gear TECHNOLOGY®

JUN 2016

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JUN 2016

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Vol. 33, No. 4 GEAR TECHNOLOGY, The Journal of Gear Manufacturing (ISSN 0743-6858) is published monthly, except in February, April, October and December by Randall Publications LLC, 1840 Jarvis Avenue, Elk Grove Village, IL 60007, (847) 437-6604. Cover price $7.00 U.S. Periodical postage paid at Arlington Heights, IL, and at additional mailing office (USPS No. 749-290). Randall Publications makes every effort to ensure that the processes described in GEAR TECHNOLOGY conform to sound engineering practice. Neither the authors nor the publisher can be held responsible for injuries sustained while following the procedures described. Postmaster: Send address changes to GEAR TECHNOLOGY, The Journal of Gear Manufacturing, 1840 Jarvis Avenue, Elk Grove Village, IL, 60007. Contents copyrighted ©2016 by RANDALL PUBLICATIONS LLC. No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or by any information storage and retrieval system, without permission in writing from the publisher. Contents of ads are subject to Publisher's approval. Canadian Agreement No. 40038760.

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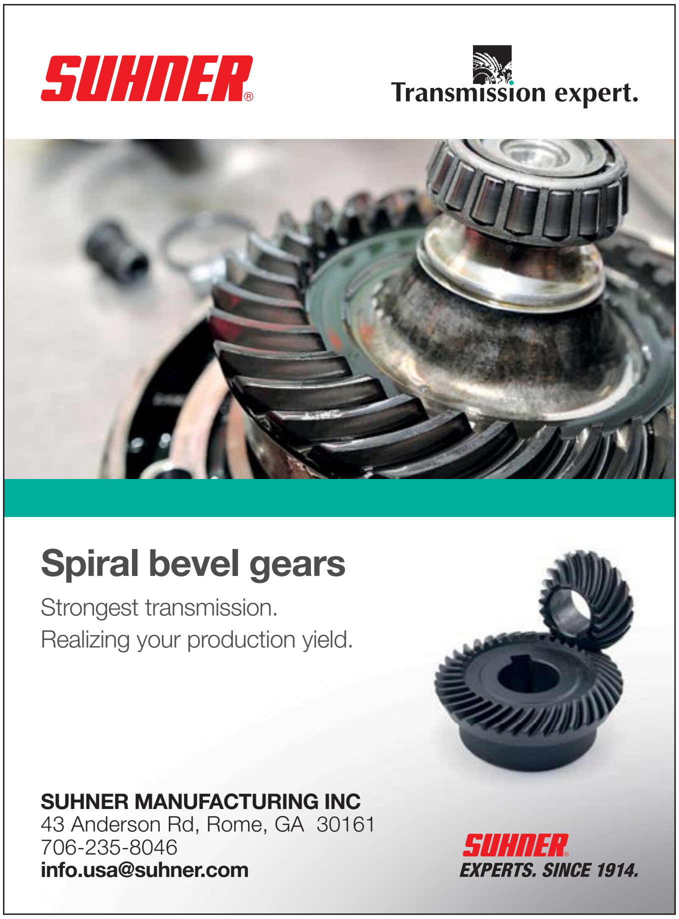

