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Gear Talk: Origin Stories

Our weekly blog has been featuring great stories about how many in the industry first became involved with gears. Read recent entries from Ernie Reiter, Ed Kaske, Joe Arvin, Yefim Kotlyar and others here *www.geartechnology.com/blog*. Be sure to send YOUR gear story to *publisher@geartechnology.com* to be included in future blog entries.

Threaded Wheel Grinding with Gleason

As the director of product management, Dr. Antoine Türich at Gleason gives insight on the development of the GX-Series Threaded Wheel Gear Grinding Machines, explains benefits of efficient manufacturing systems, state-of-the-art setup systems and mid-term challenges regarding the hard finishing of gears. Check out the video here:

www.geartechnology.com/videos/Effective-Processes-for-the-Threaded-Wheel-Grinding-of-Gears-/

Klingelnberg C30 Cutter Head Change

Thanks to continuous further development of the vertical concept, the Oerlikon C 30 bevel gear cutting machine from Klingelnberg sets new standards in dry processing. All of the bevel gear machines in this series are equipped with a thermo-stable, vibration-damping machine bed. Learn more here:

www.geartechnology.com/videos/Klingelnberg-C30-Cutter-Head-Change/

Event Spotlight

8th WZL Gear Conference USA – July 23–24

Westminster, Colorado. Attendees can expect a selection of presentations from the research portfolio of WZL including information on gear design, manufacturing, gear checking, and testing. Highlights include requirements for hard finishing, gear optimization, superfinishing, trends in gear production, Internet of production, gear hobbing, gear modifications and a workshop tour of Kapp/Niles in Boulder. Learn more here:

www.geartechnology.com/news/9540/8th_WZL_Gear_Conference_USA/

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It's Not Your Father's Gear Business

Publisher & Editor-in-Chief
Michael Goldstein

The world is changing.

I've just returned from the AGMA Annual Meeting in Scottsdale, AZ. Like always, it was a great opportunity to visit with peers, colleagues, customers and competitors in the gear industry. But this year's event was far more than just a chance to reunite with old friends.

No, this year's annual meeting was also a wake-up call.

In addition to the usual presentations by speakers with expertise in management, manufacturing and international trade, attendees also heard from experts on artificial intelligence, blockchain, cybersecurity and cloud computing.

You might think those are just high-end concepts that will never have any connection to what happens on your shop floor every day. Those are just the latest buzzwords, you think – the phrases people throw around at cocktail parties to make themselves sound smarter and more sophisticated than you.

But you'd be wrong. These things are coming, and over the next decade, they're going to have a meaningful impact on manufacturing — even in stolid old industries like gear manufacturing. These things may not be important today, but they're going to grow in importance every day, especially as more powerful computers and faster communication protocols become embedded in every aspect of society. (Did I forget to mention 5G? It's coming, too, and not just to homes and cities. Factories might be one of the biggest benefactors of that technology over the next few years.)

I don't claim to understand much about what these experts talked about. I don't know exactly what blockchain, for example, will mean to your business. But after hearing from the speakers at the annual meeting, I'm convinced now that it *will* mean something, and so will the rest of these seemingly esoteric concepts. You probably won't understand them either. No offense, but if you're reading this, you're probably too old.

We need to turn these concepts over to the next generation, the people who've grown up in a connected society. Knowledge and experience used to start at the top and trickle down in an organization. Now, these important concepts will likely start at the bottom and work their way upwards. The most recent hires, right out of school, grew up in the digital age and are already wired for digital communication. You need to make use of their expertise in ways you haven't even thought of.

Exploring these new frontiers might also be a great way to attract more young people to our industry. Even those who've shown no interest in the dirty, noisy gear business might might perk up when you tell them you're on the cutting edge of industrial cybersecurity.

These young people are the ones who are going to figure out the next industrial revolution. And you need to let them. You have to get them involved, sooner rather than later. Send them to AGMA meetings. Introduce them to organizations like MxD (*www.mxdusa.org*), where these ideas are being applied to manufacturing today. Give them the opportunity to study these ideas, experiment with them and see how they might fit into your business.

Not only will this give your organization a better understanding of the technologies that will shape your future, but it will also give your young employees something to be excited about. It will help them become invested in your business and learn about its intricacies.

I'd like to thank the AGMA for bringing some of these ideas to the forefront of gear manufacturers' minds, not only at the annual meeting, but in their overall approach. The association is heavily focused on helping gear manufacturers gain the insight and understanding of how to stay competitive in this changing landscape. Being a member of the association – and more importantly, being involved – is perhaps more important than it's ever been.

If you haven't looked at the AGMA's offerings lately, I'd say you're long overdue. But don't look for yourself. Figure out how to get the young people in your organization involved. After all, they're the ones who are going to transform your business.

Klingelnberg

HIGHLIGHTS COMPLETE PORTFOLIO AT CONTROL 2019

Headlined as "Control 2019 — Networking Science and Actual Practice," the 33rd international trade fair for quality assurance took place in Stuttgart from May 7–10, 2019. The solutions provider's "exhibition trunk" included the P16, P26, P40, and P100 G precision measuring centers, featuring an optimized machine design. This year's show highlights included gear measurement for cylindrical gears using the closed loop method, the new hybrid technology for tactile and optical measuring technology, and solutions for measurement tasks beyond gear measurement.

P16 — Precise measurement with closed loop technology for cylindrical gears

In extending the closed loop concept already established at Klingelnberg for bevel gears to the world of cylindrical gears, the machine manufacturing firm has linked machine tools to the measuring machine in this sector too. Thanks to a wide variety of associated applications and software, Klingelnberg has created a central production control system that standardizes machining results achieved on different machines, and even in different plants. Closed Loop thus uses a modern software architecture to allow data to be exchanged between design, production, quality assurance and statistical evaluation, and also actively to bring information to the consumer or, in a later development stage, to initiate process steps automatically. This totally integrated digital data exchange reduces the risks of error and guarantees complete reproducibility of all processes.

P26 — Hybrid technology: combining optical and tactile measuring technology

The standards in gear measuring technology are extremely high, requiring accuracies in the nanometer range on the one hand, and short measuring times with a higher information density on the other hand. To meet this challenge, Klingelnberg launched a new hybrid technology in 2018 that combines the advantages of both tactile and optical measuring technology. The advantage of rapid sampling by the optical sensor is combined with the flexibility and extremely high accuracy of the 3D Nanoscan tactile sensor system. This ensures that the new, highly appealing potential of optical measurement can be utilized without compromising the measuring accuracy. The hybrid system is designed so that the optical sensors can be adapted in a variety of ways. Klingelnberg avoided committing to one sensor principle only. Thanks to a high-speed scanning sensor, any number of axially symmetrical components can be digitized through rapid scanning with an extremely high point density. The "Optical Measurement" option includes the Highspeed Optoscan optical sensor with a rapid change feed unit, the software for sampling and visualizing the measured point cloud, and the GOM-3D evaluation software.

P100 G — Measurement tasks beyond gear teeth

The 100 "G variant" Klingelnberg Precision Measuring Centers are specifically designed for measurement tasks beyond gears, making them well-suited for measuring axially symmetrical components. The software for standard dimensional measurement tasks and form and position measurements included in the machine's scope of delivery also covers special evaluations such as Fourier analysis. In addition to dimensional measurement tasks, even complex contour and surface measurements can be measured in a single clamping. This is ideal in particular for the high precision requirements in the automotive and commercial vehicle industry, as well as in mechanical engineering and plant engineering. But this range will also appeal to all manufacturers of rolling bearings.

That is because it enables rolling bearings and rolling bearing elements to be accurately analyzed and measured to an extremely high degree of precision. The particular advantage lies not only in the high-precision form measurement but also in the capability of performing roughness measurements (both internal and external) fully automatically in the integrated measuring runs, even on large components. Based on the manufacturer data and specifications, measuring runs are created automatically with conclusive protocols based on current standards and regulations. The series variations and quality grades of the bearings are fully supported by Klingelnberg software. Additional measurement tasks based on specific requirements of the bearing manufacturer can also be implemented with ease.

P40 — Proven solutions for gear measurement

Klingelnberg presented the P40 series of precision measuring centers for small diameter ranges to the international audience in Stuttgart — optimal solutions for quality management processes on gears that are guaranteed to ensure future success. The machine and software concept of the Pseries is optimized for measurement of complex drive components. The technology replaces up to six conventional measuring machines: gear measurement, general coordinate measurement, optical measurement, form and position measurement, roughness measurement, and contour measurement. These measurement tasks can be fully automated in a single clamping.

All machine models can be enhanced with custom options and feature specifications that make them ideal for performing measurements in the production environment. Klingelnberg Precision Measuring Centers stand out for their patented, high-precision 3D Nanoscan probe system as well as their easy-to-use roughness probe systems for external and internal measurements. This solution brings Klingelnberg close to the market, and the user. The P series is a widely used standard in the industry — for good reason — and also serves as a reference for metrology institutes.

Klingelnberg also presented its services and software solutions, alongside the measuring centers. As usual, Dr.-Ing. Günther Gravel, Head of the Institute for Production Technology at the University for Applied Sciences (HAW Hamburg) was on site as a measured value analysis expert.

For more information:
Klingelnberg America, Inc.
Phone: (734) 470-6278
www.klingelnberg.com

KISSsoft

PROVIDES ADDITIONAL SOFTWARE TOOLS FOR GEAR MANUFACTURING

KISSsoft provides a number of useful tools for gear manufacturing throughout the design process.

When grinding helical gears an unwanted production-related twist is generated. This twist can be simulated in advance in the *KISSsoft Release 03/2018* (module ZY6), and the influence on the flank contact can be evaluated with contact analysis.

When designing hardened and ground gears, the grinding notch must be taken into account with regard to position and rounding radius in order to avoid stress concentrations. In addition to the ISO 6336 standard and FEM in 2D (module ZA24), *KISSsoft* also provides evaluation with FEM in 3D (module ZA37): This evaluation is based on the exact load distribution over the tooth width and enables the consideration of crowning and axial misalignments with respect to the load distribution, which results in a much more precise analysis of the stresses over the tooth width.

With the use of protuberance hobs, the grinding notch can be avoided or significantly reduced. The protuberance can be specified in *KISSsoft* on the reference profile as well as on the tool (hobbing cutter, cutting wheel), and checked


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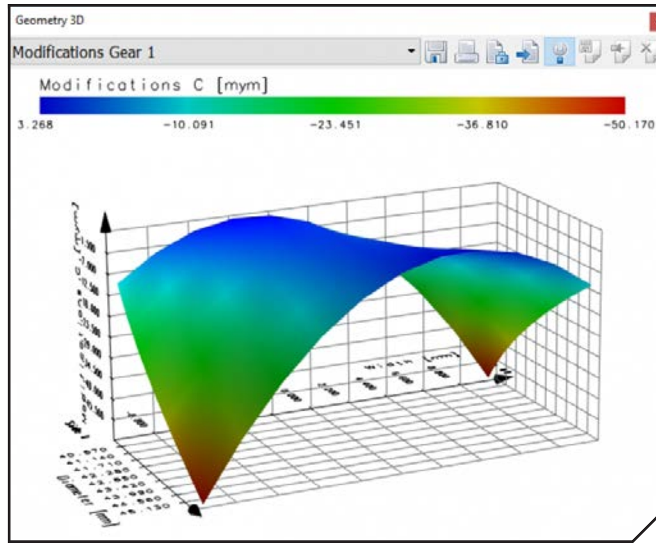


in numerous graphics for gear teeth, tools and production.

For more information:
KISSsoft AG (A Gleason Company)
Phone: (585) 494-2470
www.kisssoft.ch

Helios Gear Products

INTRODUCES HERA 90 CNC GEAR HOBBING MACHINE

Helios Gear Products (formerly Koepfer America) now exclusively offers the Helios Hera 90 CNC gear hobbing machine from YG Tech for the North American market. This gear cutting solution provides high technology features such as FANUC 0i-MF control and servo motors, direct drive hob and work spindles, Heidenhain linear scale on X-axis for precise repeatable control of size, and more. Gear manufacturers will appreciate this hobbing machine for its unique combination of technical capabilities, market-beating price, and proven domestic support.

"The Hera 90 is the first of the Hera series to meet the demanding needs of our customers, and this includes not only a globally competitive price point but also a complete hobbing solution backed by industry experts for technical support," said Adam Gimpert, business manager at Helios Gear Products.

The Hera 90 offers key features, such as 8.5 DP (3 mn) pitch rating, 6,000 rpm maximum hob speed, and up to 8 CNC axes. When equipped with the optional gantry loading and unloading system, the Hera 90 capably and productively hobs a variety of gear types. Workpieces up to 12.600" (320 mm) length can be manually loaded or 7.874" (200 mm) length automatically loaded. Centerline distance between cutter and work spindles moves between 0.394" (10 mm) and 3.937" (100 mm), providing the capacity for a wide range of gear sizes. With 6.300" (160 mm) hob shift, job shops and end-product gear manufacturers alike must consider this machine's productive mix of flexibility and capability in a small footprint.

Several standard capabilities are available via the Hera 90's dialogue programming: one and multiple gears on a single workpiece, multiple-cut cycles, any combination of radial, axial, climb, or conventional hobbing, crowning (lead modification), automatic shifting over a broken hob section, CNC hob shifting, and burr-free hobbing using two equal hobs. Straight bevel gears can also be cut by index milling or generating cutting via the Conikron method.

"In today's globally competitive market, gear manufacturers need a cost-effective, highly capable, yet versatile hobbing solution for fine-pitch gearing. The Helios Hera 90 fills this role like nothing else on that market," said David Harroun, sales manager of Helios Gear Products.

Construction features of the Hera 90 prove strong fundamentals of engineering and design. The machine uses direct-drive torque motors. A cast iron machine base provides optimum stability and dampening of cutting forces. The machine's slant bed design uses gravity to efficiently remove chips during the cutting process. Automatic X-axis (radial hob head position) retract at power failure ensures the safety of tooling during electrical loss. Total machine enclosure includes world-standard safety equipment such as electro-mechanical interlock and front splashguard doors.

For more information:
Helios Gear Products, LLC
Phone: (847) 931-4121
Heliosgearproducts.com

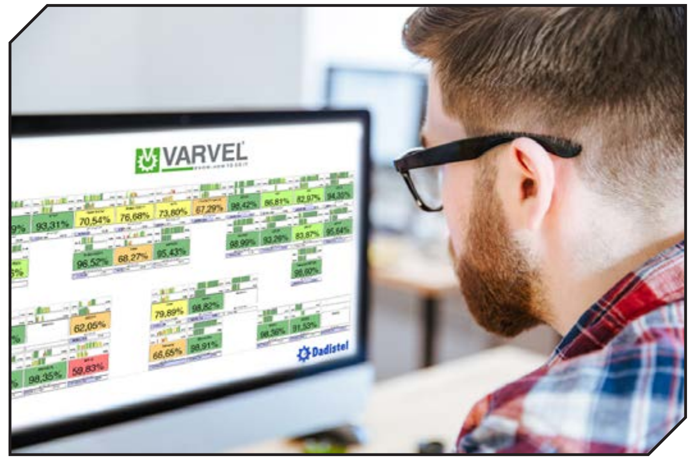
Varvel

INTRODUCES NEW AUTOMATION SYSTEM

The Varvel Group has introduced Dadistel, an automation system for control of production in mechanical machining departments that enables effective and efficient time management, providing invaluable real-time information and accurate estimates on delivery times and the availability of resources, as well as an analysis of production processes and trends.

In the coming months, this extremely advanced tool will enable integrated monitoring of production flows, with a clear improvement in terms of reliability and performance. This resource enables accurate, profitable control of timings, providing information on timing related to preparation, retooling, machining, downtime/pauses, production resumption and changeover. Equally important is the counting of parts, approved and/or rejected, in addition to the indication of average statistical times for parts produced, namely cycle, machine, loading/unloading.

These real-time calculations bring improvements in management, with benefits that affect estimates relating to delivery times and the availability of resources, favoring the entire just-in-time supply chain and producing a significant improvement in the supply chain overall. To make daily and periodical monitoring even more meticulous, Dadistel also provides analysis of production processes and trends, together with machine and loading/unloading performance details, plus essential production data.



Some product highlights:

Timings includes the information that is made available in various formulas to suit different requirements at different times: at the same time as machining; as a record of work completed; based on groupings by period and sub-period (such as shifts, days, weeks, months, quarters, years); in relation to a machine, a department or a work island and even based on references/criteria of interest.

In view of the ease and speed of installation, the Dadistel system has can be applied to all machine tools, from the oldest to the most modern, whatever brand and model they are. In addition, as it is a passive system, if offers the unique advantage of making no modifications whatsoever to existing plants.

Another feature is the fully independent data collection, which does not require operator intervention or the use of bar code readers. This means that

Dadistel guarantees objective information that cannot be manipulated, plus this information can be integrated within different perspectives, tailored to the needs of all operators — production managers, workshop managers, factory managers, owners — based on roles and requirements.

Dadistel is an artificial intelligence which, by its very nature, learns from past events and continually improves its analyses. It has already obtained a patent for the innovative combined hardware/software system on which it is based. Its introduction was facilitated by the fact that the new system integrates with the major order management and planning systems, with an interface that allows its immediate and simple use, with room for extensive customization.

For more information:
Varvel USA LLC
Phone: (770) 217-4567
www.varvelusa.com

Cutting Tool Dynamics

Meeting Today's Requirements for High-Quality Gears

Matthew Jaster, Senior Editor

Changing manufacturing technologies usually trickle down the supply chain. Modern gear grinding machines, for example, support the manufacture of higher-quality gears and said gears are now being produced with a variety of exotic materials. In turn, cutting tool development needs to stay on par with this advanced machine tool technology. Representatives from companies like Gleason, Helios Gear Products, Klingelnberg, Liebherr and Star SU recently discussed some of the cutting tool technology that is keeping up with the machine tools.

Gleason Discusses Cutting Tool Evolution

Customers keep pushing the boundaries for cutting tool accuracies for finish hobbing and finish shaping. Fortunately, modern gear tool grinders support these higher accuracy requirements.

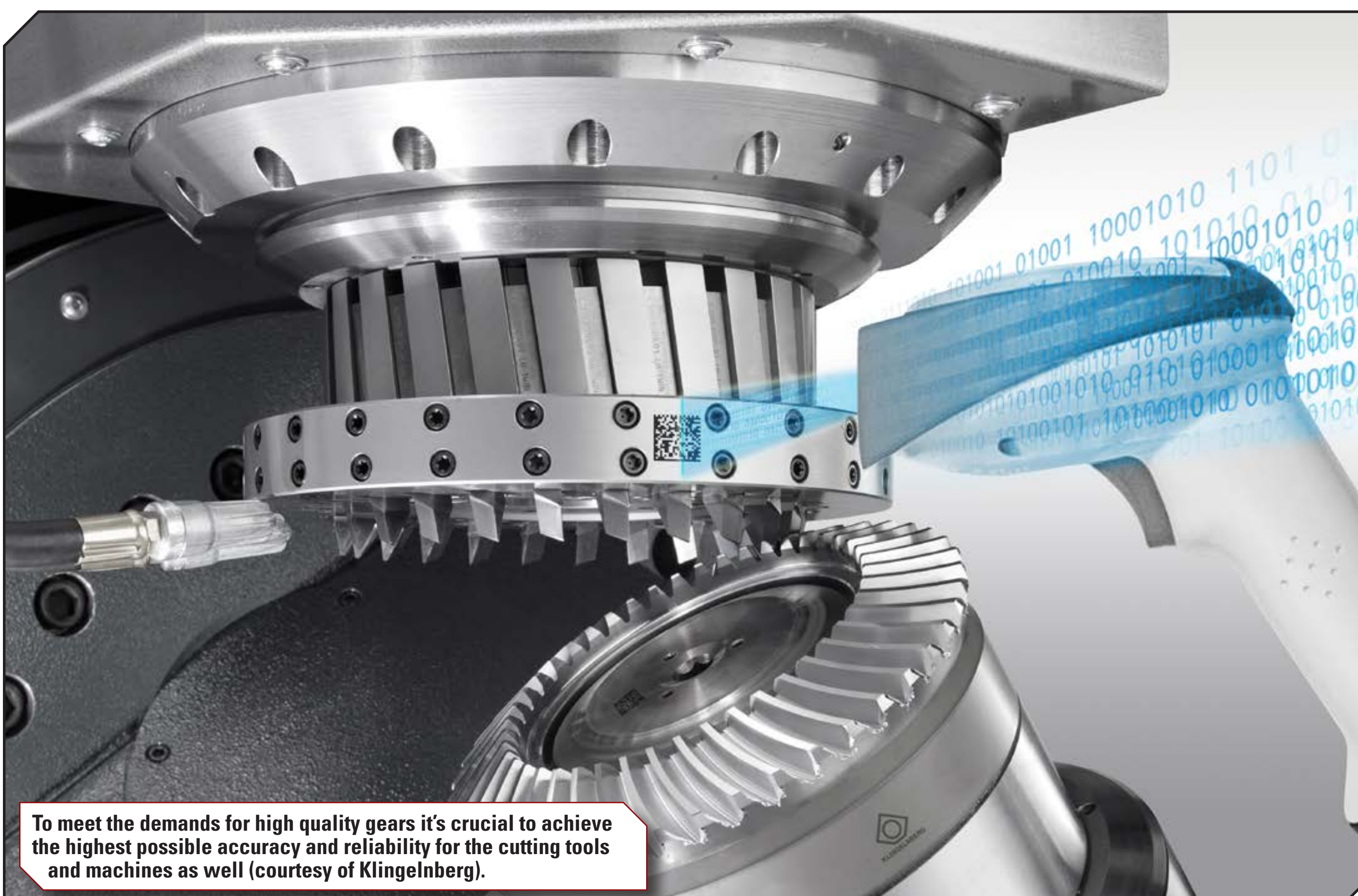
"More common however, is for our customers to utilize hard finishing processes such as grinding and honing to achieve their required accuracies. The cutting tools often require profile modifications such as protuberance to provide the required undercut clearances for these finishing operations. In spite of these hard finishing operations, high accuracy cutting tools are usually still requested for the pre-finish form to minimize the time for the finishing operation," said Keith Liston, vice president sales, Gleason Cutting Tools Corporation.

According to Liston, standard base material tools will not cut some of the exotic gear materials and still provide adequate tool life. Higher alloy base materials or even carbide are often needed to withstand the hardness or abrasive factors of the gear material. Choosing the correct coating for heat resistance is also paramount.

He also discussed the differences in requirements based on size.

Small and medium lot size customers are usually delivery sensitive, so quick delivery programs are usually of interest. Liston said that the use of lean manufacturing concepts help facilitate these quick delivery programs.

"For carbide tools, blanks can be stocked and tool designs can be tailored to the stock blank. From a process standpoint, power skiving for soft cutting and hard finishing of internal gears offers a great alternative to shaping or broaching. Power skiving is much faster than shaping and more cost effective than



To meet the demands for high quality gears it's crucial to achieve the highest possible accuracy and reliability for the cutting tools and machines as well (courtesy of Klingelnberg).

broaching for small to medium lot sizes. The short cycle time for power skiving, while longer than broaching, is much more cost effective for smaller lot sizes when considering the tool cost. In addition, power skiving allows for profile modifications unlike broaching. With hard power skiving, heat treat distortion can also be removed," Liston said.

And what about large batch size requirements?

Liston noted that large batch sizes require optimization of the cutting tools so they stay on the machine a long time. This requires premium high-speed steels and coatings for wear resistance. For hobs, a maximum shiftable length and higher number of gashes would also be desirable. For a shaper cutter, tool life can be increased using a larger diameter cutter as long as there are no interferences.

"The challenge with larger gears is with the removal of a large volume of material in a reasonable time period. To accomplish this, cutting tools using indexable carbide inserts (ICI) are often employed to rough out the material prior to a finishing or semi-finishing process. The carbide is heat tolerant and can be run at a high surface speed to allow for a relatively short cycle time. A subsequent finish hobbing, shaping or grinding operation is then required to achieve the finished part tolerances," Liston added.

In Liston's opinion, the biggest change has come with the power skiving process.

"Power skiving has grown dramatically in recent years. Primarily used for producing internal gears, power skiving is many times faster than shaping and much more flexible than broaching. This process is versatile enough to also cut external gears. Parts which require both an internal and external gear produced could potentially be done on one power skiving machine," he said.

As skiving gains popularity in the gear market, so too does the push for smart tooling and digital tool management.

