo walks using four independently powered robotic limbs. Each leg terminates in split rubber hooves designed to maintain grip on unstable terrain—rocks, scree, mud, and slopes. The leg design draws heavily from motorcycle suspension systems, especially in the rear, where swing-arm-style linkages absorb vertical impacts and maintain chassis levelness while climbing or stepping over obstacles.

Each leg likely employs multi-stage reduction gear systems—possibly strain wave or cycloidal drives—at the hip, knee, and ankle joints. These compact, high-torque mechanisms are favored in legged robotics for their low backlash and high positional repeatability. Such systems allow the robot to precisely control gait, balance, and reactive step placement. For terrain this varied, backlash minimization and joint stiffness are critical not just for control but for long-term durability.

Power is supplied by a compact 150cc hydrogen internal combustion engine, not mechanically linked to the drivetrain, but acting as an onboard generator. The electricity it produces is routed to in-leg electric motors, allowing for decoupled, distributed actuation. This hybrid approach eliminates the need for gearboxes between engine and limb but shifts precision load management to the electric actuators and their associated gear trains.

While Kawasaki has not disclosed details about the limb gearboxes, a quadruped operating under variable load and unpredictable terrain likely requires high-ratio planetary reductions combined with torque-dense actuators and robust encoders. These systems must be sealed against dust, moisture and impact loads while maintaining thermal stability and service life under repeated shock cycles.

Control is entirely body-driven. Instead of throttle or steering, Corleo uses a weight-shift interface, where pressure sensors in stirrups and handlebars detect the rider's posture and translate it into movement commands—forward lean initiates motion, lateral shifts trigger turning. The system relies on real-time sensor fusion and feedback to manage gait transitions, requiring tightly integrated mechanical response from the gear and motor assemblies to prevent lag or oscillation.

An onboard control panel provides diagnostics for route planning, hydrogen level, and center-of-gravity tracking—especially useful on sloped or unstable terrain. At night, a ground-projection system highlights navigable paths with visible markers.

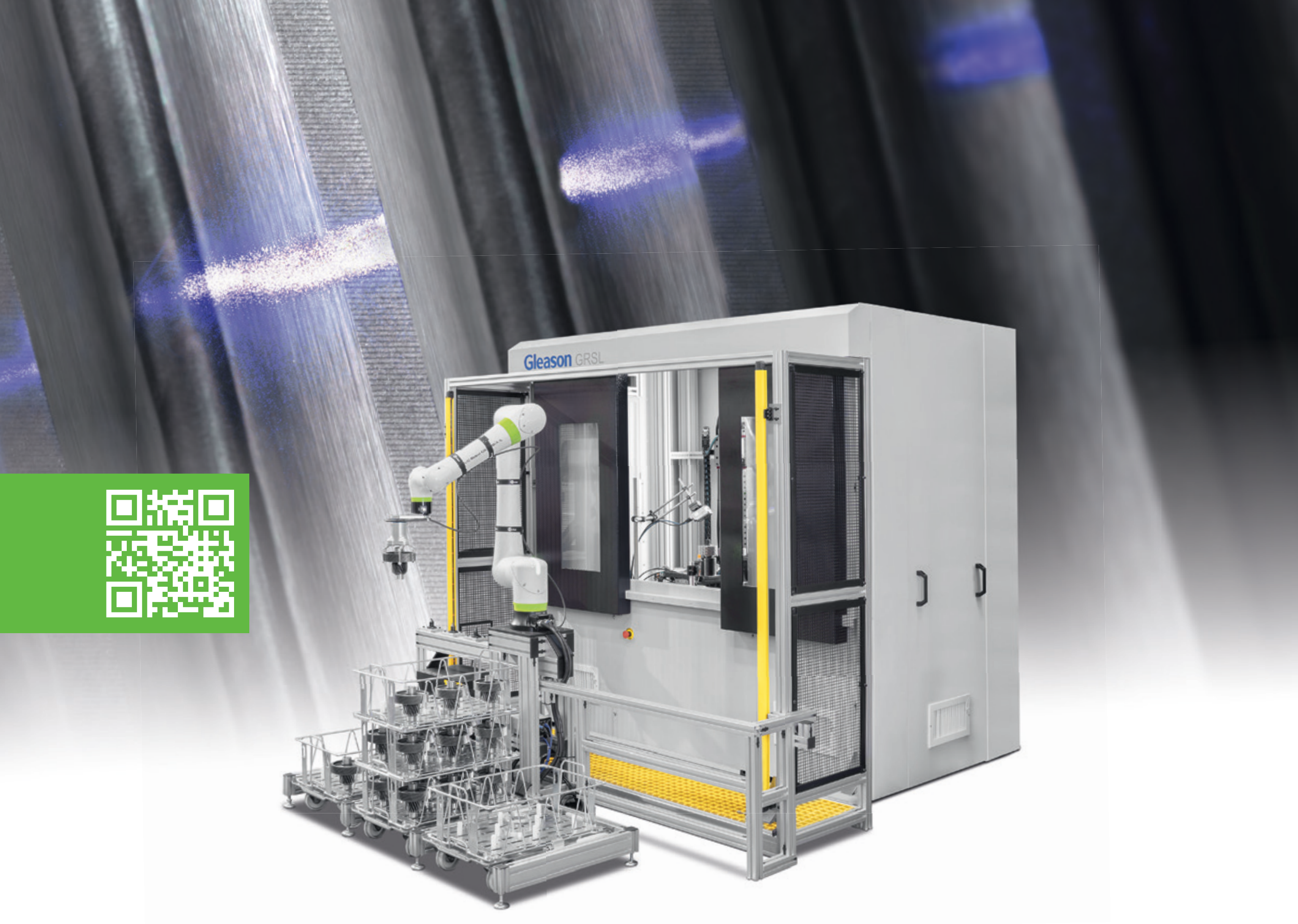
Hydrogen is stored in a rear-mounted tank, with the only exhaust being water vapor. This design avoids the energy density limitations and recharge time of lithium-ion battery systems while raising questions about hydrogen refueling logistics, particularly for field deployment.

Corleo is not a consumer product, but a prototype platform. Kawasaki presents it as a mobility research tool for legged locomotion, clean energy propulsion, and human-machine interface design. Potential applications include remote logistics, search and rescue, environmental monitoring, and defense—all settings where traditional wheeled systems encounter terrain limits.

From an engineering perspective, Corleo addresses a broad set of mechanical challenges: limb synchronization, joint torque control, gait stability, actuator thermal management, and long-term wear in field conditions. Material selection for moving parts—lightweight alloys, reinforced composites, or high-cycle fatigue-resistant steels—is key to maintaining performance under constant directional loads and unpredictable ground contact.

Corleo may never see mass production, but its engineering implications are clear: as robotics and mobility converge, the role of precise power transmission, especially in complex, multiaxis systems, will only grow. This isn't just a new type of vehicle. It's a new kind of drivetrain challenge, one that trades speed for adaptability and traction for autonomy.

To view an animation of Corleo in action, visit: *youtube.com/watch?v=vQDhzbTz-9k*



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