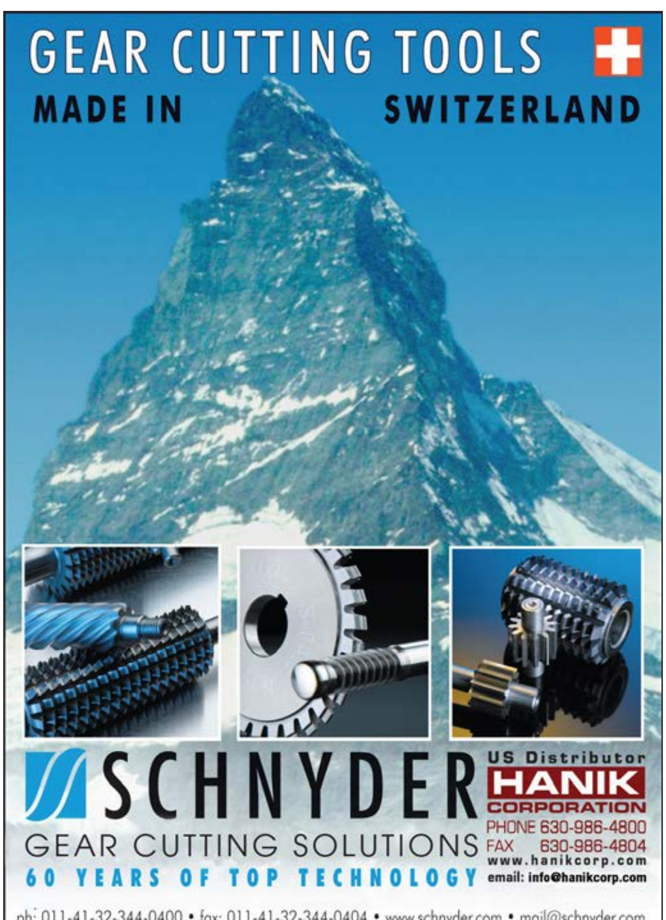

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Vol. 33, No. 4

departments

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Liebherr Performance.

New design possibilities for the micro gear geometry

- The same torque at smaller face width
- Noise reduction

Economical solutions by generating grinding of modifications of the flank

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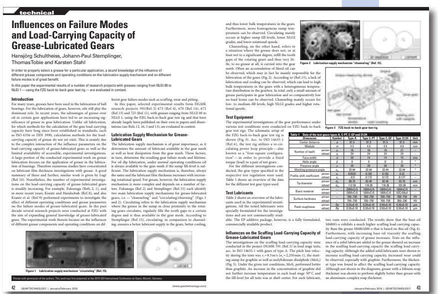
Facebook is another resource that features updates on the ***Gear Technology*** Blog, additional Ask the Expert resources and a quick and convenient way to renew your GT magazine subscriptions.


technical

Influences on Failure Modes and Load-Carrying Capacity of Grease-Lubricated Gears

Hansjörg Schultheiss, Johann-Paul Stemplinger, Thomas Tobie and Karsten Stahl

Unlock the Vault

The GT Library offers more than 2,000 technical articles published in the last 32 years. For a quick, hassle-free way to look up the gear information you need by subject, check out the **Subject Index** at (*www.geartechnology.com/subjects*).

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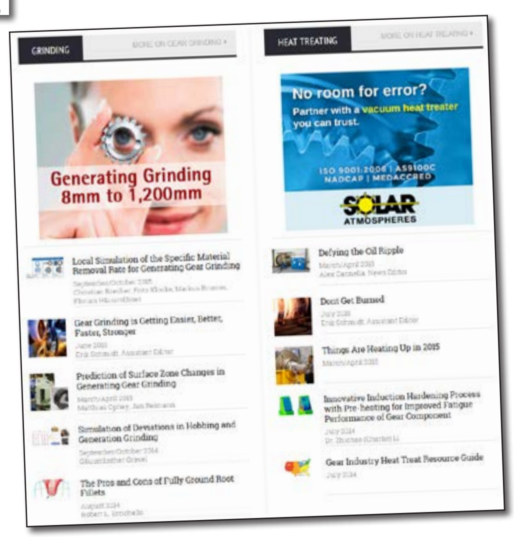
Grinding
Heat Treating



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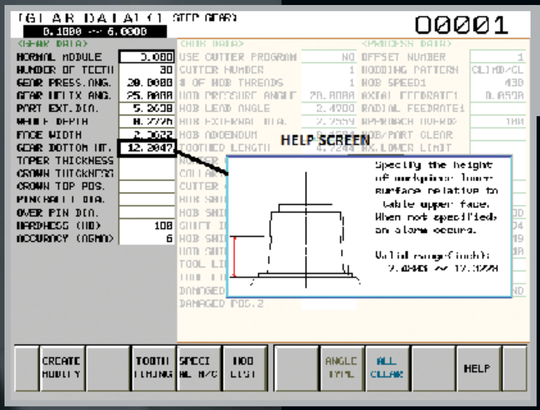
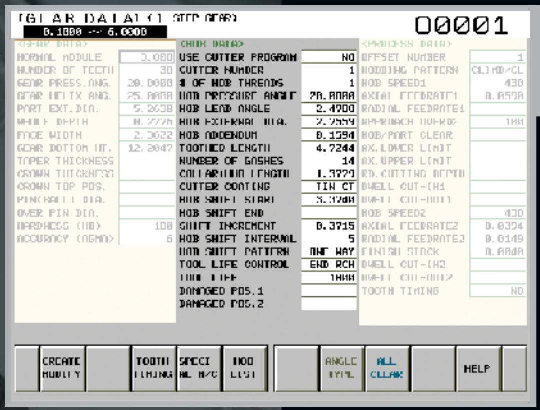
CNC Gear Machine Programming: Easy as 1-2-3