"The Internet of Things is still developing for gear cutting tools, but is being used today in a number of facilities and offers real benefits, and much potential moving forward. With the use of chips or bar codes, important data used for tool setup can be transferred to the cutting machine. Tool identification and tool size is critical in determining the correct programs to run, the positioning of the cutting head and what cutting parameters to apply. Transferring this information through an electronic reader eliminates the possibility of inaccurate data entry. Tool/machine monitoring can also identify potential tool performance problems and stop a machine cycle before producing scrap parts and/or excessive tool wear. Tool performance, tool float, and remaining tool life can be captured and used to identify tool reorder points," Liston said.

We then asked Liston to expand on how other areas in cutting tools are evolving in 2019.

"The basic designs of gear cutting tools have been constant for decades. What has changed is the speed and rigidity of the cutting machines. These machine changes have resulted in the use of higher alloy high speed steels or even carbide to withstand the high machining speeds and the heat generated. Coatings have been developed to further withstand the high temperatures," he added.

Liston said tool designers today utilize 3D modeling to further optimize the design of the tools. They not only optimize the tools static cutting clearances but are now able to also consider the dynamic cutting clearances which becomes relevant at higher feeds and speeds. This modeling can identify interference of the cutting tool with the workpiece and in the case of shaping, upstroke interference. When presented with an upstroke interference condition, offsets can be calculated to eliminate this interference. Modeling is also used to identify chip formation so cutting parameters can be specified to target specific chip thicknesses while allowing predictive wear analysis to be made.


Power skiving tools from Gleason.

And one last area that has gained more traction is chamfering.

"Chamfering of gear teeth has drawn a lot of attention in recent years. While this has always been an important process, more variations to this process have been introduced to manufacturing. Chamfer rolling has been around for many years and is a very quick and economical process. However, rolling is not suited for all applications so other methods using chamfer hobs, chamfer milling cutters, inserted carbide milling cutters and single point milling cutters have been introduced," Liston said.

For more information:
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www.gleason.com

Klingelnberg Examines Cutting Tool Technology for Bevel Gears

Klingelnberg cutting tools have been developed and optimized for milling and hobbing under dry machining conditions with very sharp cutting edges. To meet the demands for high quality gears it's crucial to achieve the highest possible accuracy and reliability for the cutting tools and machines as well.

"Klingelnberg cutting tools have to be used on special high precision machines for gear manufacturing. For highest possible accuracy on the tool side, the body of the so-called cutter heads is manufactured out of one piece of high-strength material. The chambers for the stick blades are made with high precision EDM technology. The stick blades itself are out of carbide and coated for maximum wear resistance to get a stable gear quality. Cross section and profile of these blades are grinded on high precision machines, too. At last stick blades and the cutter head body have to be assembled which takes place on a special high precision mounting machine," said Philipp Becher, product management and sales gear tooling, at Klingelnberg GmbH.

Becher said that once the profile of the blades is worn a special regrinding process ensures a like new condition after the preparation. These puzzle pieces ensures that the actual geometry of a machined gear hits except for a few microns, the calculated geometry. The use of highly wear resistant materials ensures the stability of the machined gear geometry within batches of several hundred parts without regrinding.

"Another quality affecting factor is the chip formation during machining. As the space for the chip removal within the gaps is limited through tooth root and the concave and convex flanks, chips can cause scratched surfaces or buildup welding on the teeth flanks, an issue which is handled through flexibility in the process design," Becher said.

Exotic materials walk along with other requirements on the stick blades. The strength and toughness of the material has a direct influence on forces and heat generation on the cutting edge of a blade. This requires a specific combination of carbide substrate and coating of the stick blades of a cutter head.

As far as IoT or Industry 4.0 being introduced to the cutting tools, Becher said that Klingelnberg's IoT solution is named SmartTooling by a digital twin, who is assigned via a DataMatrix Code tagged on each tool component.

"There are digital twins of machines, machining process and processes aside the machine involved as well. Through combining, recording and analyzing of the digital twins, it is possible to reduce setup time, to avoid crashes and to interlink tool parameters with recorded production data. With this extensive production data the customers are able to find interdependencies between gear quality, efficiency and tool parameters. Based on this identified interdependencies the optimization of quality and efficiency will reach a new level in the industrial evolution," he said.

Becher also discussed the different batch size requirements and the tools available.

"Smaller batches are usually accompanied with a higher variety of gear designs. A higher variety of gears causes a higher variety of necessary cutting tools. To keep tool variety under control and to reach maximum productivity Klingelnberg is offering universal carbide tools. For modules up to 10 we have established the ARCOFLEX process, which uses carbide stick blades with highly standardized blade profiles together with our high-precision monoblock cutter heads. With ARCOFLEX Klingelnberg transferred know-how from the high efficient mass production into the requirements for a small batch production. This solution reduces setup times and tooling expenses to a minimum, while increasing productivity and reliable gear quality strongly at the same time," Becher said.

Meanwhile, the greatest challenge of lager batch sizes is to keep quality stable over several hundreds of pieces without regrinding the stick blades. Once the regrinding is necessary, it's crucial to restore the quality which was achieved before the regrinding.

And what are the greatest challenges in cutting larger gears? A larger gear means in general longer contact time between cutting edge and gear. Becher said that this causes higher temperatures which require higher heat and wear resistance of the cutting material of the blades. In other words it's a specific combination of substrate and coating you choose to counter these requirements. These tools are also confronted with higher forces. To counter this, Klingelnberg uses bigger cutter head bodies for more stable blades with bigger cross sections.

As today's tool technology is very mature, the focus for further development in recent years has been mainly on the cutting material side to increase wear resistance and tool life and/or productivity. Becher said that to really lift customer's shop floors to the next level Klingelnberg will focus on digital solutions.

"The digital twin of a tool can be used for tool management as well. SmartTooling allows visualizing inventory and the condition and status of it. Further on SmartTooling allows verifying tools when doing the setup of the machine. A simple scan is enough to ensure that the tool in front of the machine operator is the right one for the next job. During production or tool preparation incidents can be attached automatically or manually to a certain digital twin. For example: If there have been troubles with run-out adjustment or a crash happened, then this information will be attached to the involved digital twin so that anybody who handles this tool afterwards will be informed about that and can react accordingly," Becher said.

Understanding the variations in tool life and gear quality has been something which has been very difficult until today, as manual data collection is very complex and time consuming.

Becher believes that the maturity of the tooling is well-advanced and the reasons for these variations are coming typically from the environment of the cutting tool.

"Typical examples are variations in the batch quality of gear material, process parameters or used machines. SmartTooling uses digital twins of the complete environment, collects data automatically and helps with tailor made analyzes to understand the interdependencies between tool life and environment," Becher said.

A future where digital manufacturing will be the key to success.

For more information:
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Phone: (734) 470-6278
www.klingelnberg.com

Helios Gear Products Looks to Bring Smart Tools to Gear Manufacturers

Coatings continue to drive innovations in cutting tools. For high-demand applications, such as dry hobbing and hard hobbing, the newest coatings such as BALINIT ALTENSA from Oerlikon Balzers Coating AG offer serious performance benefits that should be considered, according to Adam Gimpert, business manager, Helios Gear Products (formerly Koepfer America).

In addition, real-time spindle feedback can provide valuable insight to a cutting tool's degradation during production by accurately measuring load as a predictor of tool wear and gear quality. This can help manufacturers' better schedule and cost their jobs by more intelligently applying changeovers and resharpening efforts.

"Simply tracking cutting tools, applications, and performance can yield beneficial information," Gimpert said. "Helios Gear Products plans to launch a new tool in 2020 to make this collection of information easy for gear manufacturing personnel. Once this platform is ready, we can fully embrace IoT by automating the collection of this information via QR code readers, RFID chips, etc. and offer that anonymized and aggregated data back to customers for intelligent guidance on gear manufacturing applications."

On a personal note, Gimpert is excited to bring IoT solutions to gear manufacturers for something other than predictive maintenance.

One key area that continues to advance is production technologies for gear deburring and chamfering.


The image shows tandem skiving tools which makes it possible to machine two type of gears without using a tool changer (courtesy of Liebherr).

"The latest machine tool software packages offer the ability to use cutting tools for deburring. This could be burr-free hobbing with one or two hobs, or this could be proprietary systems that use unique cutting tools to accurately cut chamfers on hobbed gears," Gimpert said.

Skiving is another area of growing interest as well.

"Skiving tools are not technically new; the technology has been around for quite some time. However, the machine tools and CNC packages have advanced to make this a highly productive operation for mass-produced parts over the past decade," Gimpert added.

Industry-standard coatings have been established and the recent newcomers have yet to find their position outside highly engineered applications.

"This leaves materials, such as MC90, which continue to carve an interesting space between traditional HSS applications and demanding (and costly) carbide applications. We still see MC90 offer measurable improvements to tool life and/or productivity for some manufacturers," Gimpert said.

And another high-demand area is tool management.

We're talking about solutions specific to gear manufacturers that do not deliver a heavy cost burden. These are in short supply," Gimpert said. "Hence, it is our goal to bring to market an affordable, intelligent, mobile solution to small and large manufacturers alike."

For more information:
Helios Gear Products, LLC
Phone: (847) 931-4121
www.heliosgearproducts.com

Liebherr Addresses Cutting Tool Needs with Latest Production and Measuring Technologies

Pierluigi Catellani, managing director, Liebherr Gear Cutting Tools, says gear tools are working more or less according to the imprint principle.

"The tooth gap on the tool gives the form of the tooth on the workpiece, the more accurate the tool, the more accurate the workpiece. There's a continuous shrinking of tolerances, so tool producers must use the latest technologies in production and measuring," he said. (Liebherr addresses this trend with its AAA quality shaping cutters and skiving cutters as well as high precision CBN profile grinding discs and worms.)

In order to support more exotic materials being used in gear manufacturing applications today, Catellani said you need better tool materials, better coatings and combination of both. "Some tools still in use are now no more up to date and the investment in (I admit: more expensive) high-performance substrates and coatings will definitely pay off when cutting such exotic materials."

He also agreed that smart manufacturing will be play a role in optimizing the cutting process.

"Even the best tool needs a good cutting process to reach the desired performance. For customers it's important to trace tool data for the whole life of it, resharpening after resharpening. QR or even bar codes in combination with according scanners help to identify tools and transfer the correct data directly into the machine. But, many customers today look more at the investment than the benefit. Therefore, IoT or Industry 4.0 is much less applied in industry than it should be," Catellani said.

He also said that the area that has experienced the most change in the industry in recent years is skiving tools, simply because they did not really exist 10 years ago.

"Their design and performance is a key for the success of modern gear skiving. In general, the developments in coatings and the surrounding processes like decoating, edge prep, etc. had the biggest impact on all kinds of tools, however," Catellani added.

Another key to success in gear manufacturing is tool management. For Catellani this means having "the right tool in the right place at the right time" and it includes the reconditioning (resharpening and recoating) according to quality standards.

While areas like skiving and smart manufacturing continue to expand gear manufacturers capabilities, the future of cutting tool design will include an emphasis on more additive manufacturing processes (see sidebar).

For more information:
Liebherr Gear Technology
Phone: (734) 429-7225
www.liebherr.com

Star SU Looks at Accuracy and Tool Life

Some of the latest cutting tool technologies that are supporting higher quality gears today include the application of linear axis drives on tool grinding machines for improved tool accuracies. Jim Caldwell and Tom Ware, product managers for gear cutting tools, also reported that surface finish enhancement and prep deviation on the cutting edge is detrimental to tool life.

Changes that have been made in order to support more exotic materials in gear manufacturing include the increased development of higher alloyed grade high-speed-steels that allow for better productivity when cutting exotic materials.

"New coatings are also being developed and carbide has become a mainstream material for the gear manufacturing process," Ware added.

Smart manufacturing is able to provide benefits in cutting tool technology as well, particularly the use of RFID chips.

"These can be used to identify tool and size for accuracy and reduction of setup time. These chips are written or rewritten with each reconditioning of the hob. They contain key information about the hob such as: Tool Number and Serial Number, Outside Diameter at both ends of the hob, and Skip Zones or unusable portions of the hob due excess wear. The chip is mounting to the hob container," Ware said. "They cannot be mounted in the tool due to the temperature of the coating chamber. The hobbing machine has a reader wand and internal programing to read the chip data and adjust the machine settings to automatically make the necessary changes. This speeds up the changeover or tool change process and eliminates operator entry error. This reduces scrap gears cut during setup."

An RFID chip can be mounted to the hob container to adjust machine settings and read data (courtesy of Star SU).

"Through the use of real time in-process monitoring, machine tools are now making it possible for customers to reduce cost by optimizing tool life, using error detection to reduce the number of scrap parts, and by preventing catastrophic tool failure," Caldwell said.

Ware and Caldwell also discussed the areas of cutting tool technology that have recently had the greatest impact in the gear industry.

"Hobbing tools have gone through a significant technology change with integrated shanks and smaller diameters. Better materials and coatings allowing cutting speeds up to 500 m per minute," Caldwell said.

"Chamfer/deburring has gone back to cutting/generating chamfers on gears for improved control and tool wear," Ware added.

And another area gaining traction is technology advances in tool management.

"Onsite tool management provides the ability to assess tool wear from first use through end of life as well as reconditioning decoat/recoat for new tool conditioning," Ware said.

For more information:
Star SU
Phone: (847) 649-1450
www.star-su.com

A Hint at the Cutting Tool Technology to Come

GKN Cuts Tool Production Time with Additive Manufacturing

Many of the interviewees in this cutting tool article discussed the role additive manufacturing will play in the coming years regarding cutting tools. This is already well underway in some areas of manufacturing, particularly aerospace where designing complex tools with greater lead times is already a reality.

GKN Aerospace reported on their progress in this area at the end of 2018. GKN serves over 90 percent of the world's aircraft and engine manufacturers with aerostructures, engine systems and technologies.

According to Tim Hope, additive manufacturing center manager, at GKN Aerospace, the company decided to invest in the Stratasys F900 Production 3D Printer in a bid to cut lead times for production-line tools, and to create complex parts, impossible to make with traditional manufacturing methods.

"Since integrating the F900, we have dramatically reduced production-line downtime for certain teams and are enjoying a new found freedom to design complex tools," he said.

Traditionally, the lead-time required to produce a metal or plastic replacement tool is several weeks. Now, with the ability to use an in-house production 3D printer to do the same job, the replacement burden has been removed and the responsiveness to manufacturing requirements improved.

"We can now cost-effectively produce tools for our operators within three hours," Hope explained. "This saves critical production time, and by printing in engineering-grade thermoplastics, we can produce 3D printed tools with repeatable, predictable quality every time. All while matching the quality of a traditionally-produced tool, and reducing the costs and concessions compared to equivalent metallic tooling."

While GKN Aerospace is using a standard thermoplastic today, it is experimenting with Stratasys' high-strength, heat-resistant ULTEM 1010 Resin material for these applications.

In addition, GKN Aerospace is reporting unprecedented levels of design freedom since investing in the Stratasys F900 into its operations.

"One of the key benefits of additive manufacturing is the creative freedom this technology affords users," explained Hope. "The F900 offers the largest build-size of any FDM 3D printer enabling us to rapidly produce tools to meet any requirements. Most notably, complex geometries and cavities that would otherwise be problematic are now practical with the F900. We're utilizing it to design, and 3D print, previously inconceivable tools that enable us to manufacture complex parts that are uneconomical or just physically impossible by other methods."

In addition to design freedom benefits, GKN Aerospace has also seen a 40 percent decrease in material waste.

Hope anticipates a greater move towards the use of FDM additive manufacturing to produce high-value, flight-critical, end-use composite parts.

"GKN Aerospace's product range is vast, and we see large-scale FDM and carbon-reinforced parts as the future of additive manufacturing in aerospace. By using Stratasys additive manufacturing for tooling, we are harnessing a machine that offers us the freedom to produce unique and complex tools of any size, with the build quality to match any manufacturing requirement. All while simultaneously preparing ourselves for the future," he added.

Gear manufacturers take note as aerospace technologies eventually trickle down to other areas of manufacturing. The future for tool production looks faster, more affordable and much more versatile.

For more information:
GKN Aerospace
Phone: (877) 489-9449
www.gkn.com

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CTI Symposium USA 2019

The Past, Present and Future of Vehicle Electrification

Matthew Jaster, Senior Editor

The CTI Symposium USA is the International Congress and Expo for Automotive Transmissions, HEV and EV Drives. The event features a two-day introductory seminar, a transmission expo, evening networking party and test drives for the latest development cars. Participants include automotive suppliers, transmission manufacturers, OEMs, metal processing, mechanical engineering and others from North America, Europe and Asia. Topics include powertrain technologies, hybrid transmissions, future considerations, commercial vehicles, starting devices, manufacturing and more. Autonomous driving, NVH, tools and performance forecasting will also be discussed.

Introductory Seminar

The Symposium begins with *Basics and Practice of Hybrid and Electric Drives, Automotive Transmissions*. Newcomers and beginners will get an overview of the basics of hybrid, electric and conventional drives during the Introductory Seminar. Based on road resistance, propulsion systems and auxiliaries HEV and EV concepts will be compared, the role of launch devices, transmissions and other drivetrain elements will be defined.

The Introductory Seminar will be held by the Institute of Automotive Engineering (IAE), Technical University of Braunschweig, Germany. The IAE under the direction of Prof. Dr Ferit Küçükay has a rich and very well grounded experience in all relevant areas of automotive research and development. It is the leading institute in Germany for automotive transmission development. With its close contact to the automotive and supplier industry, technical service providers, inspection authorities and public research institutions as well as national and international interdisciplinary working methods it is very well experienced in solving complex problems and ensuring up-to-date seminars. The IAE holds this introduction regularly as an integral part of the CTI Transmission Symposium in Berlin (Germany) and in Shanghai (China).

Symposium Day One Highlights

The keynote address will be *The Ford MHT: Reinventing What is Possible in a Hybrid Vehicle* by Dave Filipe, vice president global powertrain engineering, Ford Motor Company. Other speeches include *The Electric Truck: Why?* by Alexander Edwards, president of Strategic Vision, USA and *Electrification Transformation* by Steven Tarnowsky, director, electric vehicle and charging infrastructure at General Motors, USA. A panel discussion on *Truck Electrification in the U.S. Market* will be chaired by Larry Nitz from General Motors and feature panelists from Ford, GM, Navistar, and Strategic Vision, USA.

Symposium Day Two Highlights

Speeches on day two include *The E-Mobility Eco-System as the Differentiator* by Stephan Tarnutzer, AVL Powertrain Engineering, USA, *New Mobility Concepts and Its Impact on Transmissions* by Mayank Agochiya, managing director, FEV Consulting, Inc. USA, and *The Evolution of Commercial Vehicle Drivetrains in an Increasingly Connected and Electrified World* by Professor Giorgio Rizzoni, director for automotive research at The Ohio State University.

Parallel Sessions

Throughout the week of the show, other sessions will be available to attendees on topics like EV, HEV drivetrains/transmissions, commercial vehicles, sealing and bearing lubrication, electrification enablers, and NVH improvements.

Exhibition 2019

Here's a brief look at some of the exhibitors that will be on-hand in Novi during the CTI Symposium USA 2019 that PTE readers will find valuable:

AVL is a company for the development, simulation and testing of powertrains (hybrid, combustion engines, transmission, electric drive, batteries and software) for passenger cars, trucks and large engines. The company offers combined solutions of powertrain engineering, simulation software, and testing and instrumentation systems. (*www.avl.com*)

BorgWarner Inc. provides clean and efficient technology solutions for combustion, hybrid and electric vehicles. With manufacturing and technical facilities in 66 locations in 18 countries, the company employs approximately 29,000 worldwide. (*www.borgwarner.com*)

Dana supplies highly engineered driveline, sealing, and thermal-management technologies that improve the efficiency and performance of vehicles with both conventional and alternative-energy powertrains. Serving three primary markets — passenger vehicle, commercial truck, and off-highway equipment — Dana provides the world's original-equipment manufacturers and the aftermarket with local product and service support through a network of nearly 100 engineering, manufacturing, and distribution facilities. (*www.dana.com*)

Delta Research provides prototype and production transmission components and assemblies. Throughout its 65 year history, the company's capabilities have grown in high-precision gears, shafts, carriers, machined housings and inspection services. (*www.deltaresearch.com*)

ECM USA provides high quality vacuum furnaces, spare-parts, service, and

R&D testing for customers in North, Central and South America for the ECM Group. With experienced engineering, advanced manufacturing and installation expertise, these vacuum furnaces provide high up-time to demanding production environments all over the world. (*www.ecm-usa.com*)

Klingelnberg was founded in 1863. The company provides innovations in the areas of calculation, production, and measuring technology. With the acquisition of the core business of Höfler Maschinenbau GmbH in 2012, Klingelnberg expanded its product portfolio with the addition of gear manufacturing machines for cylindrical gears, thereby strengthening its position as a single-source system supplier. (*www.klingelnberg.com*)

Oerlikon Graziano is a provider for the design, development and supply of transaxles for high performance cars, highly specialized in transmission systems for 4WD (PTU, RDM and transfer case assemblies), electric and hybrid transmissions for passengers cars and commercial vehicles, as well as a key player in applying innovative technology, as DCTs, AMTs and their hybrid derivatives to premium supercars. (*www.oerlikon.com/graziano*)

Ricardo is an independent engineering services company with niche manufacturing capability. Extensive experience of designing and developing an extremely wide range of driveline and transmission systems on a global basis, from cost-optimized MT's to advanced DCT's and AT's and on to high performance e-axles and hybrid transmissions. (*www.ricardo.com*)

Saint-Gobain Performance Plastics L+S GmbH specializes in design, testing and manufacturing of seal rings, thrust washers and radial plain bearings. In line with the global trends in automotive and transmissions developments, these solutions are designed to increase efficiency by reducing leakage, drag losses and component wear. In addition these engineered components can be used where their compact installation, low mass and easy assembly allow their high performance to be combined with economic efficiency. (*www.seals.saint-gobain.com*)

Schaeffler is a supplier and development partner to the automotive industry. Schaeffler's technology spans the entire vehicle drivetrain, including the engine and transmission, as well as the chassis and all types of accessory components for passenger cars, heavy trucks and everything in between. High-precision products from Schaeffler's INA, LuK and FAG brands help lower fuel consumption and emissions without sacrificing, safety, performance or driving comfort. The company's expansive product portfolio encompasses energy-efficient solutions for conventional drivetrains with internal combustion engines, innovative products for hybrids and components for electric vehicles. (*www.schaeffler.us*)

SMT is an international provider of drivetrain design, analysis and simulation software as well as technical consultancy services. SMT has in-depth experience in all industries that involve gear-shaft-bearing systems. Increasing development efficiency, reducing costs and driving innovation has been the core outcome from all of its global projects. (*www.smartmt.com*)

CTI Checklist

CTI is a great show to learn about the latest transmission technology and the trends and policies that will be the focal point in the coming years in the automotive industry. As an attendee of many of the previous installments, here are some insights prior to coming to the show.

Don't Skip the Basics

Are you relatively new to hybrid, electric and conventional drives? Are you new to the automotive industry in general? I cannot stress enough how valuable Prof. Dr. Ferit Küçükay's introductory seminar is at the beginning of the show. Transmission concepts, future trends and current working methods are examined in great detail and the information is current and up-to-date with the complex problems facing the auto industry today. It's well worth your time—even if you've attended the introductory seminar in the past—to listen to the information provided by the Institute of Automotive Engineering (IAE), Technical University of Braunschweig, Germany.

Move Around

It's easy to grab a cup of coffee or four and stay in one area and absorb the information of the day. Don't do this. Get up and move around to different sessions on drivetrains and powertrain controls or calibration, sensors and lubrication. There are plenty of topics of interest and while you can't physically attend all of them at once, it's a good rule of thumb to diversify your time. Learn a little bit about some areas of the industry that you may know little about.

Utilize the Exhibition Hall

See who's exhibiting and make sure to stop by and see how certain companies may be able to help solve your challenges at work. It's not rocket science, but sometimes during symposiums, people forget to take the time to chat with peers about work-related challenges and problems that need to be solved. They run from one conference to another without spending some time in the exhibit hall. Don't do this. Talk, engage, and network even if it's only during a coffee break or lunch.

And Speaking of Networking…

If time allows make a point to join in on the CTI Networking Night taking place at the Henry Ford Museum. There will be food, drink and discussions on topics that may have been missed or skipped during the day. This is a great way to meet new contacts in a more relaxed environment and ask follow-up questions.

Get the Whole Crew Involved

Is this your first CTI Symposium? Is it your fifth? Don't forget how valuable these conferences and exhibitions can be for many of your co-workers. If you attended last time, send the new hire, send your boss, or send a group of engineers tackling a new transmission project. Call it strength in numbers. There's information available at CTI that can benefit many different workers at your plant. A well-informed and educated staff can only help your business.

For more information:
Car Training Institute (CTI)
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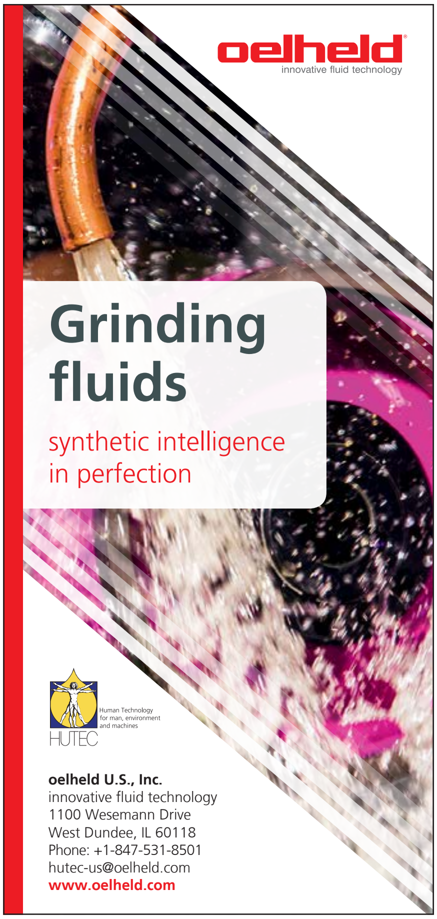

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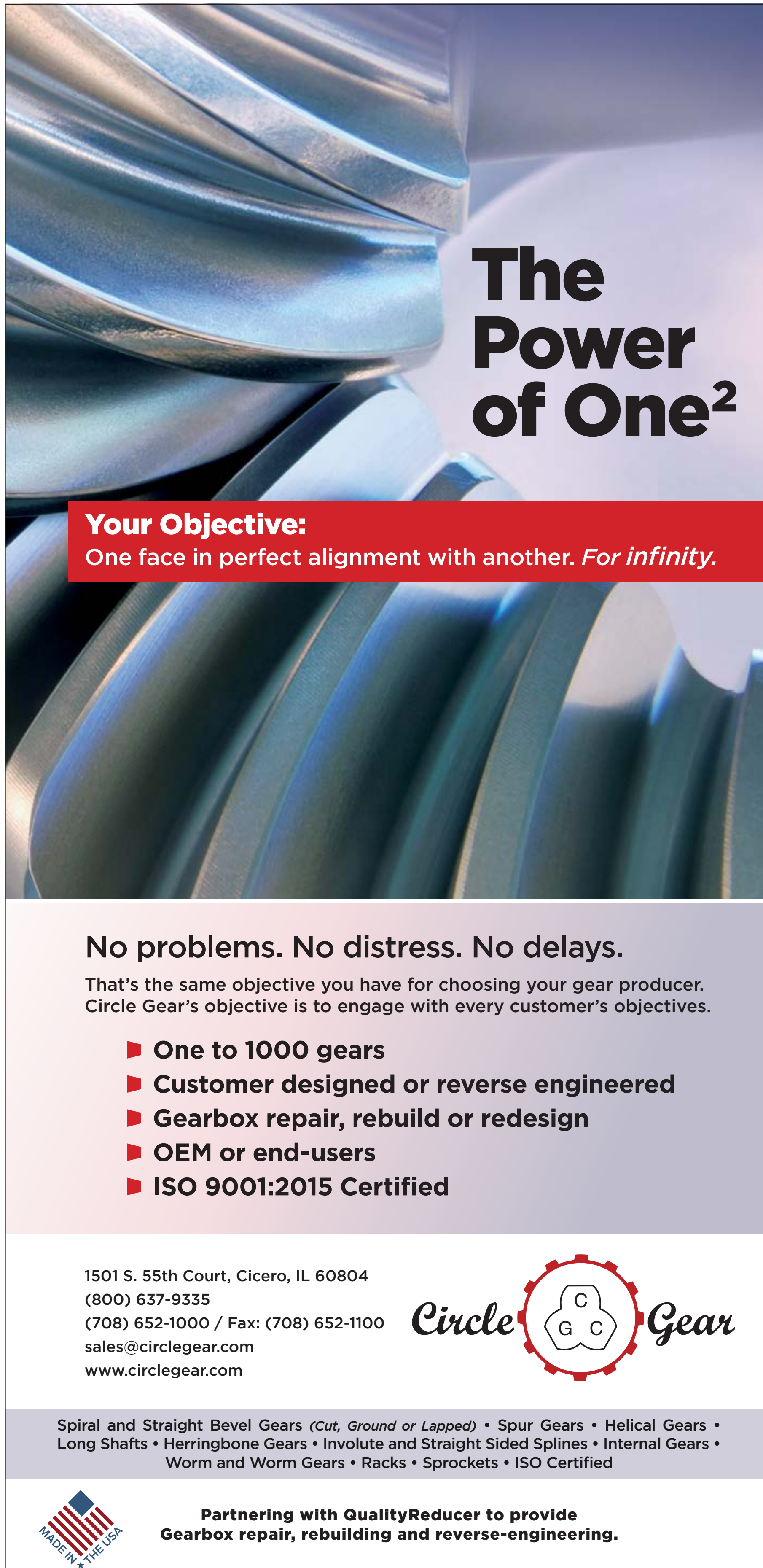

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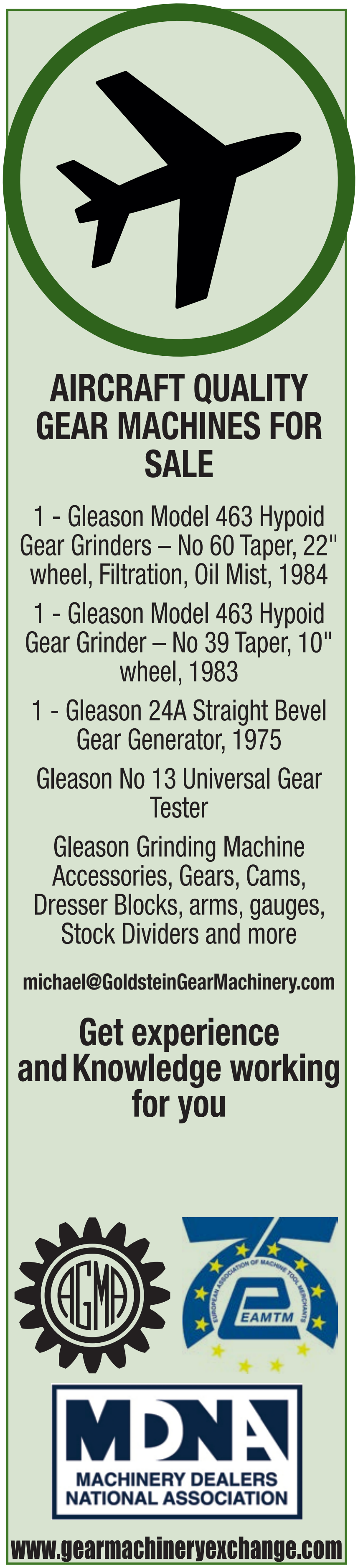
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Determining value of K_a in regards to DIN 3990 and AGMA standards

Email your question — along with your name, job title and company name (if you wish to remain anonymous, no problem) to: *jmcguinn@geartechnology.com*; or submit your question by visiting *geartechnology.com.*

QUESTION

I'd like to know about the different approaches and factors considered while determining the value of K_a in regards to the DIN 3990 and AGMA standards.

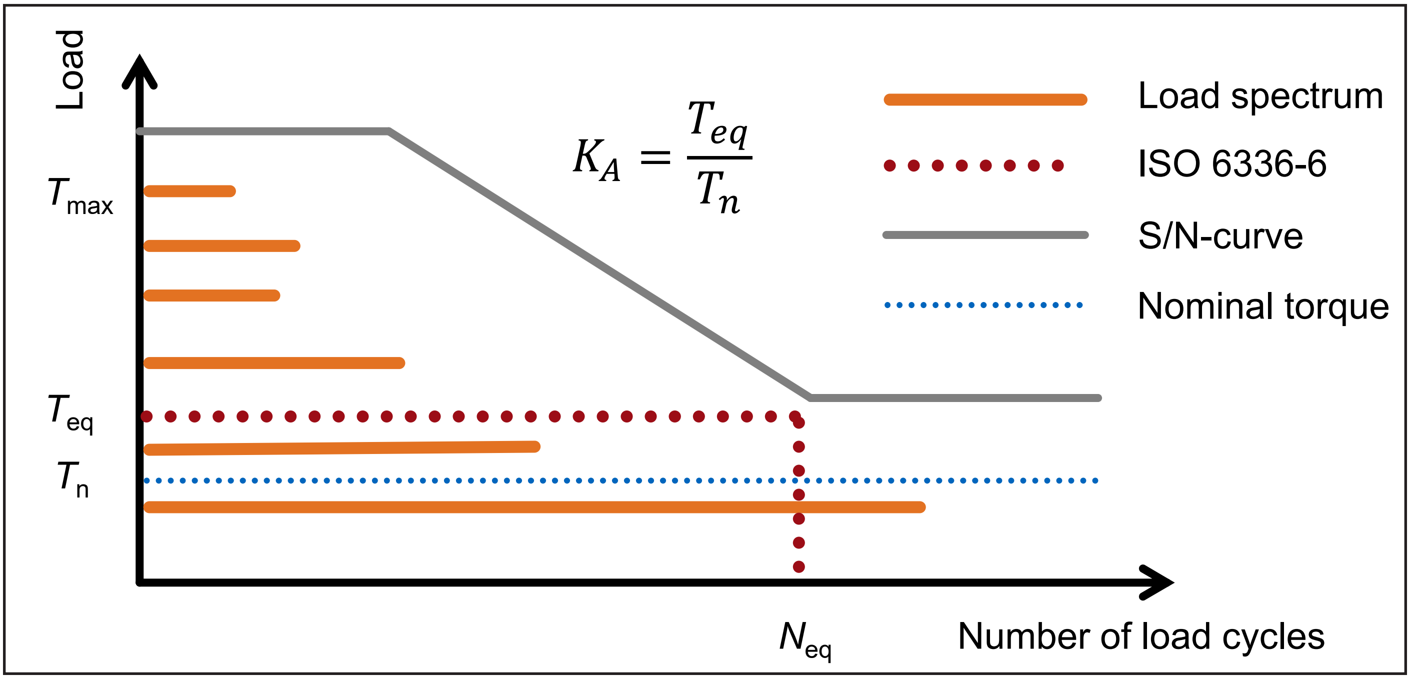
I saw a gear standard sheet in which they have considered K_a=2.0 while considering DIN 3990 standard, and K_a=2.5 considering AGMA Standards.

I also would like to know about the significance and basic approach while calculating K_a from Din 3990 and AGMA, and the difference between both calculations.

Expert response provided by Michael Hein, FZG, head of department/worm gears and bevel gears, fatigue life analysis: DIN 3990 as well as ISO 6336 define the application factor K_A as adjustment factor for the nominal load F_t to take into account all additional gear loads from external sources. AGMA 2101 uses the overload factor K_O instead. This factor K_O is also intended to make allowance for all externally applied loads in excess of the nominal tangential load, F_t, for a particular application.

AGMA 2101 only provides brief advice on how to establish reasonable overload factors for specific applications. According to the standard, all possible sources of overload — like system vibrations, acceleration torques, overspeeds, variations in system operation, etc. — should be considered. It is not stated if the overload factor K_O is supposed to be the ratio between the highest occurring load and the nominal load — or anything in between. There is also no clear indication if K_O is the same value for the calculation of the pitting load carrying capacity and tooth root load carrying capacity.

Application factors K_A, according to DIN 3990 and ISO 6336, can either be determined according to method A or method B, whereas method A is the more precise one. Method A uses load spectra which are determined by means of a careful measurement and a subsequent analysis of the measurement data, a comprehensive mathematical analysis of the system or on the basis of reliable operational experience in the field of application concerned. Based on this



load spectra, application factors for the calculation of pitting ($K_{H,A}$) and tooth root ($K_{F,A}$) load carrying capacity can be determined according to DIN 3990-6 and ISO 6336-6, Annex A. These factors are derived from a fatigue life analysis according Palmgren-Miner, with an equivalent torque T_{eq} that represents the applied load spectrum in one single load. Therefore, the slope of the S/N-curve of the considered material, as well as a failure mode-dependent load cycle limit $N_{L\,ref}$, has to be known. The equivalent torque T_{eq} is determined iteratively and is set in relation to the nominal torque T_n for the calculation of the load carrying capacity. The ratio T_{eq}/T_n then is the application factor K_A.

If no reliable data for a calculation of an application factor according to method A is available, DIN 3990 as well as ISO 6336 provide guideline values for K_A. These values are described in DIN 3990-6 and ISO 6336-6, Annex B, but will be moved to part 1 of ISO 6336 in the next revision. These empirical guideline values are dependent upon the working characteristics of the driving and driven machine, and are somewhere in the range of $1.0 \leq K_A \leq 2.25$. Other values may be used if agreed between purchaser and manufacturer.

The next revision of ISO 6336 will also include advice on how to determine application factors for calculation of tooth flank fracture ($K_{FF,A}$), scuffing ($K_{\vartheta,A}$) and micropitting ($K_{\lambda,A}$) load carrying capacity.

All in all, application factors K_A determined according to DIN 3990 / ISO 6336 can also be used as overload factors K_O for calculation of load carrying capacity, according to AGMA 2101 if no other reliable data is available. The main difference is that application factors K_A according to DIN 3990/ISO 6336 are based on the determination of an equivalent torque T_{eq}. This means that a gearbox loaded by $T_{eq} = K_A * T_n$ has theoretically the same lifetime as in real application with variable loads.

Depending on the used definition of the overload factor, K_O will be equal to or greater than the application factor K_A, $K_O \geq K_A$. If K_O is calculated as ratio between the maximum-occurring load and the nominal load $K_O = T_{max}/T_n$, the calculation will always be on the safe side — but may lead to unnecessarily large designs. If nothing better is known, it is recommended to use an application factor K_A calculated according to DIN 3990 or ISO 6336, instead of $K_O = T_{max}/T_n$ to avoid oversizing.

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Prediction of Process Forces in Gear Honing

T. Bergs, F. Klocke, C. Brecher, M. Schrank, M. Kampka, C. Kiesewetter-Marko, C. Löpenhaus, A. Epple

Introduction and Challenge

In order to improve the load-carrying capacity and excitation behavior, case hardened gears are usually hard finished. For the hard finishing, several high performance processes with undefined cutting edges are available. The dominating processes in the industrial application are gear honing, discontinuous profile gear grinding and continuous generating gear grinding (Refs. 1 and 2).

Gear honing is widely used for automotive applications to hard finish small and medium sized gears (Ref. 3). The automotive industry benefits from the high economic efficiency of the gear honing process in serial production. Another advantage of the gear honing process is the machinability of gears with interfering contours. Various preliminary tests on gears with a module $m_n > 5$ mm have shown that these gears can also be honed economically (Ref. 4). Compared to generating gear grinding and profile gear grinding, in gear honing minor deviations of the pre-processing quality have a bigger effect on the process stability. Even small changes in gear geometry, surface hardness or varying input quality can lead to process related machine vibration. The results can be inadequate gear quality, tool breakage and rejects. The low robustness results from high process forces, which vary in direction and magnitude due to the variable contact conditions between workpiece and tool. These alternating process forces can lead to a self-regenerating excitation (Ref. 5). The self-regenerating excitation makes it difficult to achieve the required quality (Ref. 6). Previous honing trials have shown that a consideration of the average process force is not sufficient to model the excitation (Ref. 4).

Due to the reasons mentioned above, it must be clarified how the process-specific parameters and tool specifications influence the gear honing process. Therefore, an understanding of the kinematics and geometric conditions during the process is necessary. In order to describe the interaction between the gear honing process and the machine structure, a force model for gear honing of external gears has to be derived and parameterized with gear honing analogy trials. With this model, it will be possible to predict the process forces during honing locally and temporally resolved, which leads to an improved process understanding.

State of the Art

Process characteristics and kinematics of gear honing. Gear honing is a grinding process with low cutting speeds and can be used for hard-finishing of both external and internal gears (Ref. 7). The most common application of gear honing is hard finishing of external gears in the module range from $m_n = 0.5$ mm to $m_n = 5$ mm (Ref. 3). In this paper, the machining of external gears by means of an internally geared honing tool with geometrically undefined cutting edges is considered. The gear honing tool meshes with an external gear under a cross-axis angle Σ. The achieved cutting speeds are very low compared to discontinuous profile gear grinding and continuous generating gear grinding. Due to the low cutting speeds of $v_c = 0.5$ m/s up to $v_c = 15$ m/s, the occurrence of thermal structural damage of the workpiece is unlikely (Ref. 8). The low cutting speed and the resulting low thermal influence on the workpiece material during gear honing lead to high compressive residual stresses in the near surface zone of the gear (Ref. 7). Despite the low robustness of the gear honing process and tendency to self-regenerating excitations, there is no scientific research regarding the process-machine-interaction.

The kinematics and the resulting contact conditions in gear honing correspond to the kinematics of a helical rolling type gear transmission. Although the contact conditions in this process are complex, the contact between workpiece and tool can be described as a line contact for each rolling position (Ref. 9). In gear honing, the main influence factor on the process productivity is the cutting speed v_c (Ref. 10). Due to the cross axis angle Σ, a relative velocity v_c exists between the gear flank and the tool so that material can be machined (Ref. 10). The relative speed v_c is composed of a tangential component in the direction of the involute (due to the rolling motion) as well as a component in the direction of the flank line (due to the cross axis angle) (Fig. 1). This results in the surface structure typical for the gear honing process, which is referred to as a "herringbone pattern" (Ref. 8).

The infeed-per-revolution is carried out continuously in the radial direction during the process and is in the submicrometer range. The cutting speed increases with the increase of the cross axis angle at a constant honing tool

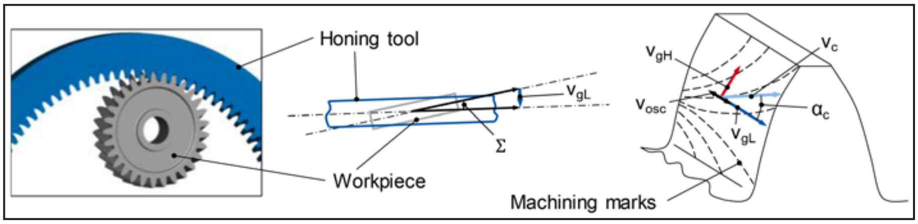

Figure 1 Kinematics and velocities in gear honing according to (Ref. 1).

This paper was first presented at the 2018 Lyon International Gear Conference.

rotational speed. Along the profile of the gear, a large gradient of the cutting speed is existent for small cross axis angles, whereas the gradient of the cutting speed is very low for large cross axis angle. This relationship results because the longitudinal sliding speed v_{gL} is lager in magnitude than the lateral sliding speed v_{gH} and approximately constant over the tooth height. At small cross-axis angles, the dominant portion of the longitudinal sliding speed is reduced, so that the change in the lateral sliding speed v_{gH} along the tooth height is more strongly reflected in the cutting speed. In addition, the tracks on which the abrasive grains of the honing tool penetrate the gear change due to the cross axis angle. While long and flat grain paths occur during machining with large cross axis angles, the grain paths are steep and short at small cross axis angles. The shape of these grain paths therefore depends on the cutting speed as well as on the position on the gear profile (Ref. 8). The relationships resulting from the contact conditions and the kinematic parameters and their influence on the local process forces are not yet sufficiently known.

Force models for conventional grinding processes. The contact between grinding tool and workpiece consists of a probabilistically disordered sequence of single interactions of different abrasive grains following a defined path through the workpiece material. Not all grains of the grinding tool get into contact. Therefore, Kassen established the term of the number of dynamic cutting edges N_{dyn}. This factor takes into account the average number of cutting edges being involved in the cutting at any given time. Neglecting the elastic and plastic deformation of workpiece and tool, the number of dynamic cutting edges is exclusively dependent on the contact geometry, the grinding kinematics and the grinding tool properties (Ref. 11). The formulated connections were taken up by Werner and extended to a force model for the calculation of the specific normal grinding force F'_n during surface grinding, Eq. 1 (Ref. 12).

$$F'_n = \frac{F_n}{b_{s,eff}} = \int_0^{l_k} k \cdot A_{cu}(l) \cdot N_{dyn}(l) \cdot dl \qquad (1)$$

The specific normal grinding force F'_n is the normal grinding force F_n related to the effective contact width $b_{s,eff}$. Furthermore, the specific normal grinding force F'_n is calculated with the chip cross section area A_{cu}, the number of dynamic cutting edges N_{dyn} and the specific grinding force coefficient k. The chip cross section A_{cu} and the number of dynamic cutting edges N_{dyn} are dependent on the contact length l. In addition to the calculation of the grinding normal force during surface grinding, Werner formulated the necessary adjustments to transfer his model onto internal and external grinding. For this purpose, the equivalent grinding wheel diameter d_{eq} needs to be calculated according to Eq. 2 (Ref. 12). The grinding wheel diameter ds is subtracted from the workpiece diameter d_w for internal grinding. For external grinding, both diameters are added to each other. This results in a modified contact length l_g for internal and external ground workpieces, Eq. 3 (Ref.13).

$$d_{eq} = \frac{d_w \cdot d_s}{d_w \pm d_s} \qquad (2)$$

$$l_g = \sqrt{a_e \cdot d_{eq}} \qquad (3)$$

Bock developed a force model for internal grinding with a transfer onto internal grinding and parameterization of the force model according to Werner. Therefore, Bock introduced the specific values of the contact length related to chip thickness h_{eq}/l_g, Eq. 4, and the normal force related to the contact length F_n/l_g, Eq. 5 (Ref. 13).

$$\frac{h_{eq}}{l_g} = \frac{v_{ft}}{v_c} \cdot \sqrt{\frac{f_r}{d_{eq}}} = q \cdot \sqrt{\frac{f_r}{d_{eq}}} \qquad (4)$$

$$\frac{F_n}{l_g} = a_1 \cdot b_c \cdot \left(q \cdot \frac{h_{eq}}{l_g} \right)^{b_1} \qquad (5)$$

The contact length related chip thickness h_{eq}/l_g is influenced by the tangential feed rate v_{ft}, cutting speed v_c, radial feed f_r and the equivalent grinding wheel diameter d_{eq}. The division of the tangential feed rate v_{ft} and the cutting speed v_c equals the velocity ratio q. The normal force F_n related to the contact length l_g can be calculated with the velocity ratio q, the contact width b_c and chip thickness related to the contact length h_{eq}/l_g. The empirical influences of tool, workpiece and cooling lubricant are taken into account by the coefficients a_1 and b_1.

Several existing grinding force models have been developed which were combined to a basic force model by Tönshoff et al. (Ref. 14). To calculate the grinding force with these force models, the contact conditions have to be constant during the process. Due to the changing contact conditions during gear honing, the existing force models cannot be transferred onto gear honing. To calculate the locally resolved forces in gear honing, the contact conditions have to be transferred into a local stationary process.

Approach to Model Process Machine Interaction in Gear Honing

Due to the existing challenges in gear honing, the project — "Process-Machine-Interaction in Gear Honing" — funded by the German Research Foundation (BR 2905/71-1 and KL 500/152-1), was initiated. The objective of the research project is the prediction of the excitation behavior in the gear honing process and thus the mapping of the occurring vibrations. The coupling of a suitable force model with a dynamic machine tool model is intended to enable the honing process to be designed more efficiently, to avoid vibrations and to derive optimization approaches for the machine tool. In Figure 2, the approach to modeling process-machine-interaction is shown.

Due to the variable contact conditions between workpiece and tool during gear honing, the grinding force cannot be calculated with existing grinding force models. Therefore, a force model for gear honing has to be developed. The intersecting volume of the honing tool and the workpiece can be calculated with a penetration calculation. The intersecting volume equals the un-deformed chip geometry, which is necessary to calculate the grinding force. After the calculation of the grinding force with the force model, the grinding force has to be transferred onto the dynamic machine tool model. Within the machine tool simulation, the force and its magnitude and direction have to be applied to the machine tool structure and the displacement has to be calculated. Afterwards, the displacement has to be taken into account in a subsequent simulation loop in the penetration calculation. In order to close the simulation loop, the gear geometry already produced by the preceding machining step has to be taken into account. As a result, the current geometry must be stored and loaded in the next increment after each simulated increment. A particular challenge in gear honing is the low infeed, which results in a high necessary accuracy of the geometric models used. The total process force in gear honing is influenced by a number of different factors. In addition to the grinding force, the total process force is influenced by gear meshing and frictional forces. The kinematic relationships necessary for determining the grinding force can be adequately described analytically, while the local geometric parameters can be determined by means of numerical approaches. In addition to the kinematic and geometric parameters, there are other factors, which must be determined in empirical trials. These influencing factors include the honing tool specification, the material to be processed, the cooling lubricant and the friction behavior.