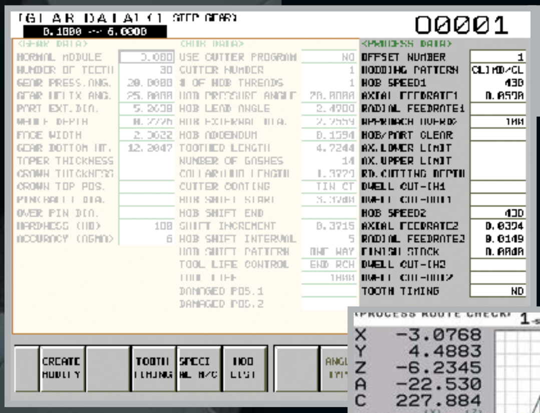
1

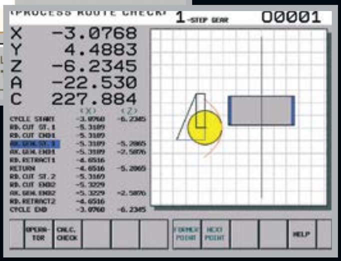
Input Gear Data from process sheet or part print. Input distance from work table to bottom of gear.



2

Input Cutter Data from cutter drawing or box.





3

Cutting speeds and feeds automatically calculated as well as cutter paths.

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For more information visit **mitsubishigearcenter.com** or contact **Sales at 248-669-6136**.

Apologies

Publisher & Editor-in-Chief
Michael Goldstein

I'd like to apologize to the dedicated people working on revisions to the AGMA 925 standard and the Technical Report ISO 15144-1, both of which deal with the issue of micropitting. In the March/April issue of *Gear Technology*, we published an opinion piece in our *Voices* column that harshly criticized the methods for predicting micropitting outlined in ISO 15144-1. The piece, called "Critique of the ISO 15144-1 Method to Predict the Risk of Micropitting," was written by Bob Errichello, whose opinions we have valued (and continue to value) as a *Gear Technology* technical editor for more than 25 years.

What we had hoped to do was educate the gear community about the very complicated failure mode known as micropitting and to highlight the hard work done by volunteers around the world to advance the science of gears.

We never intended to undermine the work of the committees by making this discussion public. ISO 15144-1 may eventually be put forth as an international standard, but there is much work and discussion yet to be done. Many of the same people working on ISO 15144-1 are also involved with revisions to AGMA 925. So specifically, we apologize to Robin Olson, chairperson of the AGMA 925 sub-committee and U.S. delegate to ISO TC 60/WG 6 & 15; Dr.-Ing. Thomas Tobie, German delegate to ISO TC 60/WG 6 & 15; and any other committee members or delegates who may have taken offense.

While I am disappointed that we were a party to exposing these internal discussions, I think there is some good to come out of it. I, for one, have a much better appreciation for the depth of discussion involved in the development of international gear standards. When you use a standard, you don't need to know every bit of research, technology and engineering that has gone into it. But it's clear every bit is discussed in committee, at a depth of understanding that goes far beyond most of us, even those who specialize in gear engineering. The people who develop standards for our industry's benefit are true experts, and they deserve our respect, across the board.

More importantly, they could probably use our help.

I invite you to re-read Buzz Maiuri's *Voices* piece, "Make Volunteering the Norm," from the May issue of *Gear Technology*. Buzz is a senior product/project manager for The Gleason Works, and he is Chairman of the AGMA Technical Division Executive Committee. In Buzz's piece, he describes the importance of getting involved with the technical committees and participating in the development of our industry's standards, information sheets and other technical documents. Whatever your formal education and training, participation on these committees can be a great benefit to you personally as well as to your company.