Gear Honing Analogy Process

For the determination of the force model factors of the grinding tool, friction and cooling lubricant, the process forces have to be measured in a stationary process. The variable contact conditions between workpiece and tool can be transferred into a local stationary analogy process (Ref. 8). The analogy process is based on the fact, that each point on an involute can be approximated by a circle with the same radius of curvature. Consequently, the gear honing process can be described for any desired point on the gear flank profile by the analogy process.

The gear honing analogy process can be seen as an internal grinding process with the particularities that the workpiece is inside the grinding tool and the contact between workpiece and grinding tool takes place under a cross axis angle Σ (Fig. 3).

The analogy process is used to determine the process forces independent of the dynamic influences in the gear honing process. The empirical influences of tool, workpiece and cooling lubricant are taken into account by the force measurements in the force modeling. A definite determination of the separate influences is not possible. The measured forces are regarded as the locally resolved grinding forces in the gear honing process and are implemented in the manufacturing simulation (Ref. 15). Afterwards, the resulting grinding forces out of the manufacturing simulation are compared to force measurements in gear honing trials.

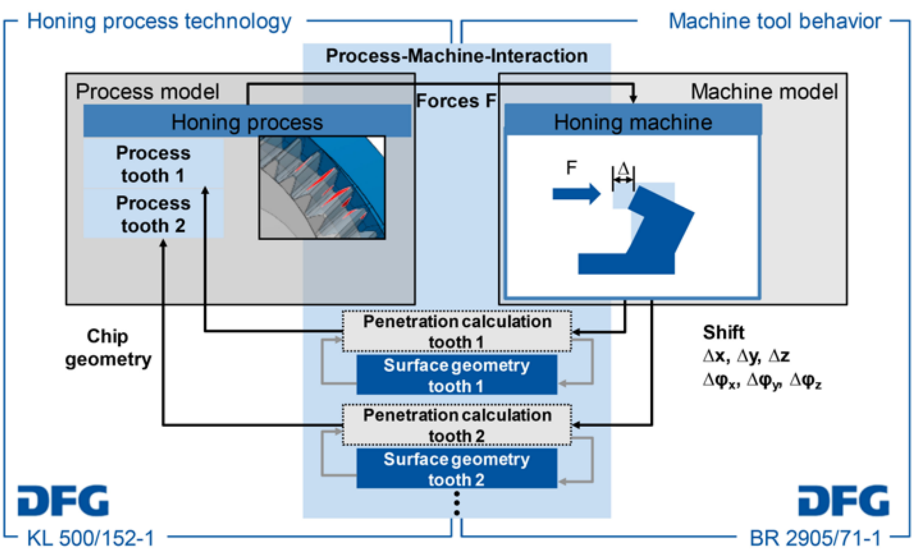

Figure 2 Approach to modeling process-machine-interaction.

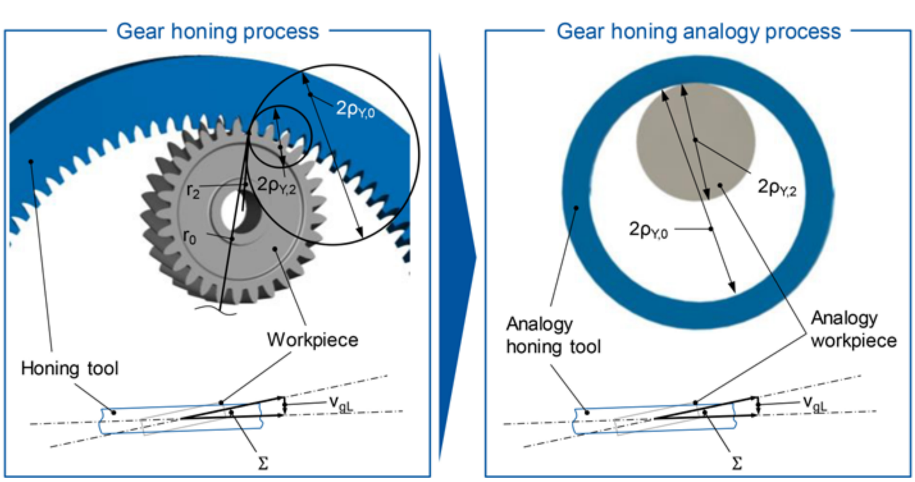

Figure 3 Derivation of the gear honing analogy process.

Trial Gear and Design of Experiments

To determine the local grinding forces during gear honing, the machining of a typical automotive type gear is analyzed. The gear has a normal module of $m_n = 2.28$ mm. Furthermore, the number of teeth is $z = 43$, the helix angle is $\beta = -33°$, the tip diameter is $d_a = 120.3$ mm and the face width of the gear is $b = 18.5$ mm. The gears are made of 16MnCr5 and casehardened to a resulting surface hardness of 59-62 HRC. Due to the reason that the honing tool is dressed during the tool life, the diameter of the tool varies. The change of tool geometry is compensated by adjustment of the cross-axis angle. For the test, different honing and analogy tools were used, dressed with a cross-axis angle of $\Sigma = 11.66°$, $\Sigma = 13.78°$ and $\Sigma = 15.42°$. These three cross-axis angles correspond to the geometry of the tool close to the new state, in the middle of tool life and at the end of tool life. The number of teeth of the honing tool is $z = -78$. The rotational speed was set to $n_0 = 800\ \text{min}^{-1}$, $n_0 = 600\ \text{min}^{-1}$ and $n_0 = 400\ \text{min}^{-1}$. The tests were carried out on a 150SPH gear honing machine from Gleason-Hurth.

Force Modeling for the Gear Honing Analogy Process

The state of the art shows that grinding force models exist, but cannot be used for gear honing due to the changing contact conditions. The process forces can be measured during the analogy process without being subjected to the dynamics of the gear honing process. With knowledge of the forces in the analogy process, it is possible to parameterize the model according to Bock. This model has to be adapted to gear honing and the final gear honing force model needs to be validated.

The grinding force for the internal grinding process was calculated based on Bock, Eqs. 2–5 (Ref. 13). The gear honing analogy process differs from the internal grinding process by the cross-axis angle Σ between the workpiece and the grinding tool, the intersecting geometry and the lower cutting speeds v_c. Therefore, the calculation of the equivalent grinding wheel diameter d_{eq} has to be adjusted with regard to the influence of the cross axis angle Σ, Eq. 6. The cross axis angle Σ causes an increasing path length of the grain through the workpiece. Considering the cross axis angle Σ, the geometric contact length $l_{g,\Sigma}$ can be determined according to Eq. 7. The indices of the diameters represent the analogy tool (index A, 0) and analogy workpiece (index A, 2).

$$d_{eq} = \frac{d_{A,2} \cdot d_{A,0} \cdot \cos(\Sigma)}{d_{A,0} \cdot \cos(\Sigma) - d_{A,2}} \quad (6)$$

$$l_{g,\Sigma} = \frac{\sqrt{f_r \cdot d_{eq}}}{\cos(\Sigma)} \quad (7)$$

With these enhancements and the equations according to Bock, a grinding force model for the gear honing analogy process is derived. The grinding normal force F_n, Eq. 8, and the grinding force F_c, Eq. 9, are calculated based on the values for the equivalent grinding wheel diameter d_{eq}, the geometric contact length $l_{g,\Sigma}$, the speed ratio q, the radial feed f_r and the contact width b_c.

$$F_n = a_1 \cdot l_{g,\Sigma} b_c \cdot \left(q \cdot \sqrt{\frac{f_r}{d_{eq}}} \right)^{b_1} \quad (8)$$

$$F_c = a_2 \cdot l_{g,\Sigma} b_c \cdot \left(q \cdot \sqrt{\frac{f_r}{d_{eq}}} \right)^{b_2} \quad (9)$$

Analogy trials were carried out with three different analogy workpieces with a width of $b_{A,2} = 18.5$ mm and diameters of $d_{A,2.1} = 26.34$ mm, $d_{A,2.2} = 41.24$ mm and $d_{A,2.3} = 52.7$ mm. The used analogy tools had a width of $b_{A,0} = 25$ mm. By measuring the forces during the analogy process, the parameters a_1, a_2, b_1 and b_2 were determined empirically (Ref. 16). The curves of the parameterized grinding force model are shown (Fig. 4). The grinding force relative to the contact area is plotted over the specific chip thickness.

Using the force model, for each point mapped in the analogy process proportionality factors $k_{c,loc}$ and $k_{n,loc}$ are determined. These take into account the different geometric kinematic contact

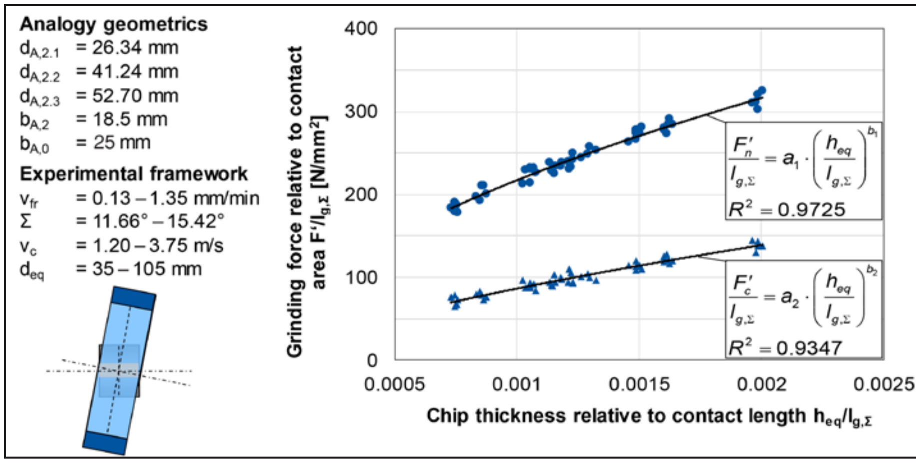

Figure 4 Force model for the gear honing analogy process.

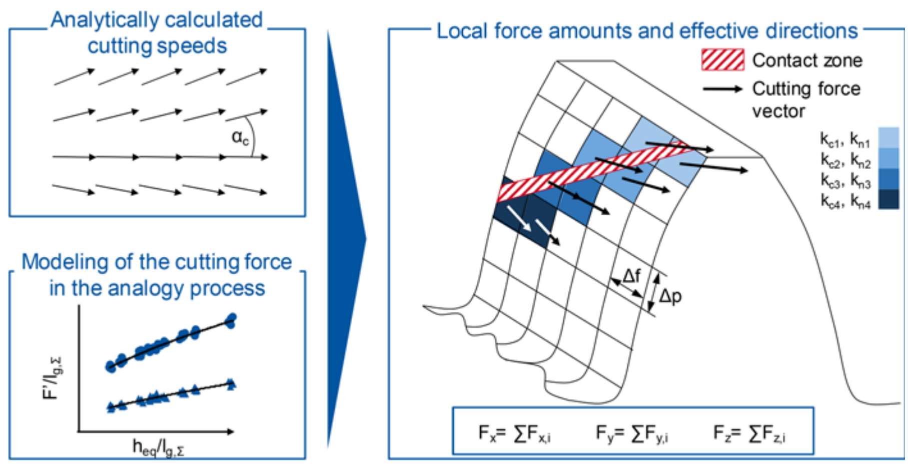

Figure 5 Map-based calculation of the grinding forces.

conditions. For each diameter combination of analogy workpiece and tool constant proportionality factors $k_{c,loc}$ and $k_{n,loc}$ are obtained. During the transfer of the local forces of the analogy onto the gear honing process, these proportionality factors represent locally specific proportionality factors on the involute profile.

Transfer of the Local Forces from the Analogy Process On to Gear Honing

With the analogy trials, a force model was derived and parameterized. This model was transferred onto gear honing by means of a manufacturing simulation (Ref. 15). For discrete meshing positions of the tool and workpiece, the undeformed chip geometry is determined. Those penetration geometries are locally comparable to the analogy trial. In contrast to the analogy process, different cutting conditions exist for each point on the involute profile. In addition to the variation in the local penetration geometries, the pressure angle, the helix angle and the cutting speed components are also variable. This results in a variable cutting angle α_c and the typical machining marks in gear honing. The cutting speed components and therefore the cutting angle can be calculated analytically (Ref. 9), (Fig. 5).

The local process forces can be calculated by multiplying the distances of the points in profile and flank direction Δp and Δf with the chip thickness $h_{cu,loc}$ and the proportionality factors $k_{c,loc}$ and $k_{n,loc}$. Contrary to the constant proportionality factors in the analogy process, the proportionality factors vary over the involute profile during the gear honing process.

Due to the analytically calculated cutting angle α_c, the process forces can be divided into the forces in the main directions of the machine coordinate system. To calculate the total force during the gear honing process, simultaneous machining on several teeth is considered by an addition of all contacts between tool and workpiece in the manufacturing simulation. Therefore, several rolling positions and the spatial positions of the penetration geometries are calculated. Subsequently, the occurring forces are added up again for each direction. These calculated mean machining forces are compared with measured forces in the gear honing process. In Figure 6, the comparison of the forces divided into the three spatial directions is shown.

For the three spatial directions, the magnitude of the measured and the calculated forces are similar. The good comparability of the measured and the calculated forces validates the transferability of the local grinding force model from the analogy process onto the gear honing process. The difference between the measured and the calculated forces may result from vibration during gear honing. The vibration leads to deviations in penetration of tool and workpiece.

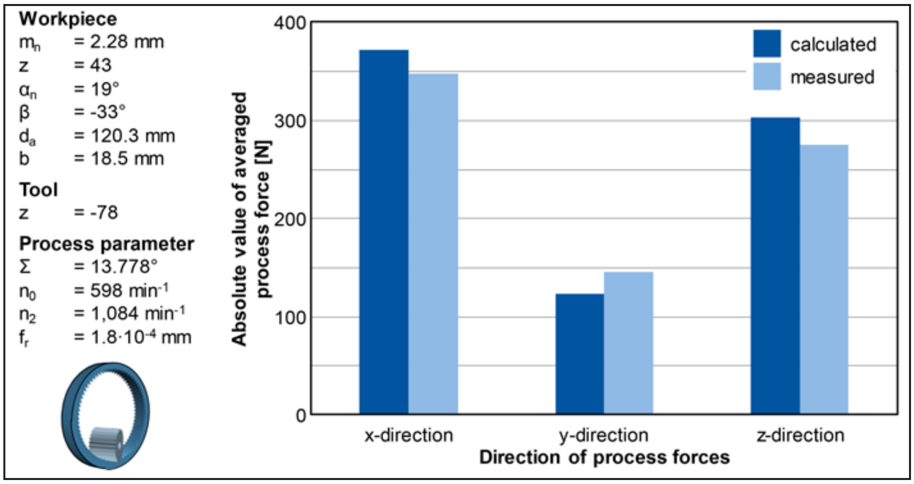

Figure 6 Calculated and measured gear honing process forces.

Summary and Outlook

Gear honing is a highly productive process for the production of small and medium sized gears and is used mainly in the serial production of the automotive industry. The low robustness of the process is a particular challenge in gear honing. The consequences range from an inadequate gear quality to an early breakage of the honing tool.

In order to describe the process-machine interaction, the machining forces must be known. The forces for internal grinding have been successfully described by Bock by adapting the grinding force model according to Werner. Due to the varying engagement between the workpiece and the tool along the tooth profile, the force varies in direction and magnitude and existing force models cannot be used for gear honing. Therefore, the gear honing process was first transferred into an analogy process. The internal grinding force model according to Bock was transferred to an internal grinding set up under a cross axis angle. The geometric and kinematic similarity between the analogy process and the internal grinding was used to parameterize an empirical-analytical force model. Taking into account the cross axis angle, the model according to Bock was parameterized with the results of the force measurement in the analogy process and therefore a force model for the analogy process was derived. By combining this force model with a penetration calculation of the gear honing process and an analytical calculation of the effective velocities, the process forces during gear honing could be determined locally and temporally resolved for all three spatial directions. The comparison of the measured and calculated process forces in the machine coordinate system showed a good agreement and, thus, validated the presented method.

In the future, the coupling of the presented force model with the machine model must take place. This allows not only the prediction of the average grinding force, but also the force amplitudes. In addition to the coupling of the process model to a machine model, a further step is the implementation of the oscillating motion of the gear honing process in the penetration calculation as well as in the force model.

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Generative Gear Milling

Yefim Kotlyar

Introduction

This paper outlines the basic principles of involute gear generation by using a milling cutter; the machine and cutting tool requirements; similarities and differences with other gear generative methods; the cutting strategy; and setup adjustments options. It also discusses the applications that would benefit the most: for coarse-pitch gears the generative gear milling technologies offer improved efficiency, expanded machine pitch capacity, decreased cutter cost, and a possibility for reducing the number of machining operations.

While this method for gear cutting had started gaining visibility and being offered by various machine & tool makers, probably no more than a decade ago, the Maag Gear Company had introduced this gear cutting concept and received a U.S. patent (#4565474) in 1986; see Figure 1 depicting how the disc cutter can be used for involute generation.

The generative gear milling principle is based on an incremental (or continuous) positioning of the cutting edge tangentially to the involute curve along the "line of action." The cutter can have a form of:

- Milling "disc" cutter with:
  - ¤ trapezoidal cutting edges
  - ¤ parallel cutting edges
- End mill cutter

Hypothetically, the generative gear milling has always been possible on a 5-axis milling machine that had a rotary table. However, it was impractical without a special software, as the operator would have had to perform bulky calculations to determine the cutter and gear positions for each generative cut and for every tooth.

With the advancements of software development and expanding libraries of functions and features, multiple machine and tool makers are now offering software for this technology under their respective brand names.

In this paper, "generative gear milling" refers to a general method of gear cutting by using milling cutters, while "*Generative Gear Milling*" refers to proprietary MTB software to enable such a process on hobbing or milling machine that has a rotary table.

While conceptually the generative milling method borrows a little from several established involute generative methods — such as Maag gear

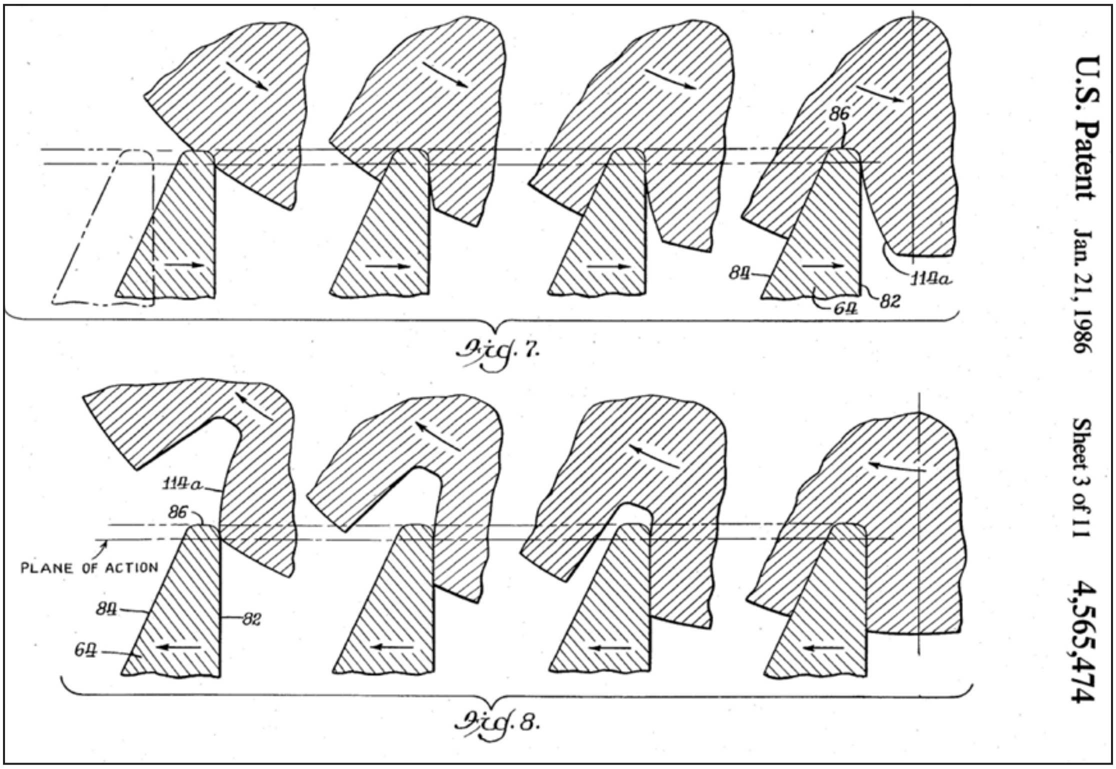

Figure 1 Maag patent 4565474 (Ref. 1).

cutting with rack cutters, Maag gear rolling grinding, Hobbing, and Index Milling — the recent innovation is in the computerized math model that combines discrete (or continuous) cuts into a system that generates involute profile and completes the entire gear cutting.

Another innovation is how this technology can be acquired and implemented - via a software "app" that does not necessarily require a new machine.

The minimum hardware requirement for this feature is a 5-axes (4 axes for spur gears) CNC milling machine with a rotary table, or a CNC hobbing machine that has a precision tangential (hob shifting) axis. The reason for a 5-axes requirement is that all axes — X, Y, Z, C-table, and A-swivel — are mathematically interrelated for every generative cut.

Similarities with Other Gear Generation and Form Cutting Methods

There are several established methods for involute generation of parallel axes gears such as hobbing, cylindrical shaping, Maag rack shaping, zero and non-zero Maag line grinding, generative grinding as well as form milling/gashing with straight-sided cutter, or form milling/grinding with an inverse involute cutter profile.

All generative gear cutting/grinding methods take some advantage of involute properties to position the cutting edges (or the grinding wheel) tangentially to the involute curve. In the case of hobbing and shaping, the points of tangency (generative points or cuts) line up along the line of cutting action. When the operating pressure angle (OPA) defined by a line tangent to the base circles of both mating gears (Fig. 2) and the cutter pressure angles are the same, the line of gear mesh action and the line of gear cutting action coincide (Figs. 2 and 3).

Similarities with hobbing. Figure 4 depicts the hob cutting edges lining up along the line of action. Similarly, the generative gear milling is based on the incremental (or continuous) positioning of the cutter edges tangentially to the involute curve along the line of action and making successive cuts. Combined together, these successive cuts will approximate the involute curve.

Similarly, the generative milling process combines individual cuts to generate an involute cure. During the hobbing process, the precise positioning of the involute generating cuts is achieved by synchronizing the rotations of the hob and the gear.

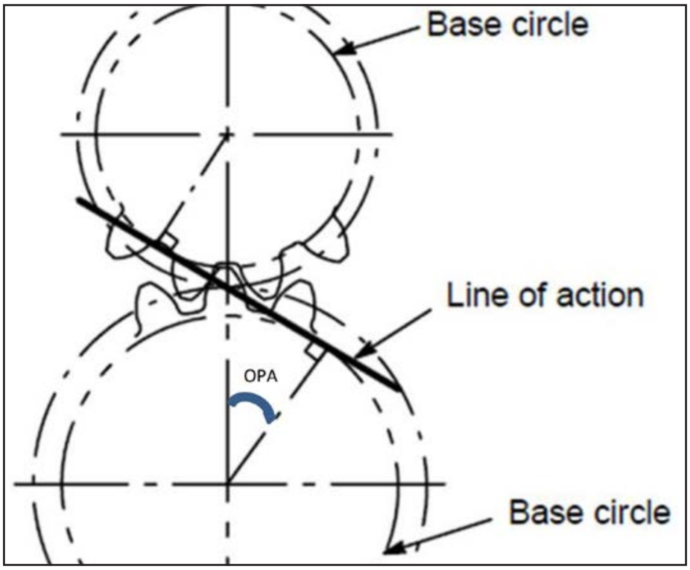

Figure 2 Line of action/gear mesh (Ref. 16).