At one point, Buzz describes a young engineer who joined one of the technical committees early in his career. That engineer was often charged with doing research and working with some of the more experienced experts on the committee. After years of participation, he became an expert himself, eventually moving up to become the vice president of engineering at a very large gear manufacturing company. The probability is that he would not have had the knowledge or opportunity to rise so high in his career had he not participated in the AGMA committee.

If you're curious or ambitious, and seek to obtain knowledge and stature within the field of gearing, participating in AGMA or ISO technical committees is a natural extension in your growth as a gear engineer. In fact, it's more an opportunity than an obligation. No matter what our educational background, the education we receive by working with other dedicated professionals in our industry provides a foundation for our future. As we move through our lives and our careers, we should be looking at opportunities to build on that foundation to grow personally and professionally through our lifetimes.

If you have any interest in becoming one of the experts of the future, get involved today. If your company is already a member of AGMA, I encourage you to get started by contacting Amir Aboutaleb at AGMA (*aboutaleb@agma.org*). If not, then access to this type of lifelong learning and networking is a great reason to consider joining.

Michael Goldstein

Benefits of Asymmetric Gears

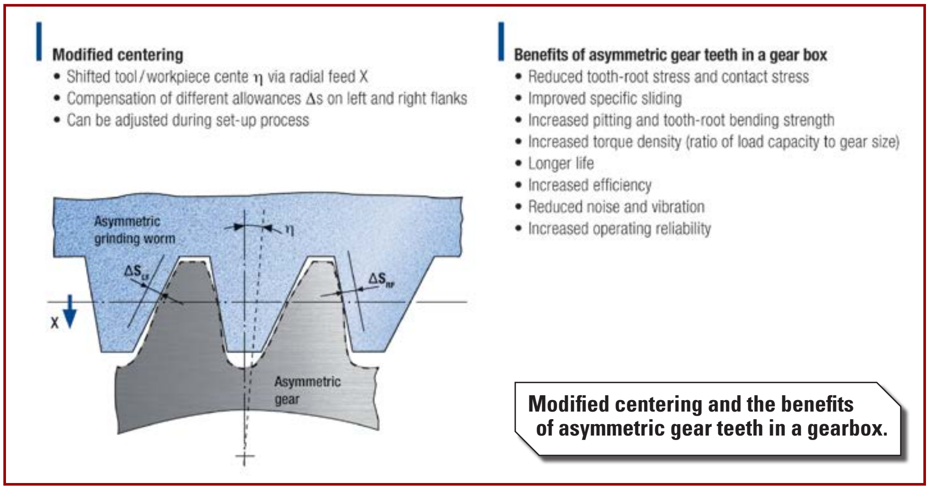
LIEBHERR EXAMINES PRODUCTIVITY AND QUALITY ADVANTAGES

Gear wheels often rotate in only one direction throughout their entire service lives. This applies particularly in the case of cars, commercial vehicles, ships, lifting gear or generators. In the case of these gear drives, the tooth load on one flank is considerably higher than on the opposite one. This means that little or no load is applied to opposite-coast flanks during a relatively short work cycle. An asymmetric tooth shape reflects this functional difference.

"One of the design objectives of asymmetric gear teeth is to improve the performance of primary drive profiles at the expense of opposite-coast profile performance," Dr. Alexander Kapelevich, president of AKGears, explained. He is an expert in the mathematics of tool profiles and other parameters for asymmetric gear teeth.

"Asymmetric tooth profiles make it possible to simultaneously increase the contact ratio and operating pressure angle beyond those limits achievable with conventional symmetric gears," Kapelevich said. Gear tooth stiffness can be significantly improved by means of latitudinal and frontal load-sharing as well as by altering dynamic contact. Tooth-flank load capacity also benefits from an increased pressure angle on the stressed tooth flanks. Tooth-root load capacity is also improved.

The main advantage of asymmetric gears is contact stress reduction on the drive flanks. That results in higher torque density, i.e. ratio of load capacity to gear size. Another key advantage is the opportunity afforded of designing opposite-coast tooth flanks differently to drive tooth flanks. This effectively manages tooth stiffness, whilst at the same time retaining the desired pressure angle and contact ratio of the drive flanks. This allows for increased tooth tip deflection, thus damping tooth mesh impact and resulting in a reduction of gear noise and vibration.



Modified centering and the benefits of asymmetric gear teeth in a gearbox.