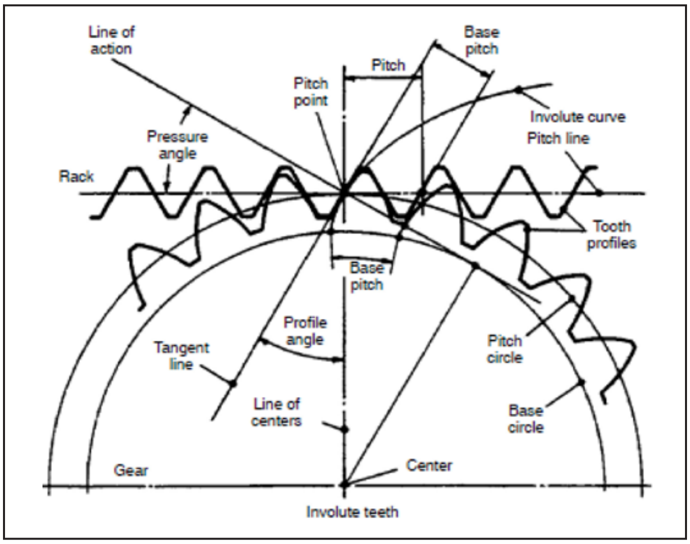

Figure 3 Line of action/cutting by rack (Ref. 15).

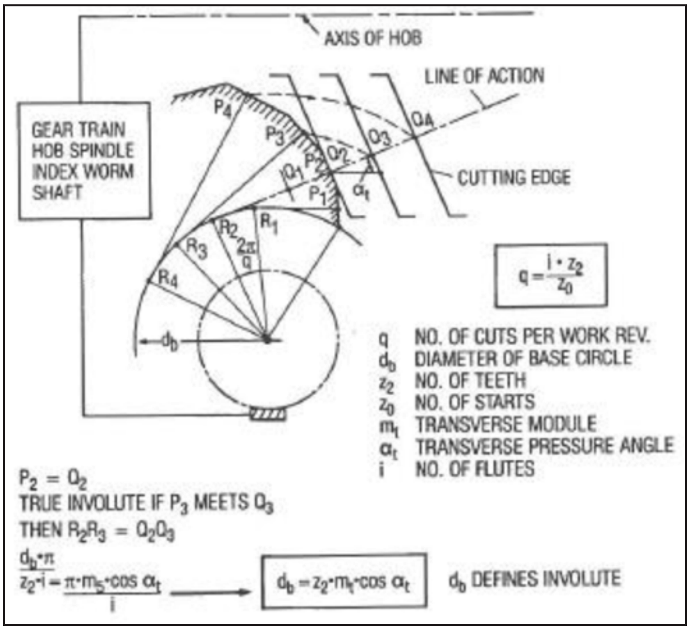

Figure 4 Tooth generation by hobbing (Ref. 13).

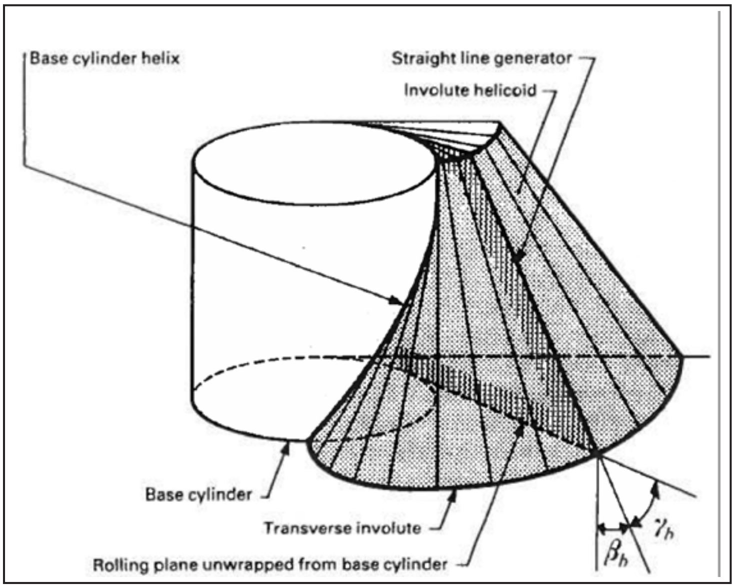

Figure 5 **Base helix angle (Ref. 11).**

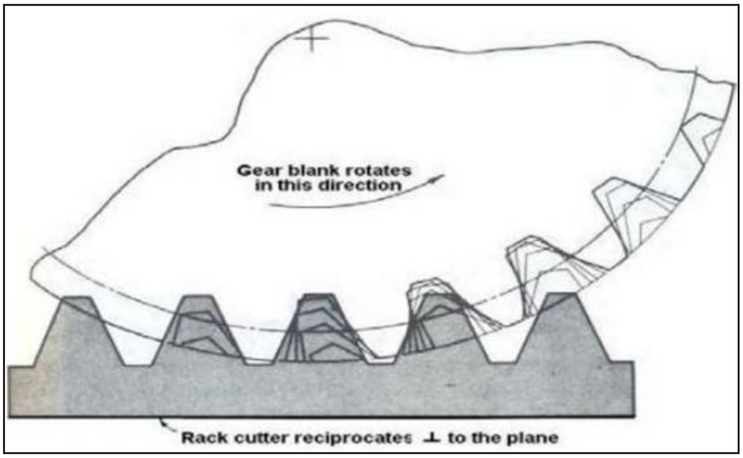

Figure 6 **Maag gear cutting (Ref. 17).**

Similar to the hobbing process, a greater number of generative milling cuts will lead to a closer involute approximation — a smoother curve. Unlike the hob cutter, however, the generative milling cutter has to be moved to precise X & Y positions relative to the gear rotation for every discrete cut along the line of action.

Another difference with the hobbing process is that the hob is swiveled to the angle equals to the algebraic sum of gear helix angle and hob lead angle, while the *Generative Milling* disc cutter is swiveled to the angle calculated as

$$A = \sin^{-1}(\sin(\beta b)/\mathrm{Cos}(CA)) \quad (1)$$

where:

A is cutter swivel angle

β_b is gear base helix angle (Fig. 5)

CA is cutter side angle (Fig. 9)

When the cutter side angles equal zero (parallel sides), the cutter is swiveled to the base helix angle, as cos (0) = 1 (Fig. 5)

When cutting a helical gear, the milling cutter axial travel needs to be synchronized with the gear rotation:

$$\Delta C = \Delta Z \cdot 360/\mathrm{Lead} \quad (2)$$

where:

ΔC is gear rotation angle corresponding to the cutter axial travel

ΔZ is cutter axial travel

Lead is gear lead equals to the axial advance of the helix over one gear rotation

Similarities with Maag shaping with rack cutters. There are also some similarities between the generative milling and the legacy Maag shaping process using rack cutters. This type of cutting is based on rolling the gear around the rack cutter (Fig. 6). The kinematics of the generative milling

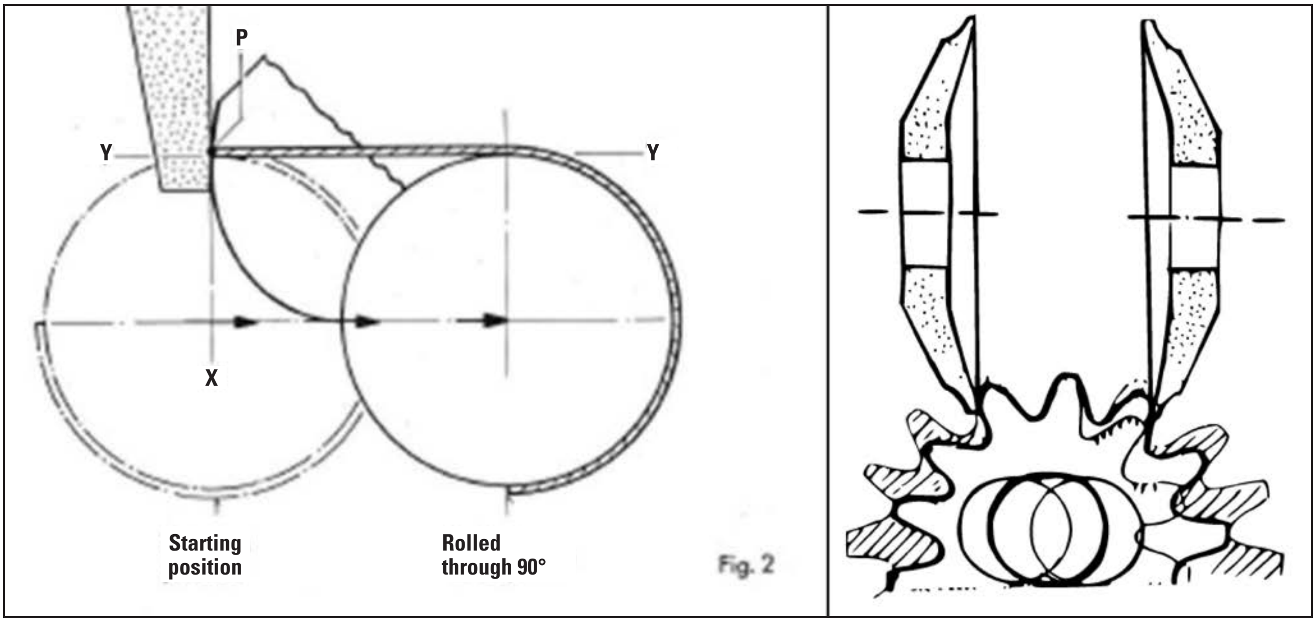

Figure 7 **Maag 0° grinding method (Ref. 18).**

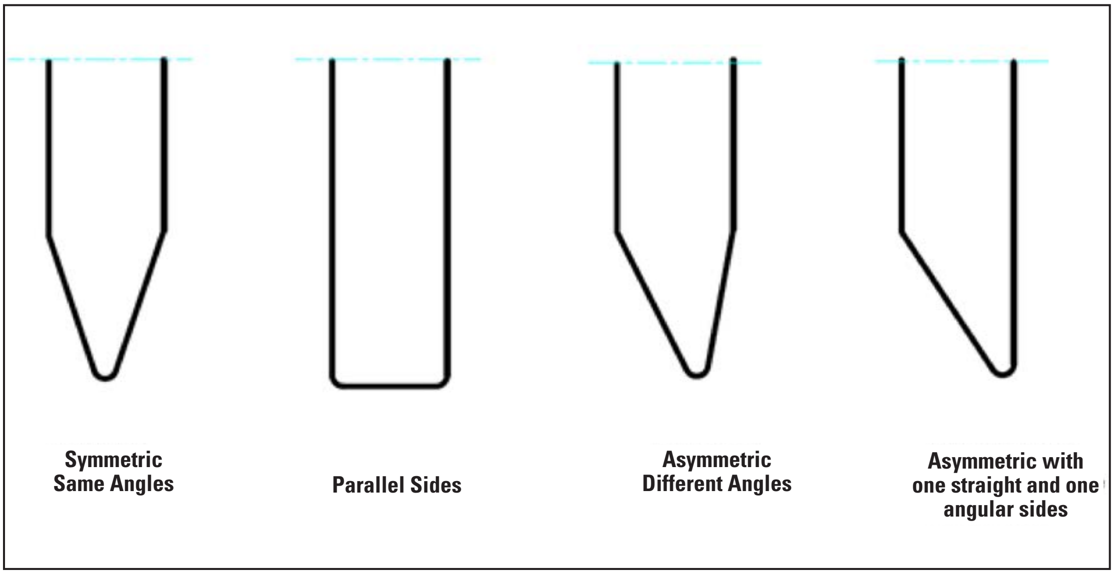

Figure 8 Milling cutter profiles.

are also based on gear rolling around the disc cutter. While Maag rack-type cutting method employs a single cutting edge for each generative point as the rack cutter traverses the gear face width, the generative milling cutter has the benefit of many cutting edges around the cutter periphery, thus facilitating an increased productivity.

Similarities with Maag 0° grinding method. The legacy line grinding method (Fig. 7), employed by Maag, Hoefler, and others, has probably the most similar kinematics to the generative milling. While kinematics of machine movements is similar, the generative milling is different than line grinding in many ways, including:

- The entire tooth gap is milled out, while line grinding required a prior roughing operation
- CNC controls align the milling cutter with gear teeth, while the legacy grinding machines relied on mechanical linkages between the grinding wheel and the gear
- Milling material removal rate is several magnitudes greater as compared to grinding

Similarities with index milling/gashing. Lastly, the kinematics of generative milling has some similarity with the index milling (gashing). Moreover, the gashing cutters can be employed for generative milling as is, thus making it possible to combine gashing and involute form generation within one set up, or even eliminate the gashing operation. Both the index milling/gashing and the generative milling require that the cutter traverses the face width to complete the cut. The kinematics of gashing machines, as well as hobbing machines that have precision tangential slides, make them capable (software would have to be added) of the generative gear milling process.

Milling Cutters

The disc cutter's simplicity and universality are the major advantages of the generative gear milling. The geometry of the inserts can be very flexible. The cutting inserts can have parallel sides (Fig. 8), or trapezoidal sides, symmetrical or asymmetrical when the right and left side angles are different. Angles of the left and right side are specified independently (Fig. 9).

Unlike the hob cutter, the milling cutter tooth depth does not have to match the gear tooth depth. Compared to the gear, the cutter can have a

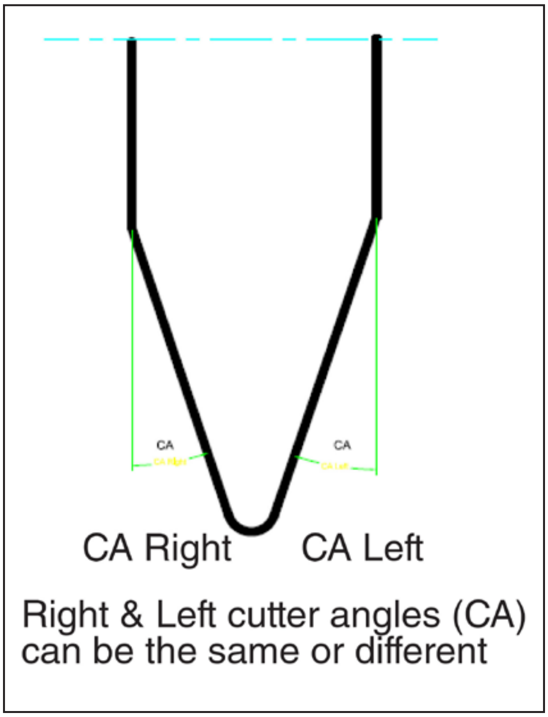

Figure 9 Cutter left- and right-side angles.

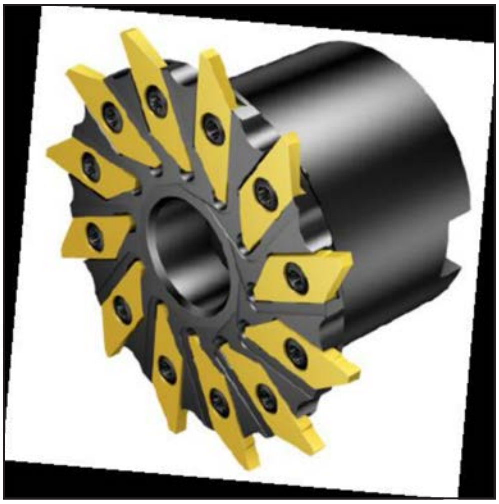

Figure 10 Milling cutter with parallel sides (Ref. 9).

Figure 11 Milling cutter with non-parallel sides (Ref. 9).

Figure 12 Cutters with carbide inserts (Ref. 7).

smaller or larger tooth depth. The cutter can have carbide inserts (Figs. 10, 11, 12, and 13; or be a solid HSS (Fig. 14)). Generally, the larger the cutter diameter, the more cutting edges could fit around the cutter's periphery, prolonging the cutter life.

In addition to the disc cutter, the end mill cutter type (Fig. 15) can be employed in the situations where the disc cutter would interfere with a part's shoulder, for example, when cutting a double-helical gear with an insufficient gap for a larger diameter cutter. However, the end mill cutters may necessitate an additional milling axis. A hobbing machine would certainly require a special attachment in order to drive an end mill cutter.

While there is a lot of flexibility with respect to cutter form and size, there are a few limitations.

- The cutter tip radius should be smaller or equal to the gear fillet radius
- The cutter tip width should be smaller than the tooth gap in its narrowest location
- The width of the parallel side's cutter should be smaller than the chord of tooth gap at its narrowest location (typically at the form gear diameter)

When a tooth undercut/protuberance is required, the cutter may have some additional limitations in order to generate the required undercut.

The smaller the cutter tip radius, the more flexibility there is to generate undercut/protuberance

To minimize a chance of cutter interference with the root diameter, the insert's tip should be a semicircle without a flat area

The Involute Generation

Since the involute profile curve exists only in the transverse plane (plane perpendicular to the axis of gear rotation), it's advantageous to determine the profile generative points and their respective cutter positions in the transverse plane. The same set of formulas could be used for both helical and spur gears because the transverse and normal planes coincide in the case of spur gears. While formulas may vary depending on machine's kinematics, for a traditional hobbing machine the Cartesian profile coordinates and their respective gear rotation angles for each generative point can be determined (see Fig. 19 for visual depiction of coordinates):

$$X_i = R_i * \cos(TPA_i - CA_t) \quad (3)$$

$$Y_i = R_i * \sin(TPA_i - CA_t) \quad (4)$$

$$C_i = C_o + \theta_i \quad (5)$$

where:

X_i, Y_i are coordinates of one generated point on the involute curve, considering the Cartesian coordinates origin is in the gear center

C_i is the gear's angular position for the generated point

R_i, TPA_i is the radius and the transverse pressure angle of the generated point, respectively

CA_t is cutter side angle in transverse plane:

$$CA_t = \tan^{-1}(\tan(CA)/\cos(A)) \tag{6}$$

where:

CA is cutter side angle (Fig. 9)

C_o is the involute origin angle

θ_i is roll angle of the generated point

The corresponding cutter coordinates will need to be determined as functions of generative points, the cutter swivel angle, and the cutter geometry. An example of a coordinate system of a hobbing machine is represented (Fig. 16).

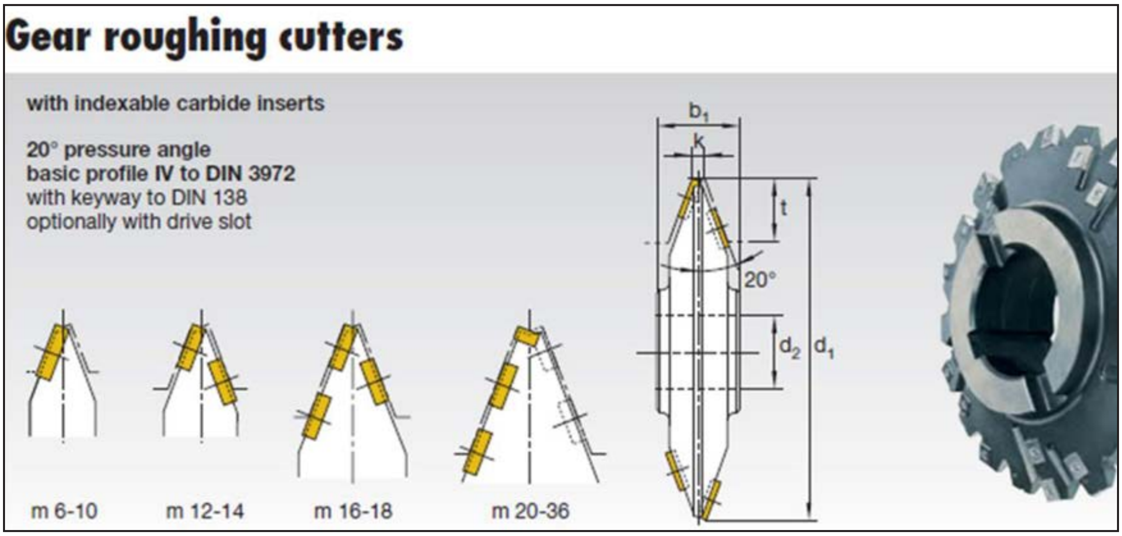

Figure 13 Roughing cutters (Ref. 7).

Figure 14 Solid cutters (Ref. 8).

Figure 15 End mill cutter (Ref. 9).

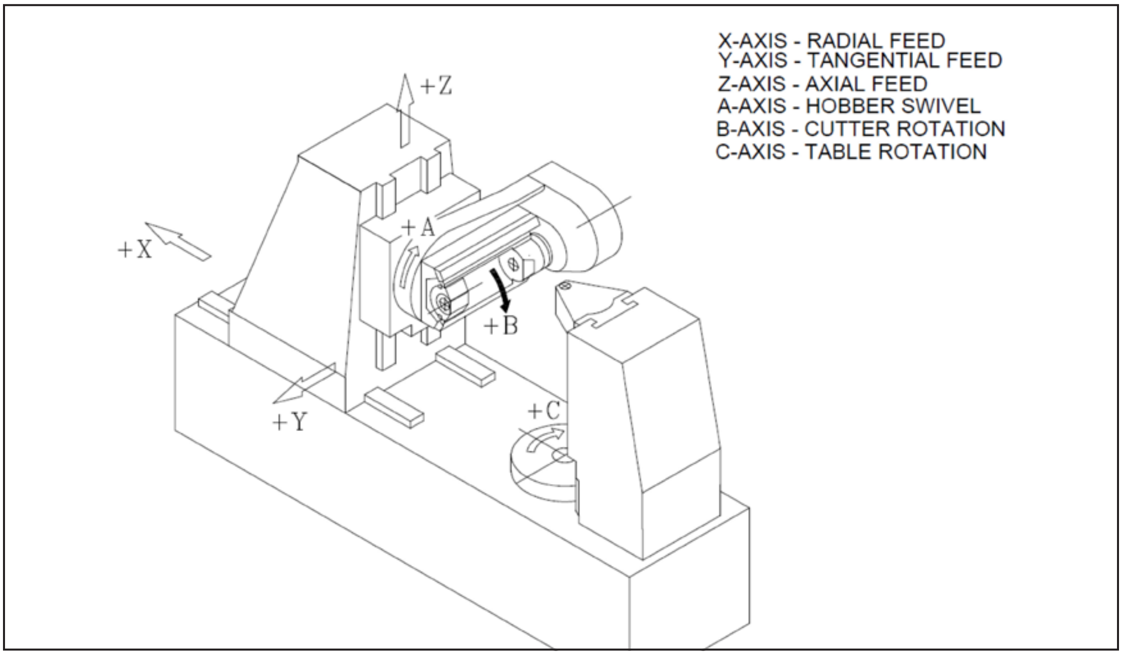

Figure 16 Gear hobbing machine.

Parallel sides disc cutter. The tooth generation with parallel sides cutter is similar to the Maag 0-grinding method (Fig. 17). The cutter width should be less than the tooth gap at the minimum gear diameter. This method will require the longest cutter travel in the tangential direction. The tangential machine slide should allow for a minimum ± travel to be equal to the length of roll plus one-half of the cutter width (Eq. 7).

Trapezoidal disc cutter. Cutters that have trapezoidal form (Fig. 18) provide greater flexibility, as there are fewer restrictions for the cutter width — only the cutter tip width has to be less than the tooth gap at the minimum gear diameter. This type of cutter can cut a much larger range of gear pitches and sizes. Another benefit of such a cutter is that the machine tangential travel can be much smaller. To simplify the illustration of the tangential cutter travel TT, Figure 19 depicts an example for a spur gear when $CA_t = CA$. Note that Equation 7 below is universal for cutters with parallel or trapezoidal sides.

$$TT = R * \sin(TPA\text{-}CA_t)/\cos(A) + W \qquad (7)$$

where:

TT is tangential travel required for cutting one side of the gear tooth; note that for parallel sides cutter ½ of the cutter width needs to be added to determine required machine tangential travel for a specific gear application.

R is largest gear radius (OD/2)

TPA is involute transverse pressure angle at the largest radius (OD/2)

CA_t is cutter side angle in transverse plane (Eq. 6)

W is the tangential distance from the generating point to the middle of the cutter (*W* is one-half cutter width for parallel sides cutter)

A is cutter swivel angle (for spur gears, the cutter swivel angle is zero)

Since the right and left flanks are generated independently, the cutter does not have to have a symmetrical profile. One gear can be generated by a cutter that has different left- and right-side angles.

Regardless of the cutter form (parallel or

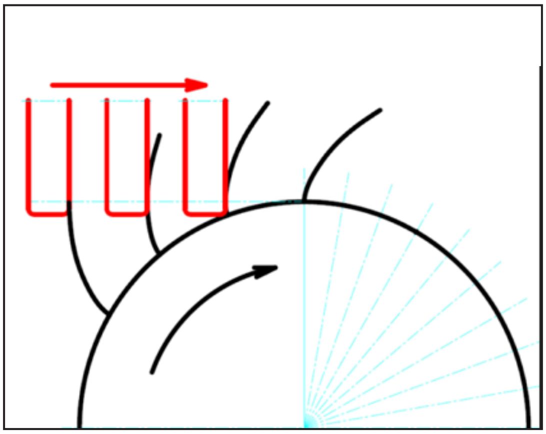

Figure 17 Gear generation with parallel sides cutter.