Dedicated Tools Required

Kapelevich defines asymmetric tooth-root geometry irrespective of the model of gear rack used, which distinguishes him from other gear technology researchers. Kapelevich's Direct Gear Design approach enables asymmetric gear tooth and tooth fillet geometry to be optimized to achieve maximized performance for specific gear applications. Such an approach of course requires special tools. Once tooth-root geometry has been optimized, Direct Gear Design also defines tool profiles and other parameters. "One of the design objectives of asymmetric gear teeth is to improve the performance of primary drive profiles at the expense of opposite-coast profile performance," he said.

Smart Contouring

Roughing, tempering and subsequent hard finishing (skiving or profile-grinding) have been the industry-standard method of producing asymmetric gear teeth for years. Skiving is effective, although it does not quite deliver maximum gear tooth quality (DIN 6 to DIN 7). Profile-grinding delivers a significantly higher standard of quality, but takes longer than a continuous generating method. Liebherr-Verzahntechnik GmbH developed its asymmetric gear tooth generating grinding method upon customer request. This method combines maximum productivity with superior quality.

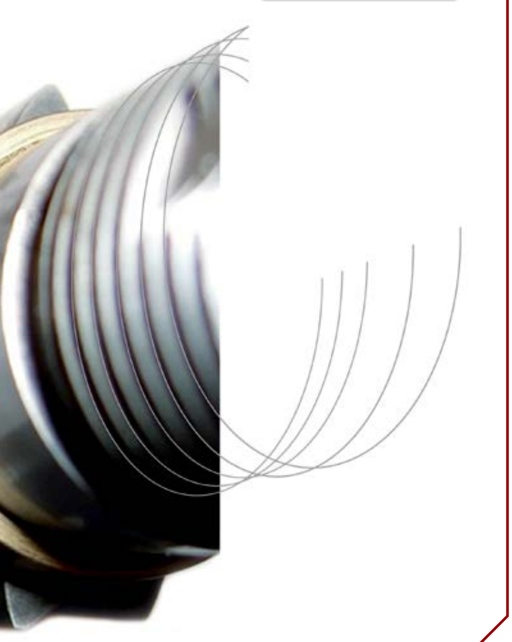
Asymmetric gear teeth however represent more of a challenge in terms of the generating-grinding method, as well as grinding and dressing tools, rather than in terms of the grinding process itself. Developing this grinding method raised a number of issues all at the same time. "We were faced by twin challenges," said Dr. Andreas Mehr from Liebherr-Verzahntechnik's grinding and shaping technology development and consultancy team. "On the one hand we required dressing technology to produce an asymmetric grinding worm. On the other hand we needed to develop the entire grinding process, including centering the grinding worm in the tooth fillet."

Profile Angle Adjustment During Dressing

For dressing purposes the experts developed a software package that can work with both asymmetric and symmetric dressing units. "An asymmetric dressing unit is ideal for serial production purposes. A symmetric dressing unit can also be pivoted as appropriate for prototype construction purposes," is how Mehr describes the corresponding benefits. The machine features a pivot range of up to 7.5 degrees. A major challenge as far as dressing was concerned were the complex mathematical calculations of the degree of pivot travel required by the dressing unit. During the dressing process the diameter of the grinding worm is reduced, which in turn necessitates a profile-angle correction – after each dressing sequence.

A quite different dynamic in respect of tooth-flank contact between the grinding worm and workpiece occurs during the grinding process itself, as compared with conventional, symmetrical grinding processes. Since left and right tooth flank offsets change during the asymmetric gear wheel grinding process, given differing pressure angles,

Asymmetric gear.



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– Steve Souva, Grinding Group Leader, AXLY Production Machining

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this requires electronic correction. This degree of correction is determined by means of modified centering during the set-up procedure. In the case of asymmetric gear teeth, this so-called centering procedure, i.e. centered meshing of the grinding worm with the tooth fillet, has to be slightly shifted and maintained during the grinding process using precision monitoring and control technology.

Asymmetry's Time Has Come

Asymmetric gear wheels will be used more frequently, thanks to this new grinding process. "Their benefits are obvious and have been generally known for a long time," said Mehr. "Dr. Kapelevich's calculations have facilitated a simple interpretation of the macro-geometry involved. The generating grinding process can now be reliably managed as well. At the same time our customers can use the generating-grinding process for initial prototyping purposes without any great effort, the software package is up to the job. Customers need to invest in an asymmetric dressing unit once they get to the serial production stage." It seems that asymmetric gear wheels' time has come at last.

For more information:
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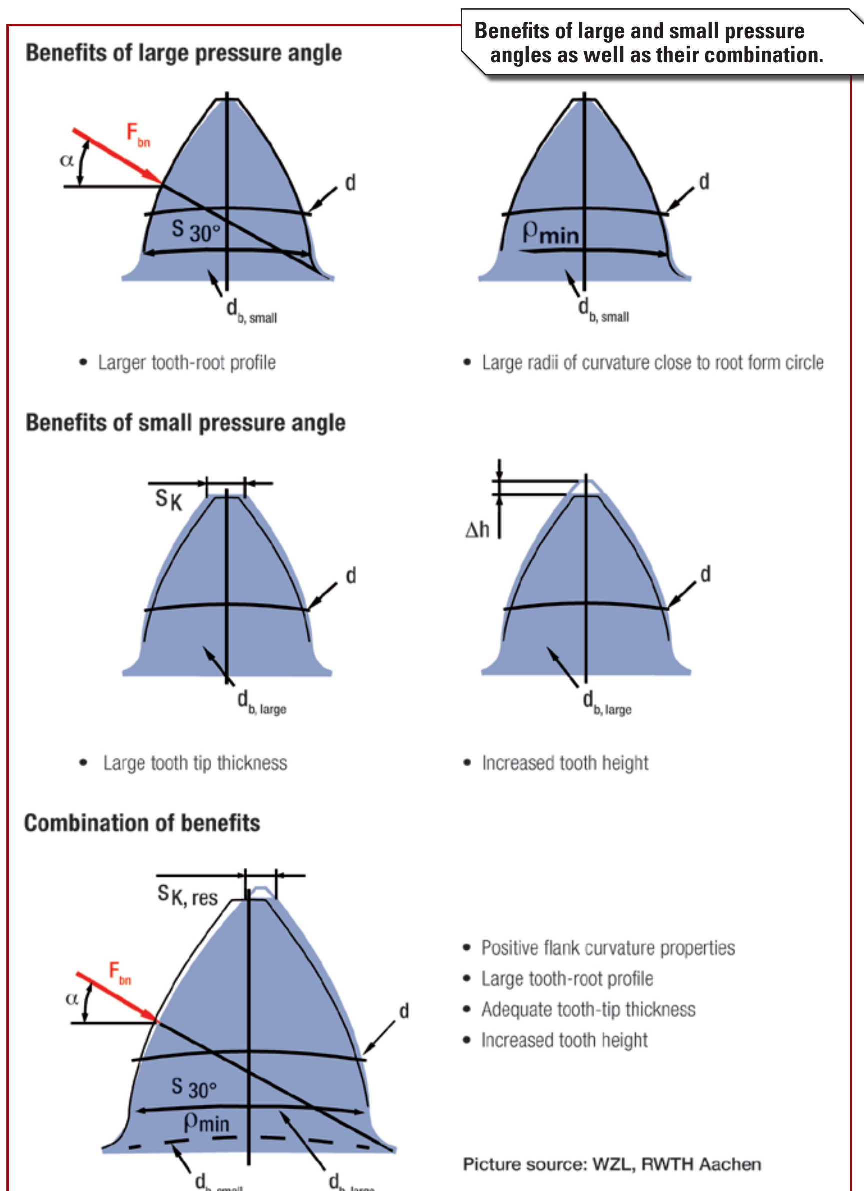
www.liebherr.com



ARROW GEAR'S COMMITMENT TO QUALITY

WHEN FAILURE ISN'T AN OPTION

When you're hovering at 5,000 feet, gearbox failure is simply not an option. In fact, few applications demand the quality and precision crucial to the helicopter industry.