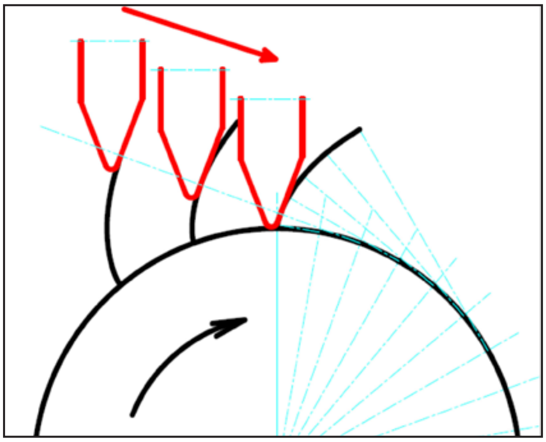

Figure 18 Gear generation with trapezoidal form cutter.

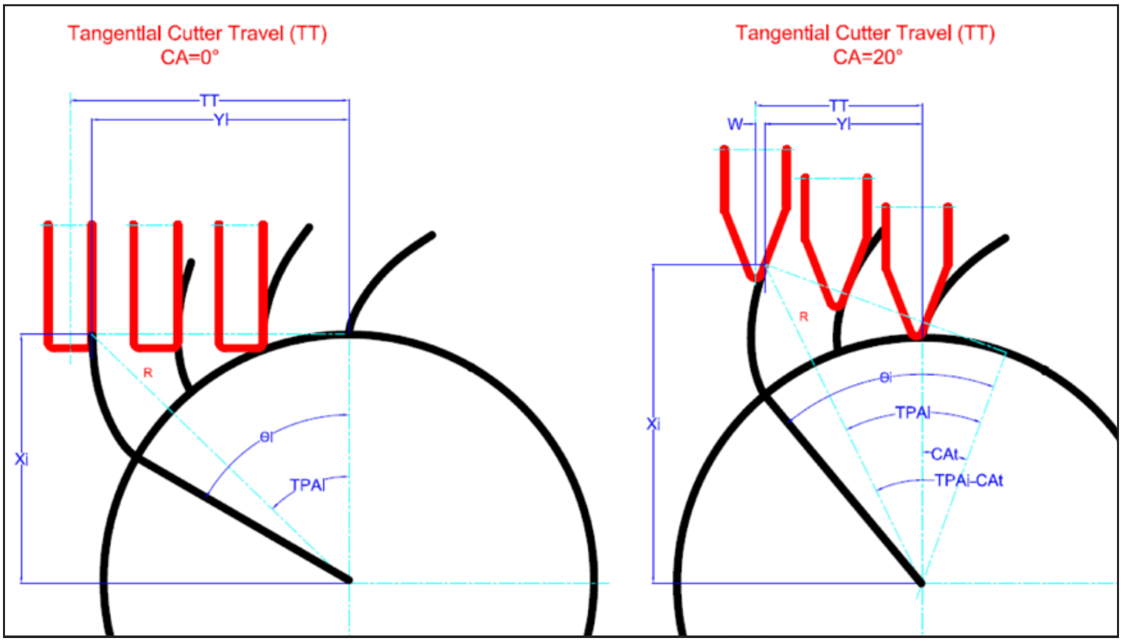

Figure 19 Cutter tangential travel.

non-parallel sides), the radial distance between the point of tangency and the cutter tip can migrate throughout the tooth generation. At the beginning of the cut, when the involute points are generated closer to the gear OD, it may be prudent to take a deeper cut. As the cutter gets closer to the root area, the radial distance between the generated point and the cutter tip may have to be shortened to avoid undercutting the root diameter.

Generative cuts. During the hobbing process, the number (density) of generative cuts is pre-determined by the number of hob gashes and starts, and the number of gear teeth (Fig. 20). The cuts are incremented by a pre- determined angle of gear rotation (degrees of roll) per every successive generative cut.

The pattern of generative milling cuts (thus profile surface pattern) can be the same as hobbing when the angular increment of generative cuts is applied (Fig. 21). Or, the pattern can be slightly different when a radial increment for generative cuts is applied (Fig. 22). The operator has a choice of applying angular or radial increment.

Unlike hobbing, however, the number of milling cuts for either mode (radial or angular increment) is infinitely variable — programmable. It is a part of the process data entry in that the operator can provide the number of cuts or accept recommendations based on a built-in algorithm for an optimum material removal.

The ability to control the density of generative cuts can be beneficial for:

Adjusting the material removal rate depending on cutter and gear materials, number of cutting edges, cutter width, and gear's number of teeth

Reconciling a need for increased productivity versus a need for a smoother profile surface

The Cutting Strategy

With respect to the cutter selection, the generative gear milling process provides a lot of flexibility. On the other hand, a smaller cutter (when "t" cutter height (Fig. 13)), is significantly smaller than gear's tooth whole depth) requires a different strategy for sequencing the gear cutting steps.

Gashing. A small cutter may require additional center cuts — gashing — to remove most material in the middle prior involute generating cuts.

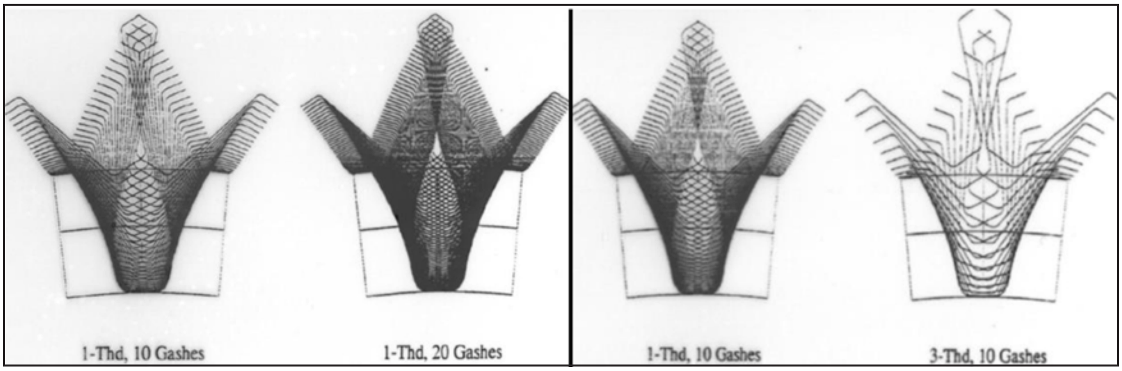

Figure 20 Generative cuts density (Ref. 12).

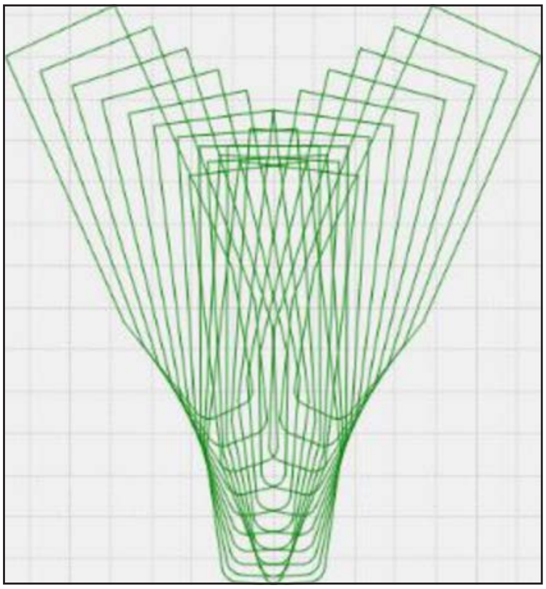

Figure 21 Generative cuts indexed by roll angle.

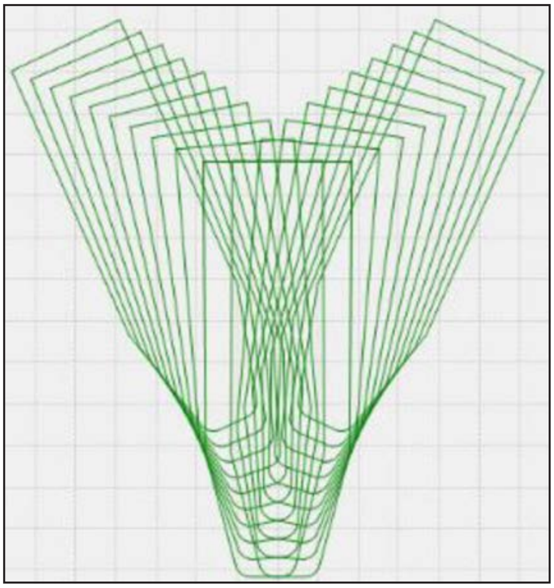

Figure 22 Generative cuts indexed by radial change.

Such initial material removal reduces a chance of unwanted interference of the cutter body with the opposite gear flank.

Regardless of the cutter size, a safe approach to avoid unwanted side interference would be to center cut/gash out most of material before initiating the involute generation cutting. However, when the cutter whole depth is larger than the gear tooth depth, an initial center cut (gashing) may not be necessary. The simulation may provide visual clues whether the center cut could be skipped.

Involute profile generation:

Discrete generative cuts with traversing the cutter along the gear face. One strategy for the involute generation is to make discrete generating cuts by traversing the cutter along the gear face for each generation increment along the line of action. This will create a tooth surface pattern that is similar to the legacy Maag or Hoefler line grinding pattern.

The other strategy is a continuous profile generation for each discreet cutter "Z" position along the gear face.

Tooth undercut, root radius, and special modifications. Additional generative cuts are to be applied for generating a tooth undercut, a tooth root radius when it is greater than the cutter tip radius, or for a profile modification. Unlike during hobbing or generative grinding, the twist or bias phenomenon is not present because a) each flank is generated independently, and b) the cutter swivel angle is related to the base helix angle that is a constant for each gear.

Setup adjustments for profile correction can be achieved by two methods. Since all generative milling positions are functions of the base circle diameter and the cutter side angle, either of them could be mathematically adjusted to counterbalance machining dynamics, axes alignments, cutter quality, and other system errors affecting the profile slope quality. A similar methodology is used for profile adjustment on CNC-controlled gear grinding machines. It is also possible to make profile and lead modifications such as crown, taper, heat treat compensation, etc.

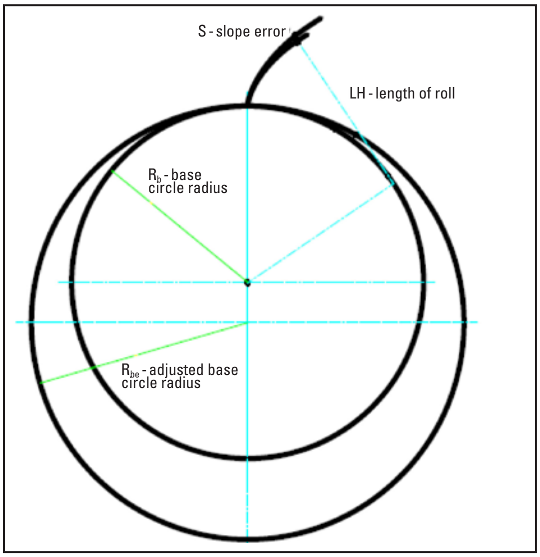

Figure 23 Involute profile adjustment.

Base circle adjustment (Fig. 23). If the cut gear has an excessive slope error, the generative cuts can be re-calculated using the adjusted base circle instead of the theoretical base circle indicated on the gear drawing.

$$R_{be} = R_b\,(1 - S/LR) \tag{8}$$

where:

R_b is base circle radius specified on the drawing
R_{be} is adjusted base circle radius to be used for calculating generative cuts
S is profile slope error with its sign (± according to the material condition at the tooth tip)
LR is length of roll over which the slope error was determined
A is cutter swivel angle

Cutter angle adjustment. The other alternative for eliminating the profile slope errors is re-calculating the generative cuts based on adjusted cutter profile angle CA_e instead of CA.

$$CA_e = \tan^{-1}(\tan((CA_t - \tan^{-1}(S/LR))) \cdot \cos(A)) \tag{9}$$

where:

CA_e is adjusted cutter side angle
CA_t is cutter side angle in transverse plane, see Eq. 6
S is profile slope error (± according to the material condition at the tooth tip)
LR is length of roll related to the slope error
A is cutter swivel angle

Applications and Benefits

Applications of generative gear milling process. While in principle the generative milling method is capable of cutting gears of any pitch size, this method is most economical for cutting or re-cutting coarse-pitch gears (typically coarser than 3-2.5 DP). Generally, the coarser the pitch, the less economical is the hobbing process, the more economical is the generative gear milling process. Examples of applications that offer most benefits:

- Cutting coarse pitch gears that are beyond hobbing process capability
- Cutting gears that exceed the maximum pitch rating of an existing hobbing machine
- Small lot size gears when a hob or a form cutters are not available, too expensive, or require a long lead time
- Gear re-cutting/thinning/repairing when a hob or form cutter are not available
- Decommissioning of legacy Maag gear cutting machines for course pitch gears
- Replacement of a two- or three-step operation, e.g. — gashing (roughing) followed by a secondary hobbing or other finishing process

Benefits:

Reduced number of process steps/cost. Sometimes, a coarse-pitch gear is machined in two or more steps. First, the gear is roughed by a single index cut on a hobbing machine. After that, the gear is moved to a Maag rack shaper for a finish cut. The generative gear milling will enable roughing and finishing of the gear on the same machine using one cutter with much greater efficiency while maintaining accuracy similar to the Maag method.

Reduced cutter cost and delivery time. Off-the-shelf standard disc cutters with rectangular or trapezoidal carbide inserts (typically less inexpensive than hobs for coarse-pitch gears) would be used to produce precision- quality gears. Side cutter angles do not matter; as the only requirement for the cutter is that it fits inside the tooth space (cutter tip should be smaller than tooth space at its narrowest location).

Expanded pitch range capability. The *Generative Milling* software feature can expand the pitch range of a hobbing machine. As long as a gear and cutter fit within the machine working range (do not exceed center distance and swing diameter limitations), the gear could be coarser pitch than the original hobbing machine rating allowed.

Improved efficiency. Compared to a legacy Maag gear cutting machine with rack cutters, the cutting efficiency is improved as multiple (instead of one) cutting edges remove material with every stroke.

Summary

- ***Technology.*** Generative gear milling is an innovative, software-centered gear cutting technology that offers new cost reduction opportunities for machining coarse-pitch gears.
- ***Software app.*** A hobbing machine or a milling machine with a rotary table can be equipped with a generative gear milling software app that would expand the machine capabilities to include generative milling, increase pitch capacity, and improve efficiency for cutting coarse-pitch gears.
- ***Flexibility.*** Since generative gear milling allows for an infinitely variable density of generative cuts, a hobbing machine or a milling machine equipped with software can cut much coarser gears as compared to the hob cutting process.
- ***ROI.*** The implementation of the generative gear milling technology does not necessarily require a new hobbing or milling machine. An existing CNC hobbing or milling machine with a rotary table could be upgraded with a software app to enable the generative gear milling process, providing an appealing ROI.
- ***Opportunity.*** Confluence of machine computerization, legacy mechanical gear cutting concepts, and a possibility of a relatively inexpensive way of technology acquisition and implementation, e.g. — adding a software app and a PC if necessary — makes the generative gear milling technology accessible to a wider range of coarse-pitch gear manufacturers.

Computer simulation
(*www.machinetoolbuilders.com/115*)**:**

- Unequal sides
- Equal sides
- Parallel Sides

For more information. Questions or comments regarding this paper? Contact Yefim Kotlyar — *YKotlyar@machinetoolbuilders.com*.

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Design and Optimization of a Hybrid Vehicle Transmission

Massimiliano Turci

Introduction

The hybrid vehicles seem to be the fastest solution for the containment of consumption and of pollution for personal transportation.

The designer of a hybrid transmission has to address additional issues with respect to the classical cases, in particular the high speed of the electric unit and the bidirectional motor/generator operation. In this case, a lot of attention should be paid to how to consider the four combinations of signs for torque and speed in the load spectrum for the gear calculation. The paper presents some topics, like several approaches for the alternating bending factor, the effects of the asymmetric crowning (especially the helix modification, tapered or parallel) and how to consider the housing stiffness in the TCA.

Finally, the paper presents an interesting solution from the kinematic point of view, the compound planetary, relatively well known in the automotive, but much less so in the industrial gearboxes design.

The data presented in the paper are taken from some recent jobs of the author. For reasons of confidentiality (the projects are still under development) there will be not quantification of the parameters, but only the description of the procedures followed, with details indicated in the bibliographical reference, and of the software used. The latter two types of information are probably the most interesting part of the paper, since they enable the reader to repeat the procedures by himself on his own context. The paper is therefore almost a guideline for the designers.

The need to reduce air pollution has led to the introduction of electric engines for the propulsion of road vehicles. Without making a general introduction in this regard, suffice it to say that the design of the transmission for this new type of vehicle requires special attention. A comprehensive discussion on the subject is available in (Ref. 1). This paper examines two cases addressed by the author: the optimization of a single-gear transmission (two helical stages speed reducer) for full electric vehicles and the design and optimization of the transmission for a hybrid vehicle. The topics discussed in the first case provide a basis for the second case, which involves greater kinematic complexity because it is based on a compound epicyclic. In particular, the paper presents the calculation method, critical points, bibliographical references and software tools. More information about this type of automotive transmission are in (Refs. 2–3).

Single-Speed Transmission with Double-Stage Helical Gear Reduction

Two different configurations were examined for different applications. The first one is more classic and simple, and the second one is more compact (Fig. 1). The same approach, described below, has been followed for both cases: some macro-geometric configurations had been proposed (module, number of teeth, pressure angle, helix angle, tooth height) with the need to optimize the micro-geometry, i.e. the contact pattern. Several applications (for different vehicles) were studied in the first case, and only one in the second.

Contact pattern optimization. An optimization procedure starts with the definition of one or more objectives, variables "to play with" and constraints to respect. The contact pattern between gears is not only a "visual" objective and an analytical expression is necessary to be able to proceed with numerical optimization. The contact pattern should be expressed and evaluated as an objective metric. Two parallel procedures are followed.

Crowning. The effect of the crowning can be quantified with the root and flank safeties in accordance with ISO 6336 (Ref. 4), as long as the real distribution of the load along the flank is taken into account. In this regard, the method

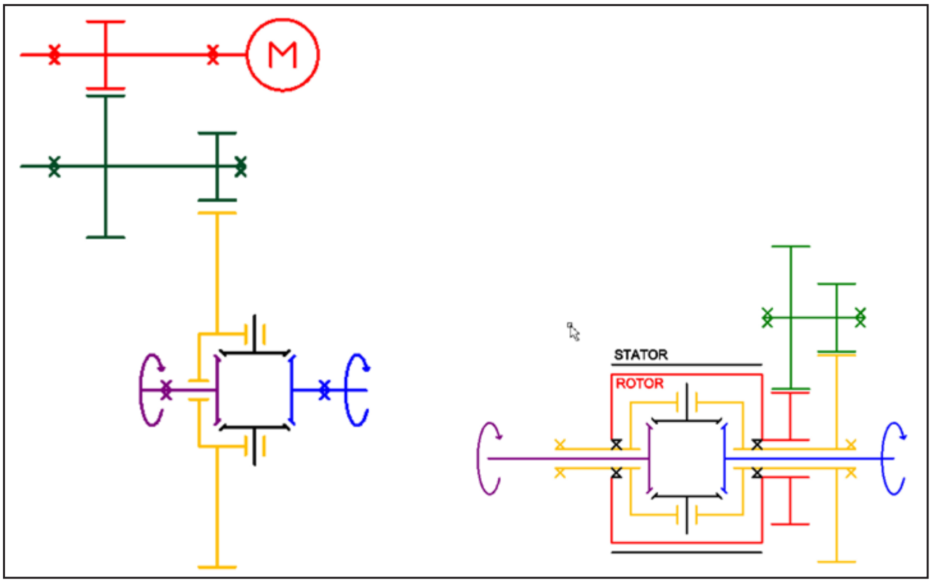


Figure 1 Two different layouts for 2-stage single-speed transmission.

described in ISO 6336-1 Annex E was used, considering the micro-geometry of the gears and the deformation of the shafts. This leads to reliable results in a short time and provides the value of the $K_{H\beta}$ factor necessary for the calculation of the load capacity. The implementation of this method, which utilizes single dimension LTCA, is described in (Ref. 5). SF and SH are thus the objective, i.e.—how these values have been calculated using the load spectrum.

The variables chosen are the two dimensions separately defining the two components of the asymmetric crowning, set as the sum of the symmetric crowning and the helix angle modification. The helix angle modification, conical (tapered) or parallel, has been added as a further variable.

Tip relief. After selection of the optimal (asymmetric) crowning, the tip relief is determined in order to minimize the PPTE (Peak to Peak Transmission Error) and peak contact pressure. Since these values depend on the load, a graph has been made on various torques levels, letting the human eye choose the relief value leading to the graph of PPTE without high value at lower torque.

Alternating bending, drive & coast flanks and spectrum. As stated previously, the first problem faced was to calculate SF and SH with the load spectrum in Table 1. ISO 6336-5 explains how to calculate cumulative damage with the Palmgren-Miner's Rule. This method is widely used but is only valid when the driving gear is the same one and the drive flank does not change. In the present case, however, the spectrum shows all four combinations of signs for the torque and speed, since the electric engine acts as a motor or brake in one direction and the other. It is therefore necessary to take this into account in calculating the

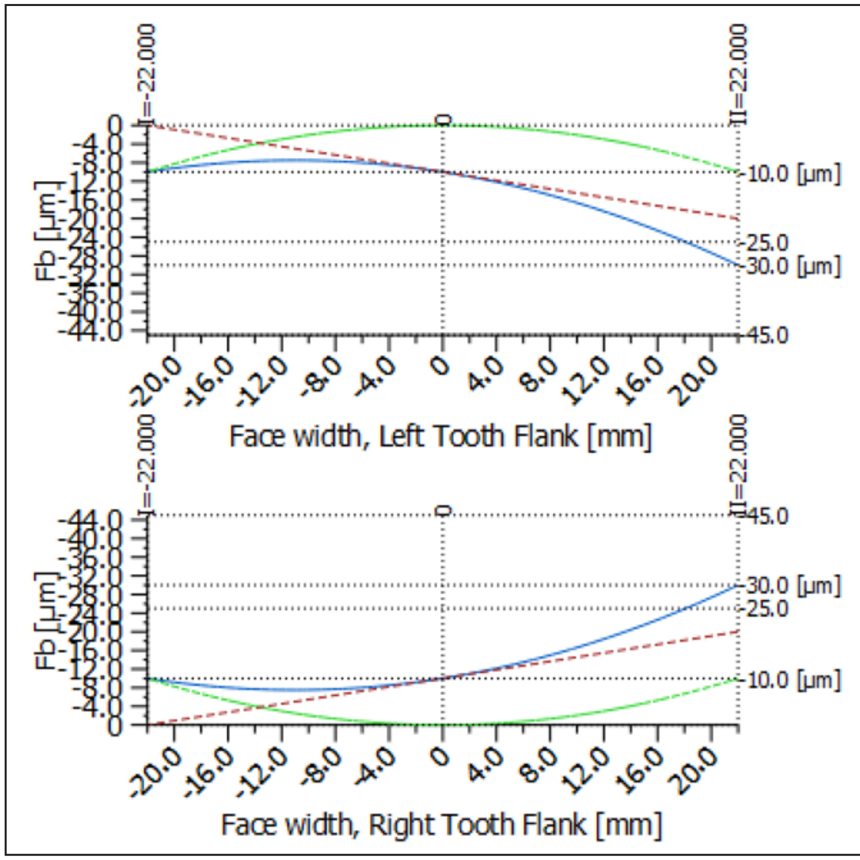


Figure 2 Asymmetric crowning (blue) = symmetric crowning (green) + helix angle modification (red).