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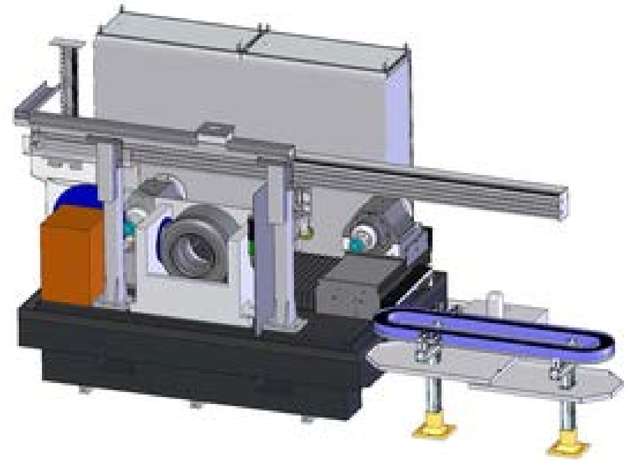
GMTA Präwema SynchroFine 205 HS

FEATURES DIRECT-DRIVEN, DIGITALLY CONTROLLED SPINDLES



German Machine Tools of America (GMTA), now offers the Präwema SynchroFine 205 HS gear honing machine featuring direct-driven, digitally controlled spindles for the tool and the workpiece, enabling precise, rigid synchronization. The Präwema Honing gear finishing process produces quality comparable to grinding results for spur and helical gears, as well as shafts. The machine's software checks the stock allowance and workpiece runout and then optimizes the x-axis approach distance. Measuring the workpiece does not affect the cycle time and the process can reduce cycle times by three to five seconds.

The machine features a pick-up design to enable automation. The workpieces and dressing tools are loaded and unloaded by the workpiece spindle. The large X-axis travel enables placement of additional stations adjacent to the loading/unloading station inside the machine, such as a two-flank roll-checking device. External robots and conveyor systems can also be integrated by GMTA engineering.

The honing machine is constructed on a natural granite bed to promote stability and control thermal fluctuations. The x and z axes are equipped with linear motor drives. The cutting tool is clamped with a hydraulically operated system and the tool spindle can be swiveled into a vertical position, enabling easy access. Additional options are available for machining oversized drive shafts as long as 850 mm and the Präwema SynchroFine 205 HS-D model, equipped with two spindles, is offered for further reduction of cycle times.

For more information:
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Doimak RER Series

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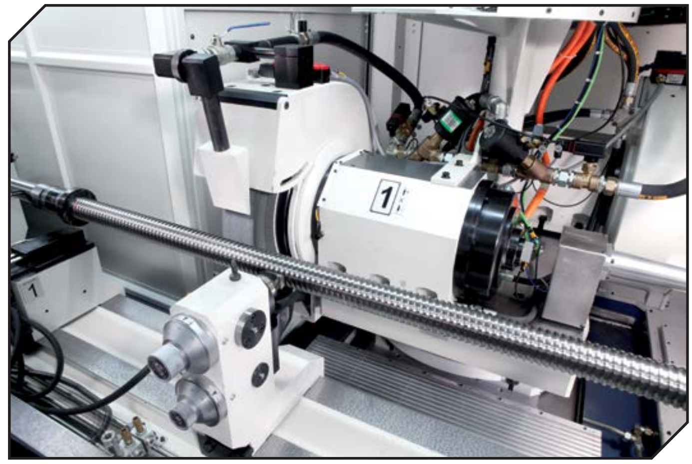


At IMTS 2016 (Booth N-6698), Doimak will display the RER-G Combi 500 Grinding Center with Fanuc CNC and two wheelheads. Designed for grinding OD, ID and threads, the RER-G is equipped with a fast automatic changing grinding head by means of a rotary base turret enabling multiple grinding operations in a single setup. The RER series offers a compact design, external/internal thread grinding in fully automatic transition, OD and gear grinding with optional CBN or peeling and b axis for tapers, flexible multi-task grinding, 2-axis contour dress or full form. The machine is available in a two or three wheel head design.