Table 1 Load spectrum with mixed sign on torque and speed; shows torque and speed factors with respect to nominal data

% Time (Σ = 100)	% Torque	% Speed
3.673	100.000	100
10.034	100.000	200
1.233	100.000	400
10.116	72.370	600
11.062	61.852	–800
2.558	30.701	1000
10.697	33.333	1200
0.032	29.630	1400
6.125	–81.580	–100
2.221	–81.481	200
10.693	–81.481	333
6.280	–81.481	467
2.060	–71.370	600
3.453	–55.556	720
12.002	–48.148	890
7.762	–40.741	1000

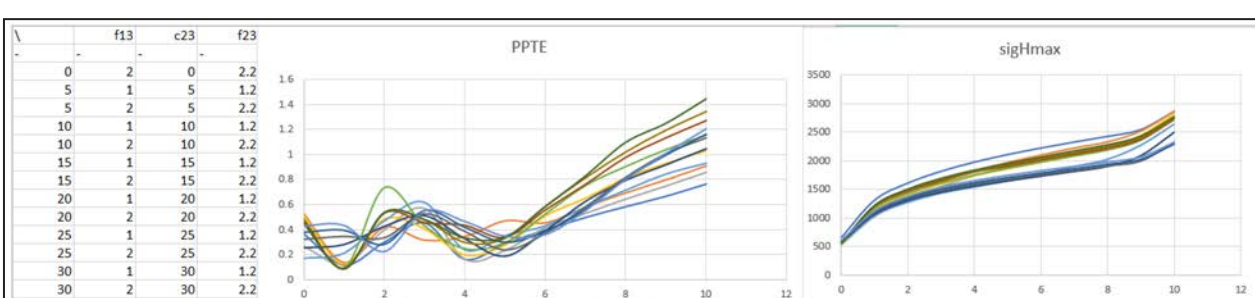


Figure 3 PPTE and max pressure in different load condition from 1 to 100% of the Max Torque, with different microgeometry solutions.

bending (which is neither pulsating nor fully reversing) and pitting, for which the number of hours on each flank is not the same and it is also different for bending calculation. For each line of the spectrum the $K_{H\beta}$ factor (function of the crowning and the deformation of the shafts) must obviously be recalculated.

For the calculation of surface durability, two separate calculations are made, one for each flank, each for the number of hours actually occurring on that flank, as shown from the spectrum. The flank safety is the lowest of those calculated.

The calculation of tooth bending strength is a little more complex.

The rules for the calculation of the load capacity of gears show the fatigue limits of materials with one way bending. In the case of fully reversing bending, AGMA 2001-D04 (Ref. 6) states that this should be reduced to 70%.

ISO 6336-5:2016 also reduces resistance for fully reversing bending to 70%. In the other cases, ISO 6336-3:2006 Annex B states that it should be dimensioned by a Y_M factor, a function of the stress ratio (i.e. the ratio between the loads on the two flanks of the same tooth), of the material and, for case hardened gears, of the tooth root form (Table 2).

$$Y_M = \frac{1}{1 - R\,\dfrac{1-M}{1+M}} \qquad (1)$$

where

$$R = -1.2 \cdot \frac{\text{load per unit facewidth of the lower loaded flank}}{\text{load per unit facewidth of the higher loaded flank}}$$

M considers the mean stress influence on the endurance (or static) strength amplitudes, and is defined as the reduction of the endurance strength amplitude for a certain increase of the mean stress divided by that increase of the mean stress, as defined in 6336-3:2006 Annex B

Table 2 Mean stress ratio, M (Ref. 4)

Material	M
Case hardened	$0.8 + 0.15\,Y_s$
Case hardened and shot peened	0.4

A few years ago, a paper was presented on how to calculate this reduction in fatigue resistance for alternating bending according to the theories of Gerber and Goodman (Ref. 7). Both theories put Y_M at levels lower than 0.7 for pure alternated bending, respectively 0.569 and 0.699.

The same "evolution" can also be seen in the change in Y_M from 0.7 to 0.65 shown in the two subsequent editions of the book on cylindrical gears (Refs. 8–9). This shows the formulation for intermediate cases, referring to the number of inversions, with the stress factor in any case unchanged, i.e. with the same value of force applied to the two flanks (Fig. 4).

For the calculation here, it was chosen the formulation most adapted to the data contained in the spectrum involved. As explained in (Ref. 10), two calculations are performed:

1. with $Y_M = 1$ for the lines with positive torque and $Y_M = 0.7$ for those with negative torque
2. with $Y_M = 0.7$ for the lines with positive torque and $Y_M = 1$ for those with negative torque

The final safety *SF* is the best between the two (not the worst). This is called the "most realistic" one because, since the number of inversions is not known, choosing the worst value (as done however in the calculation for pitting) would be excessively conservative. It should be observed that the spectrum used is already condensed and does not represent the actual load history (in the sense of chronological sequence); the change between positive and negative sign of the spectrum lines does not represent a change in the functioning of the transmission.

Contributions to the contact pattern. As discussed previously, the contact pattern is a function of the shaft microgeometry (to be optimized) and the shaft deformation. The latter is affected by the stiffness of the gear body, the shaft, the casing, the bearings (with the operating clearance) and the accuracy of the bearings arrangements.

A detailed description of the method used is available in (Ref. 11). A model of the entire transmission has been made for making a totally automatic iterative calculation without operator intervention. The calculation is as follows:

1. Kinematic calculation of the gears (forces acting on the tooth)
2. Application to the shafts of the forces calculated in the previous point
3. Calculation of the reactions, considering only the stiffness of the bearings with the relative pretension
4. Calculation of the displacement of bearings housing on the casing (FEM)
5. Calculation of the real deformation of

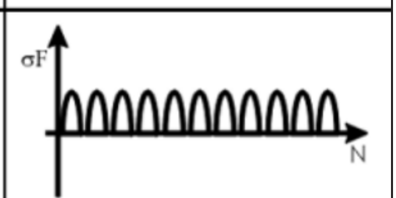
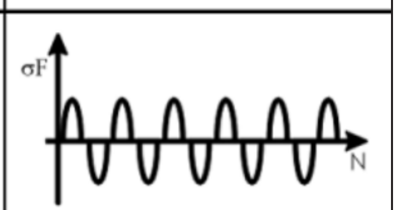
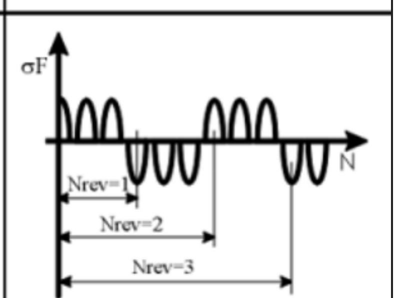
Operating Mode	Alternating Bending Factor (Mean Stress Influence Factor) Y_M	Load Direction
Pulsating	1	
Alternating	0.7 (1) 0.65 (2)	
Oscillating	$0.85 - 0.15 \cdot \frac{\log N_{rev}}{6}$ (1) $0.85 - 0.20 \cdot \frac{\log N_{rev}}{6}$ (2) $(1 \le N_{rev} \le 10^6)$ 0.7 (1) 0.65 (2) $(N_{rev} \ge 10^6)$	

Figure 4 Alternating fatigue according to (Ref. 8) (1) e (Ref. 9) (2).

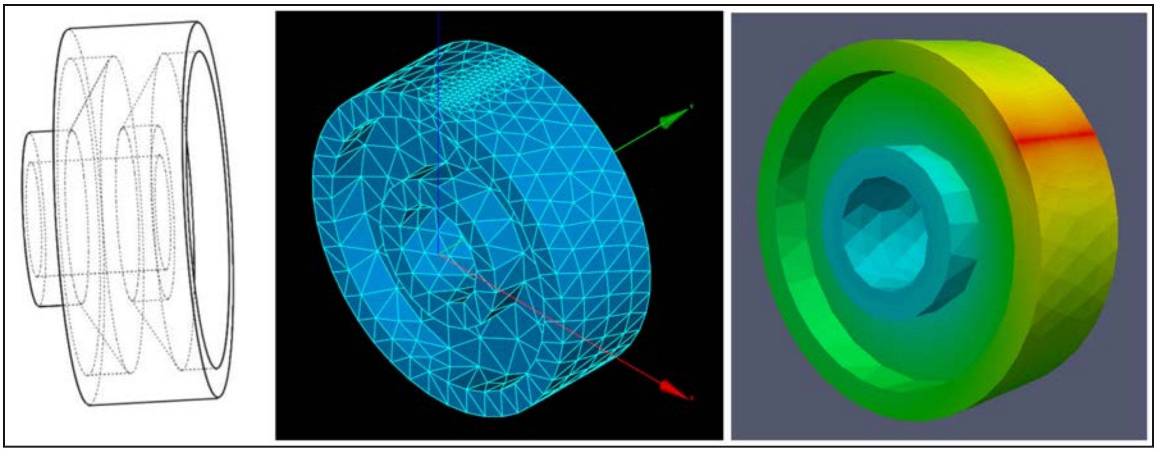


Figure 5 Gear body FEM calculation (Refs. 10 and 15).

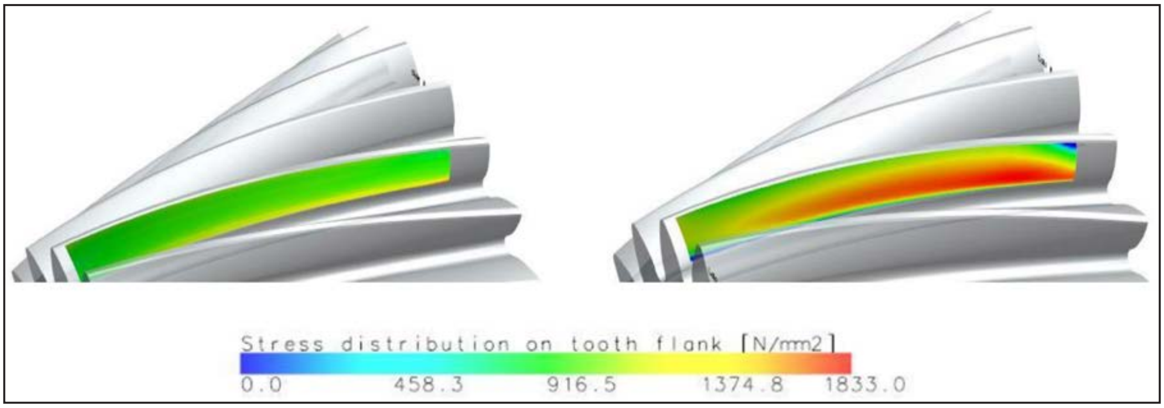


Figure 6 Contact trace at the max torque calculated with the LTCA before optimization (A) and after optimization (B).

the shaft
6. LTCA on gears with the misalignments
7. Updating of the figures in point 1 and repetition of the calculation until convergence.

The shaft calculation was conducted according the Timoshenko Beam theory. The bearings stiffness calculated as explained in ISO/TS 16281 (Ref. 12). Detailed geometric data of the bearings were requested from the producer, that provided also a software (Ref. 13) to check the results. The contribution of casing stiffness was taken into consideration by exporting from FEM the condensed stiffness matrix in the geometrical centers of the bearings (Ref. 14) and importing it to the calculation model. The contribution of the stiffness of the gear body was also considered in the model. The FEM used in this case is open-source (Ref. 15). Without these integration from the various software, allowing for exchange of data (loads and deformation) without operator intervention, the calculation of deformation would have simply been one-shot and less accurate.

Among the results of this calculation, it was also decided to include the various lives of the bearings (Ref. 16), with the accumulated damage method, also taking into account contamination of the oil on each single bearing. The maximum contact pressure was calculated too, because this value is a good indicator of bearing operation conditions.

Optimization algorithm. It has been previously mentioned the two separate calculations for contact optimization on the two directions of the flank and of the tooth profile. Now that all the interactions of the model are known, the algorithms behind them can be examined. As already explained, in this phase a professional optimizer was not used as was done for the study (Ref. 17), but two different research loops are simply defined.

For longitudinal optimization, the 4 variables for crowning and helical modification were evaluated on 10 values, 10 times from 1% to 100% of the nominal torque. To avoid the proliferation of solutions (up to 10^5), the corrections of the two gears are increased synchronously, thus obtaining only 10^3 variants. The range of variants for the crowning was from 0 to double the value necessary to compensate the deformations at the maximum torque. For the helix modification, variation was between the two values that are positive/negative opposites to the one suggested, thus transiting through 0. It was observed that on the basis of the spectrum, for configuration of Figure1a, the optimal micro-geometry consisted of helical corrections that were sometimes parallel and sometimes conical, in a way not predictable *a priori*.

For the profile modification, the progressive tip relief only was used (avoiding the root relief as being hard to implement), with variations of 10 values between 0 and the value necessary to compensate the deformation of the tooth at the maximum torque, between the long one and the short one (Re. 18). As already stated, the best combination is the one maximizing the safeties against bending and pitting with the given spectrum.

Since it is not possible to establish whether the optimal relief value and the optimal crowning value, when combined,

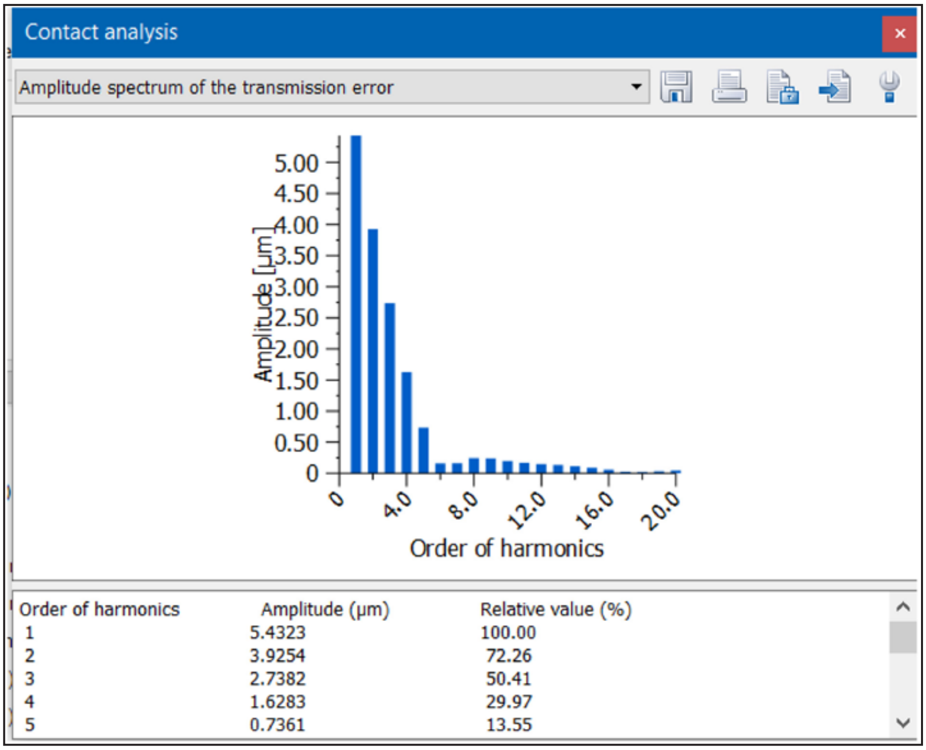


Figure 7 FFT of Transmission Error for a torque level.

Table 3 Empty example of efficiency map

		Input speed										
		0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
Input Torque	0											
	400											
	800											
	1200											
	1600											
	2000											
	2400											
	2800											
	3200											
	3600											
	4000											

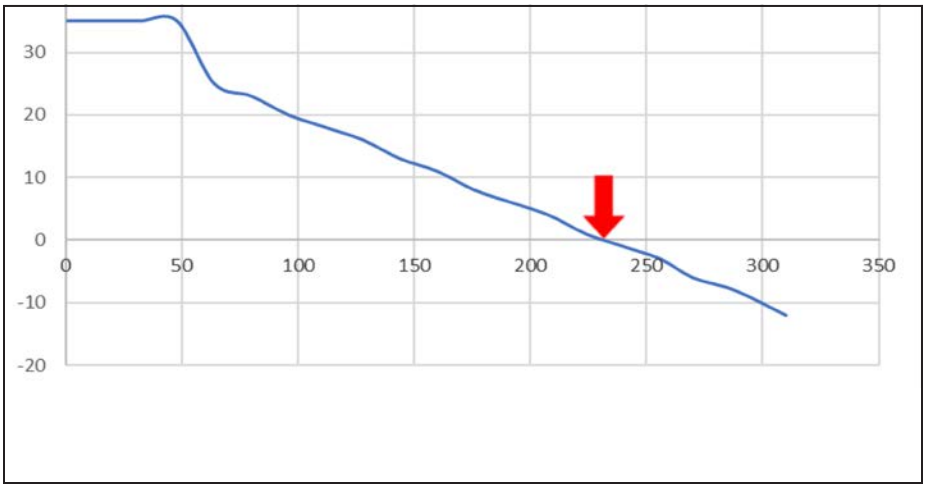


Figure 8 Backlash vs Torque; the value is calculated taking in account all deformation already considered in the LTCA.

lead to the optimal solution, the two research loops should be nested. In this phase we have merely conducted a visual check of the contact trace calculated with the LTCA in the various load conditions present in the spectrum.

Subsequent calculations. Once the macro-geometry and micro-geometry of the gears was defined, transmission noise and efficiency were assessed. Although these should be design values, in this case we identified them subsequently.

FFT of the TE. The graph of the Fourier spectrum for transmission error was generated for 10 levels from 1% to 100% of the maximum torque (Fig. 7).

Efficiency map. In order to evaluate the overall efficiency of the transmission, an efficiency map like the one in Table 3 was used. The table is blank, it's only an example. It was filled for the project but not shared in this paper.

To complete this, the transmission calculation model implemented the power losses due to the bearings, sealing and meshing, with an approach similar to the one described in (Ref. 19). Without going into detail, we can simply recall that the losses on the bearings follow the formulas of the catalogue (Ref. 20), sealing losses (Ref. 21) and meshing losses (Ref. 22). This is the same calculation model as the thermal capacity according to ISO/TR 14179 (Ref. 23). In this case the system temperature was set at 40°C and 80°C and the contribution of oil churning was not considered, since this would have required a CFD analysis to obtain realistic results.

Backlash. The LTCA is the calculation of the tooth deformation: it's a good opportunity to calculate the backlash, that is a function of the load.

It is not possible to avoid checking the meshing of the macrogeometry concentrating exclusively on optimization the microgeometry. A wrong choice of the tolerances of the tooth thickness in the first step of the design could generate interference and wear under load.

Figure 8 shows the decrease of the backlash as the input torque increase. If the input torque is bigger than the marked value, there will be wear by interference on the teeth.

Compound Epicyclic for Hybrid Transmission

Description of kinematics. The experience acquired in the activities above described was then applied on the hybrid transmission (Fig. 9). In this case too, the kinematic layout was applied to different products.

In general, the core of the hybrid transmission is the need to mix in the same axle (the one to the wheels) the torques coming from two completely different engines, the electric one and the IC one, which have very different speeds. Also, as seen in the previous case, the electric engine has the double operation mode motor/generator.

In this case, the bevel gear differential mixes the torque coming from the IC engine (upstream from the parallel stage) and the electric engine (connected to the epicyclic gearset, which provides two different speeds).

There follows a description of the design activity regarding only the compound epicyclic gearset (Fig. 10).

The input is on the first sun z_{s1}, connected with a double planet gear $z_{p1}|z_{p2}$. There is only one ring z_r which is fixed. The outputs can be the second sun z_{s2} or the planet carrier.

If the second sun is neutral, the ratio n1/nc is from Equation 2 as stated in Figure 3 and Table 2B of (Ref. 24). An example of the Ravigneaux graphic method for this configuration is in Figure 11, as explained in (Ref. 25).

In the other case, the transmission ratio is calculated solving the Equation 3, where the Willis formula is applied as usual for simple epicyclic, when the input is the carrier, the output is the sun and the ring is fixed.

$$\frac{n1}{n_c} = 1 + \frac{z_r \cdot z_{p1}}{z_{s1} \cdot z_{p2}} \quad (2)$$

$$\frac{n2}{n_c} = 1 + \frac{z_r}{z_{s2}} \quad (3)$$

where

n_1, n_2 and n_c are the speed of sun1, sun2 and carrier

z_{s1}, z_{p1}, z_{p2}, z_r, z_{s2} are the number of teeth of the gears (Fig. 10)

Design requirements. The design objectives are two well defined transmission ratios i_1 and i_2.

The constraints are both the geometry (radial and axial max dimensions) and the load capacity, with 5 load spectra

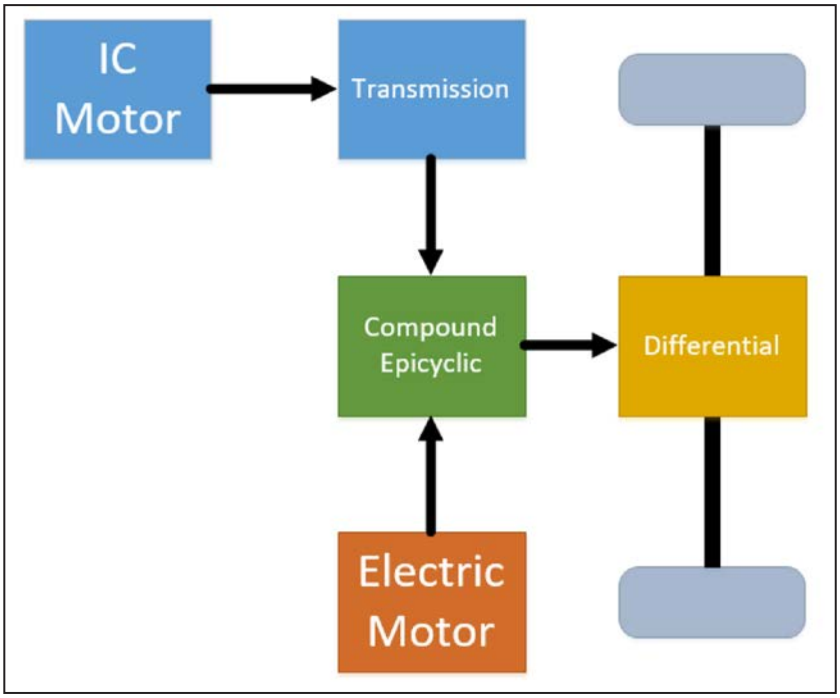


Figure 9 Parallel transmission for hybrid vehicle with IC and E motors.

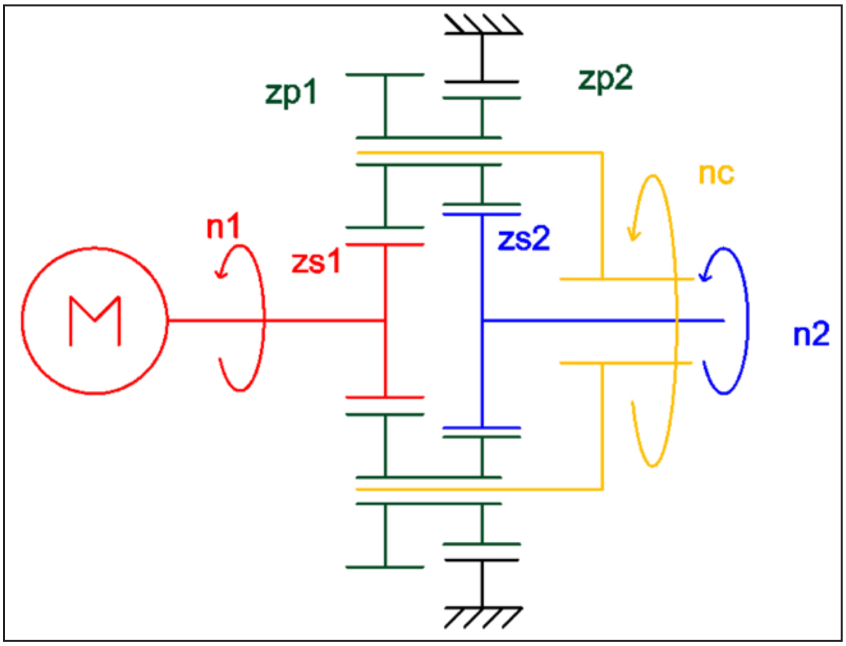


Figure 10 Compound epicyclic; it is used in hybrid passenger cars but also in bikes (Ref. 26).

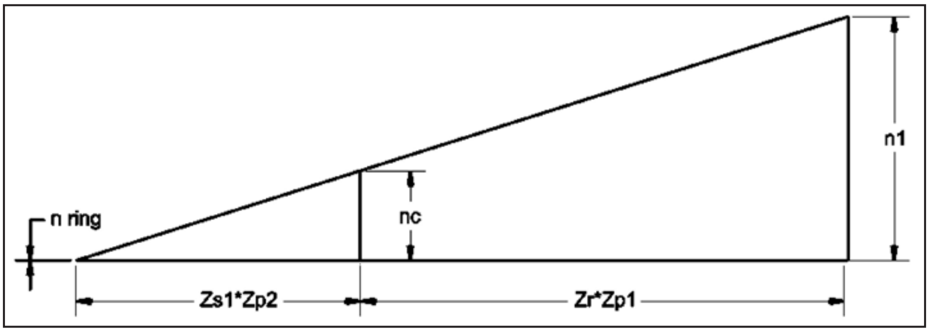


Figure 11 Ravigneaux graphic method for the calculation of the ratio n_c / n_1 of the compound epicyclic of the previous figure.

```
Sub CercaDenti()
    ' DATI
    i1ObjMin = 11.1
    i1ObjMax = 12
    i2ObjMin = 4.1
    i2ObjMax = 5
    Y = 123 ' il massimo è 125, mi tengo largo
    beta = 21
    nsat = 3
    hap = 1.3 ' fattore di addendum (1 standard, >1 dentatura alta)
    zmin = 15
    beta = beta * 3.1415 / 180
    For z5 = zmin To 100 ' sol2
        For z4 = zmin To 100 ' sat2
            For z2 = (z5 + 2 * z4 - 4) To (z5 + 2 * z4 + 4) ' cor (dcor = dsol+2*dsat circa)
                For z1 = zmin To 100 ' sol1
                    For z3 = ((z5 + z4) - z1) - 4 To ((z5 + z4) - z1) + 4 'sat1 (z3 e z4 hanno lo stesso centro, 
                        i1 = 1 + z2 * z3 / z1 / z4
                        i2 = i1 / (1 + z2 / z5)
                        ' rapporti
                        If i1 >= i1ObjMin And i1 <= i1ObjMax And i2 >= i2ObjMin And i2 <= i2ObjMax Then
                            ' fattorizzabile
                            If z1 Mod nsat = 0 And z2 Mod nsat = 0 And z5 Mod nsat = 0 Then
                                ' integrabile
                                If max(z3, z4) Mod min(z3, z4) = 0 Then
                                    ' satelliti equispaziati
                                    If (z5 + z2) Mod nsat = 0 Then
                                        ' calcolo approssimato del modulo dalla relazione Y= a54 + da3/2
                                        m = Y / ((z5 + z4) / 2 / Cos(beta) + (z3 / Cos(beta) + 2 * hap) / 2)
                                        a54 = (z5 + z4) / 2 / Cos(beta) * m
                                        ratio_c = z3 / z1
                                        ratio_e = z2 / z5 + 1
                                        Debug.Print z1, z3, z5, z4, z2, i1, i2, ratio_c, ratio_e, m, a54
                                    End If
                                End If
                            End If
                        End If
                    Next
                Next
            Next
        Next
    Next
End Sub
```

Figure 12 ***Excel*** **macro sample with nested loop for generation of variants. It involves only some geometrical variables, leaving the strength calculation to a next step. A different approach is used by (Ref. 27) to design of minimum volume spur and helical gearsets, considering pitting, bending and scuffing resistance.**

being set in the various operating conditions:
1. Electric drive speed 1
2. Electric drive speed 2
3. Electric coast speed 1
4. Electric coast speed 2
5. IC drive

Out of all the possible solutions, the least noisy one should be chosen.

Design steps. The first phase involved seeking all the combinations of teeth leading to the two transmission ratios.

As in the previous case, a VBA macro was developed on *Excel* to generate and filter variants. This is a series of nested loop on the number of teeth z_{s1}, z_{p1}, z_{p2}, z_r, z_{s2} filtered on assembly requirements: a factorizing planetary geartrain (as described in (Ref. 24)), with planet gears mounted with equidistant spacing. An indication of the module respecting spatial criteria was made by setting the addendum factor and using it to calculate the tip diameters of the various gears (except for the x factor). This enabled to draw up an initial list (Fig. 12).

The choice of a high addendum (HCR) is typical in the automotive industry. It ensures quiet operation without adverse effects on resistance (Ref. 28).

The variants found on *Excel* were then developed in greater detail on a gear analysis and optimization software, to define the profile shift coefficient, balancing the specific sliding and thus to calculate their resistance and the noise level.

In order to rapidly evaluate the noise level of a pair of gears, at least for purposes of comparison with other similar solutions, the Sato formula (Eq. 4) (Ref. 29) was used. It comprises the variables linked to the load (power and speed), the macro-geometry (contact ratio and transmission ratio) and accuracy (dynamic factor). More in-depth calculation would require LTCA (Masuda formula, Eq. 5 from the same reference), but also a timespan too long to compare hundreds of solutions.

$$L = \frac{20 \cdot (1 - \tan(\beta/2)) \cdot \sqrt[8]{u}}{f_v \sqrt[4]{\varepsilon_\alpha}} + 20 \cdot \log W \quad (4)$$

$$L = \frac{20 \cdot (1 - \tan(\beta/2)) \cdot \sqrt[8]{u}}{\sqrt[4]{\varepsilon_\alpha}} \sqrt{\frac{5.56 + \sqrt{v}}{5.56}} + 20 \cdot \log W + 20 \cdot \log \tilde{X} + 20 \quad (5)$$

where

L is the overall noise level at 1 meter from a gearbox in dB(A)
β is the helix angle
u is the gear ratio
ε_α is the transverse contact ratio
W is the transmitted power in hp
f_v is the speed factor, analogous to the AGMA dynamic factor v.
v is the pitch line speed in m/s
$\tilde{X}$ is the vibration displacement amplitude normalized by static deflection and it can be calculated by TCA

Once the optimal solution (the one respecting geometric requirements, transmitting the two set ratios, maximizing resistance and low noise level) is found, the next step was to define the micro-geometry as in the case of the electric transmission, while avoiding modifications of the teeth on the internal crown.

In the case of the hybrid transmission, the efficiency map was newly compiled for 2 temperatures (40°C and 80°C) but in all the 5 operational cases indicated previously.

Further development

The analyses required did not include the optimization of contact for the bevel gears. In any case, the same approach can be used as for cylindrical gears: exchange of data between the calculation of deformation of shaft and gears from the software (Ref. 10) to (Ref. 30) for LTCA and definition of the microgeometry, as described in (Ref. 31). The bevel planet of the differential gears should be calculated with a static (fixed) torque, independent from the motor: the slip torque of the wheels.

A next step for a faster optimization could be the definition of an object metric to evaluate the contact pattern, i.e. the percent of full contact or the position of the max pressure in the grid of the tooth flank.

Conclusions

The paper is not the proof of a discovery, but it is the description of a method: the optimization of the microgeometry for cylindrical gears. The method has been applied and described on some transmissions with helical gears and compound epicyclic, used on different hybrid vehicles. However, the method is also valid for industrial gearboxes.

Since the objective is "micro," it has been seen that it is necessary to pay attention to the "smallest" causes of deformation of the geometry to optimize, in particular the deformation of shafts, bearings, housing as well as of tooth as a cantilever on flexible gear body.

It has been seen that the objectives are manifold and of different types: on the one hand the safeties against bending and pitting, which are indicators summarizing the load history, and on the other hand the trend of the transmission error, of the maximum pressure, of the noise and of the efficiency over the load.

It has also been pointed out that the deformations taken into consideration also influence the backlash between the teeth in operation, which must therefore be verified and guaranteed at the maximum torque, the condition that further reduces the backlash.

All these calculations are possible with commercial software already known and widespread.

Finally, in the case of a planetary compound, a simple algorithm for optimizing the macrogeometry was proposed, introducing the existence of multi-objective optimization software.

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For more information. Questions or comments regarding this paper? Contact Massimiliano Turci — *massimiliano@turci.biz*.

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Massimiliano Turci is a consultant in gears and cam mechanisms design. He received his master's degree in mechanical engineering at the "Alma Mater Studiorum" University of Bologna in 1996. He began as a CAD manager and he developed X-Camme — a cam-design software used in the packaging and beverage machinery industry. In 2004 he started working on gears as application engineer for KISSsoft in Italy: he is now the team leader of the Italian technical staff of KISSsoft. His professional experience is primarily in the development of computational models for vehicle transmissions and enclosed gearboxes (planetary, helical, bevel and wormgear). He is a member of the AGMA worm gear committee, the UNI (Italian national body) gears committee and the ISO workgroups for gear calculations. Turci has published several papers in this field.

Machine Tool Builders

ANNOUNCES PERSONNEL CHANGES

Machine Tool Builders Inc. (MTB), recently announced and welcomed **K.C. Warren** as the company's new director of sales and marketing. Warren will report directly to the ownership team and is tasked with further developing the company's rapidly growing position in the machine tool marketplace. He will oversee sales and marketing operations and will be responsible for team leadership, planning and implementing sales, marketing and business development programs, business strategy execution, product development as well as general management responsibilities. Warren will focus on driving revenues through long-term customer relationships, delivering customized high-value solutions to meet each individual customer needs and pursuing new business opportunities that continue to increase MTBs market share of best-in-class products & services.

Warren comes to MTB with 17 years of executive-level experience and held technical sales & marketing leadership positions with several companies where he responsible for building, managing & leading global sales organizations. He is a well-known figure in a variety of industries and markets that include automotive, industrial automation, process control instrumentation, industrial manufacturing and environmental technology. He received national recognition for customer service excellence and has been a key contributor in a number of product innovations and technology advancements that were crucial to each organizations success. Warren brings a deep understanding of highly engineered systems and applications allowing him to quickly identify customer needs and provide high value solutions. He brings a proven record of forging relationships with some of the largest companies in the world, working directly with OEM's, integrators, dealers, representatives, distributors, engineering firms, sales partners, reseller accounts and end-users. MTB believes his versatile business experience, technical knowledge and unwavering commitment to serving customers coupled with a contagious winning attitude and outgoing personality are assets that complement and enhance MTB capabilities as well building upon their already stellar reputation.

MTB also announced that **Dale Bridgewater** has recently joined Machine Tool Builders, Inc. as the shop, service and engineering manager. Bridgewater comes to MTB with a long history in the gear manufacturing industry having worked for Seattle Gear Works as maintenance supervisor for nearly 30 years, charged with maintaining over 200 machines. With a vast skill set of operating, rebuilding, and debugging gear shapers, hobbers and grinders, Bridgewater's leadership and hands-on skills perfectly blend with MTB's mission and work environment. Involved locally on a Counsel at Hononegah Community High School (in Rockton, Illinois) for Youth in Manufacturing, Bridgewater has actively and seamlessly blended into this new community of Northern Illinois.

Some of his responsibilities range from directing personnel, determining daily tasks on machine rebuilds and recontrols to project managing activities and interacting with customers on those milestones. Please welcome Bridgewater as part of the Machine Tool Builder's team. (*www.machinetoolbuilders.com*)

Robert F. Handschuh

ENDS 35-YEAR CAREER AT NASA GLENN RESEARCH CENTER

Dr. Robert F. Handschuh has retired from NASA, concluding a more than 35-year distinguished career as the Chief of the Rotating and Drive Systems Branch at NASA Glenn, directing the research efforts of over 20 NASA, ARL and contractor research engineers and technicians. His work at NASA Glenn included invaluable NASA and DoD research in rotorcraft drive system analysis and experimental methods. He previously served as the Drive Systems Team leader for the Tribology & Mechanical Components Branch at NASA Glenn for 20 years. This also included research in high-speed gearing — including windage, loss-of-lubrication technology, and hybrid gearing. Handschuh also successfully developed many experimental research test facilities, including: high-temperature ceramic seal erosion; blade-shroud seal rub test; planetary gear train test facility; spiral bevel and face gear test facility; high-speed helical gear train facility; single tooth bending fatigue test facility; and high-speed windage. Honors received over the years include: 2016 — Patent #9,296,157, Hybrid Gear; 2009 — Elected American Helicopter Society Technical Fellow; 2008 — NASA Silver Snoopy Award; 2004 — Elected American Society of Mechanical Engineers Fellow; and many others. A prolific contributor, he penned over 130 Formal, Referenceable, and other Publications (including ***Gear Technology***), as well as over 30 International Conference Presentations. Not leaving the scene completely, he continues to serve on the ASME Power Transmission and Gearing and AHS Propulsion Committees. (*RHEngineer990@gmail.com*)

Gleason Corporation

ACQUIRES FAESSLER HONING BUSINESS FROM DAETWYLER GROUP

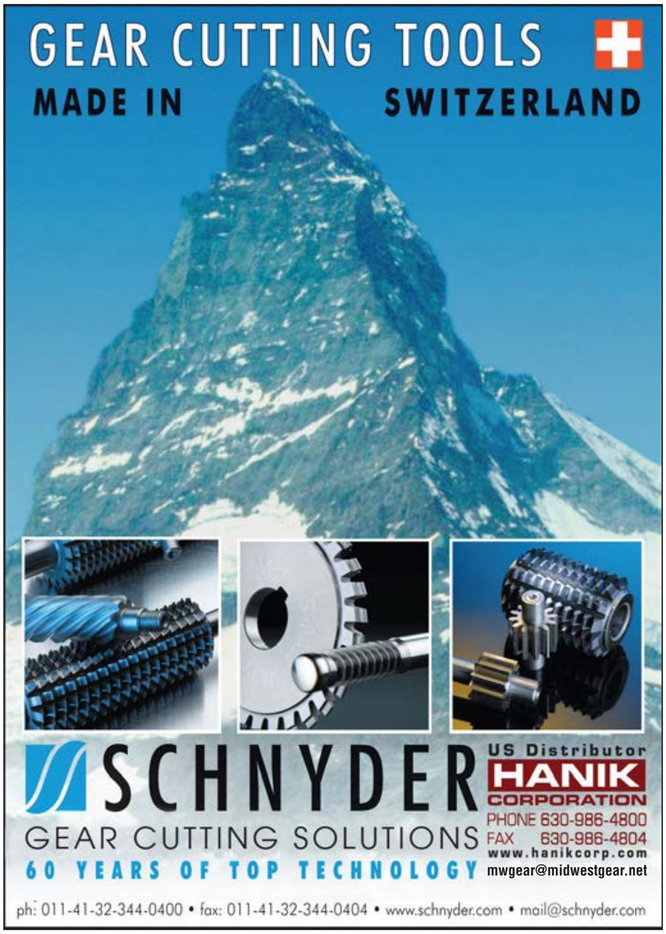
Gleason Corporation has announced the signing of a definitive agreement with Daetwyler Industries AG and MDC Max Daetwyler AG to acquire all assets of Daetwyler's Faessler gear honing business.

Under the Faessler brand, Daetwyler has been producing gear honing machines, related workholding and tools for the high-precision hard finishing of gears. The business operations of the Faessler division, which has approximately 70 employees, will be acquired by a new Gleason subsidiary, Gleason Switzerland AG, and will continue to operate at its current locations in Bleienbach and Dietikon, both located in Switzerland. Gleason will retain Faessler's existing management team and expects Faessler's current employees to join Gleason.

The transaction is structured as an asset deal whereby substantially all assets and certain contractual relationships of the Faessler business shall be transferred by way of a bulk transfer according to the Swiss Merger Act. It is subject to employee notice periods and other customary closing conditions. It is expected to be completed in April 2019.

Commenting on the acquisition, John J. Perrotti, president and chief executive officer of Gleason Corporation, said, "Faessler is a leader in honing technology for gears and ideally complements Gleason's existing product line for gear hard finishing solutions. Faessler's established presence in the global marketplace and Gleason's extensive sales and service organization will create great synergies for existing and new customers."

Ralph Daetwyler, chief executive officer of Daetwyler Global Tec Holding, said "We are pleased to have a company such as Gleason with its long tradition in gear technology and the gear production equipment market become the new owner of this business. We are proud of the accomplishments of the Faessler team, and we believe the potential for Faessler's continued growth and success by being part of Gleason, with its market leadership and global reach, is truly exciting." (*www.gleason.com*)



Brelie Gear

ANNOUNCES NEW PLANT IN WISCONSIN

Brelie Gear Co, Inc. announced plans to build a new 36,800 sq ft facility on a recently purchased 4.3 acre site in Waukesha, WI. Construction is planned to start in April 2019 and will be completed in November 2019. The announcement comes on the heels of an all-time annual sales record in 2018. Upon completion Brelie will be moving from their current plant in Milwaukee to the new, larger plant.

"We're very excited to announce the building of our new facility," said Steve Janke, President of Brelie Gear Co, Inc. "Our current building has had numerous additions over the years, but we didn't have a good product flow or space to expand our staff."

The new larger space will continue to run as a full-service gear manufacturing facility that houses the latest in equipment technology and automation. Brelie continues to reinvest revenue into state-of-the-art technology and training to stay on top of efficiency and quality assurance.

"This new space will increase our production and ensure continued quality to best serve our customers," Janke added. "We will have room to expand our company for years to come."

Brelie Gear Co, Inc. is a leading manufacturer of fine and medium pitch spur and helical gears, worms, and worm gears. The company continually invests 20 to 30% of revenues back into the latest technology and employee training.

(*www.breliegear.com*)

June 12–14—Gear Failure Analysis Seminar St. Louis, Missouri. Explore gear failure analysis in this hands-on seminar where students not only see slides of failed gears but can hold and examine those same field samples close up. Experience the use of a microscope and take your own contact pattern from field samples. Gear engineers, users, researchers, maintenance technicians, lubricant experts, and managers should consider attending. Instructors include Rod Budny (RBB Engineering) and Andy Milburn (Milburn Engineering). For more information, visit *www.agma.org/education/advanced-courses/2019-gear-failure-analysis/*.

June 23–26—Powdermet 2019 Sheraton Grand, Phoenix, Arizona. The leading North American technical conference on powder metallurgy and particulate materials, Powdermet 2019 is a hub for technology transfer for professionals from every part of the industry, including buyers and specifiers of metal powders, tooling and compacting presses, sintering furnaces, furnace belts, powder handling and blending equipment, quality-control and automation equipment, particle-size and powder-characterization equipment, consulting and research services, and more. It is co-located with the Additive Manufacturing with Powder Metallurgy (AMPM 2019) conference where attendees will have access to over 200 technical presentations from worldwide experts on the latest research and development. A new metal additive manufacturing tutorial will take place Sunday, June 23 from 1:30pm - 4:30pm. Powdermet is sponsored by the Metal Powder Industries Federation and APMI International. For more information, visit *www.mpif.org/Events/POWDERMET2019.aspx*.

June 25–27—Rapid Tech + FabCon 3D Erfurt, Germany. Rapid.Tech + FabCon 3D is one of Europe's key information and communication platforms for additive manufacturing processes. It focuses on the latest developments in rapid prototyping, the manufacturing of end products using additive techniques, and how the technology can be transferred into mass production. The unique nature of Rapid.Tech + FabCon 3D has been impressing exhibitors, visitors and participants alike for some 15 years now. The 2018 show boasted 5,000 guests visting with 208 exhibitors from 14 countries about innovations in industrial and creative 3D printing. A whole forum is being dedicated to software and processes for the first time this year. The lectures will cover a broad spectrum of processes, from adapting the design of internal development and production processes to 3D printing, establishing secure processes between several partners, to new disruptive business models that are only possible thanks to additive manufacturing (AM). Discussions from Autodesk on additive design and 3D printing optimization from Dassault Systèmes will also be a part of the program. For more information, visit *www.rapidtech-fabcon.com*.

July 10–11—Dritev 2019 Bonn, Germany. Increased CO_2 discussions, sustainable mobility and electrified drives: The automotive transmission world is changing. Why the understanding of the transmission changes, how it is to be understood as part of the overall powertrain and why cross-component know-how becomes more and more important are some of the subjects that will be discussed. Attendees can expect more than 1,500 developers, around 100 international exhibitors and 80 specialist lectures on one of the world's largest networking platforms for powertrain and transmission development. A special thematic focus of the Dritev 2019 is on the special topic Noise, Vibration, Harshness (NVH), which is both audible and tactile vibrations in motor vehicles in the range from 20 Hz to 100 Hz. Innovative analysis techniques identify these vibrations, reduce them and thus increase ride comfort for the passengers. Another special topic is the increase in powertrain power density. Here, the use of new materials and procedures should help. More than 100 national and international companies present innovative solutions at the accompanying trade exhibition. The exhibition has become the central marketplace of the industry. Here, participants will get an overview of the most important suppliers in the development, simulation and production of transmissions and transmission components. Conferences include "Powertrain solutions for commercial vehicles," "EDrive," and more. For more information, visit *www.dritev.com*.

July 10–11—AGMA Bevel Gear System Design Oak Lawn, Illinois. Learn how to design and apply bevel gears systems from the initial concept through manufacturing and quality control and on to assembly, installation and maintenance. Engage in a practical hands-on guide to the bevel gear design, manufacture, quality control, assembly, installation rating, lubrication and, most especially, application. Engineers, technicians, and others involved in the selection, application and/or design of bevel gear systems should attend. Ray Drago is the instructor. For more information, visit *www.agma.org/education/advanced-courses/2019-bevel-gear-system-design/*.

July 23–24—8th WZL Gear Conference USA Westminster, Colorado. Attendees can expect a selection of presentations from the research portfolio of WZL including information on gear design, manufacturing, gear checking, and testing. Highlights include requirements for hard finishing, gear optimization, superfinishing, trends in gear production, Internet of production, gear hobbing, gear modifications and a workshop tour of Kapp/Niles in Boulder. For 50+ years the annual WZL Gear Conference in Aachen, Germany, has been the basis for the exchange of experiences and close cooperation between the members of the WZL Gear Research Circle. The WZL Gear Conference takes place for two days which are exlusively devoted to the latest research on gear design, manufacturing, and testing for the North American market. Register at the website*: www.kapp-niles.com/index.php?id=811&L=4*.

August 6–8—CAR Management Briefing Seminars Grand Traverse Resort, Traverse City, Michigan. 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. Seminars include targeted sessions on manufacturing strategy, vehicle lightweighting, 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. CAR MBS 2019 will focus on the auto industry's commitment to change, across the spectrum of technology, strategy, mobility, policy, and manufacturing issues. This August, join us to connect with more than 1,000 stakeholders, representing automakers, suppliers, startups, media, government, and academia. For more information, visit *www.cargroup.org*.

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The Toys That Make Engineering Noise

Matthew Jaster, Senior Editor

Last year, Hot Wheels celebrated its 50th anniversary. While a writing gig in manufacturing and engineering probably sounded surreal to the 8-year-old version of this author, truth be told, he was obsessed with Hot Wheels and Matchbox toys for most of his childhood. Somewhere in a box in the basement there's a 1967 Camaro and a 1953 Corvette that would still bring a smile to this face.

My brother and I spent a great deal of time with Hot Wheels driving around a town we built near a model railroad. These "car chases" were reminiscent of a certain 1970s/1980s television program where Bo and Luke Duke tried to avoid the authorities of one Hazzard County (*The Dukes of Hazzard*). Oh, the memories! The Hot Wheels eventually led to building intricate LEGO sets and designing our own automobiles, spaceships and vehicles.

We spoke to some regular contributors of the magazine to get some feedback on some of the toys that may have influenced *their* career paths. Here's what that had to say:

Ray Drago, chief engineer of Drive Systems Technology, Inc. (DST) said his father was a longshoreman but he was also one of those guys who could build or fix anything so he spent a lot of time in his workshop fiddling with all sorts of tools. He also fixed cars including, and especially, their transmissions.

"In my youth, most cars still had manual transmissions and I recall helping my dad rebuild them in his rented garage. He was more a mechanic than an engineer, but he did know about ratios, numbers of teeth, diametral pitch, etc. I learned these terms from him and was fascinated by the way shifting gears made the car move at different speeds," Drago said.

Drago's parents gave him an old, used Erector Set when he was about 8 or 10 years old. In those days, Erector Sets had gears in them and were often used to build working machines. He used the parts to build lots of different operating toys.

"Building things that moved was great fun and trying to figure out how to make the stuff I built move in specific ways fascinated me. I built a Ferris wheel by following a plan that came with my first kit, but I was much more interested in creating machines that did stuff like steam shovels, steam rollers, and what was my idea then of cool cars!" Drago added.

For resident gear blogger and president of Beyta Gear Service, Charles Schultz, was all about the slot cars in his youth.

"There were several different styles, some with a face gear and pinion drive, others with a 'pancake' motor and 4-gear-system between the motor and the rear axle. Slot cars used to be on TV shows like *Batman* (Bruce Wayne had a huge layout in his mansion). In fact, slot car shops still exist; my friend Eddie Sauer runs one in Loves Park out near Rockford, Illinois."

Schultz also wanted an Erector Set, but never got one so he had to make do with Lincoln Logs and pre-LEGO building blocks. "I also built plastic model car kits; learned to make exploded view assembly drawings from those instructions," he said.

In 2019, the amount of toys and playsets dedicated to STEM fields is staggering. There are plenty of options available to entice future generations in areas like manufacturing, engineering, robotics and automation.

"Building real things rather than just playing with toys or, even worse, video games, causes kids to think. When they think about how something works they are more likely to try to make other things that work," Drago added. "I see this in my own grandkids today. They all (granddaughters and grandsons alike!) have LEGO sets and motors that go with them. It is interesting to watch the sophistication of their 'stuff' increase with age."