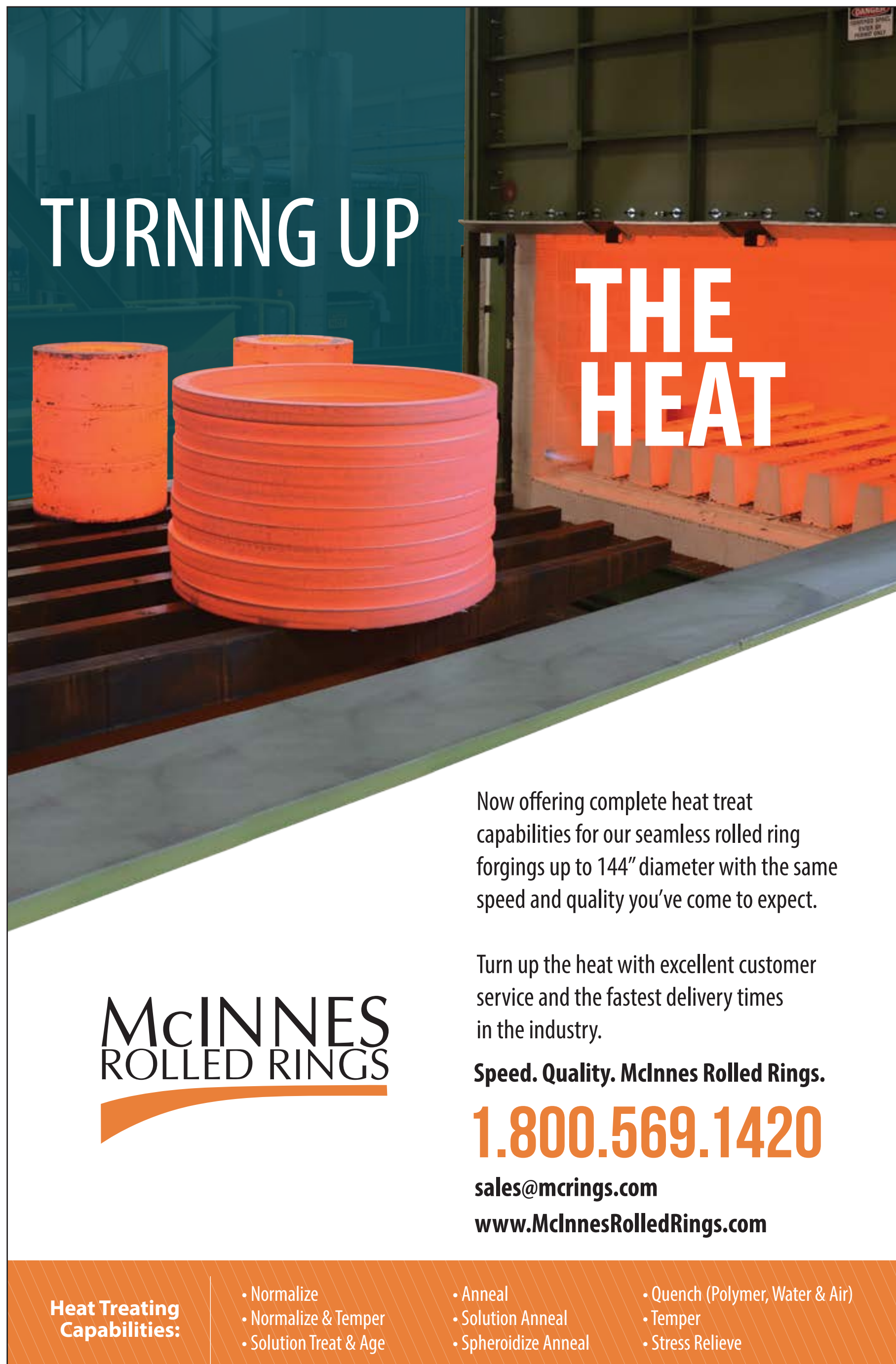
Additionally, Doimak recently delivered two REN-T spline and gear grinding machines for the machining of cycloid, helical and spur gears. Doimak tested and delivered these models that included integrated probing technology for gear inspection. The machine inspects gear diameter, run-out or teeth alignment just after grinding takes place, reducing machine setup times and providing a more efficient overall machining process thanks to the integrated inspection technology. The following is a brief rundown of some of Doimak's other machining capabilities:

Thread Grinding

Thread grinding machines for all types of threading technology is the most representative product line of Doimak. The latest CNC technology is implemented with built-in drives and linear motors. These machines include a wide range of spindle designs offering optimum stiffness and damping response. Any type of profile can be dressed thanks to the flexible contour dresser, which also accommodates plunge forming rolls. Multi-ribbed wheels are used for improving process productivity and mass production machines are equipped with robot or gantry type loaders. They offer higher degree of process automation thanks to different probing and component measuring solutions.

Cylindrical Grinding

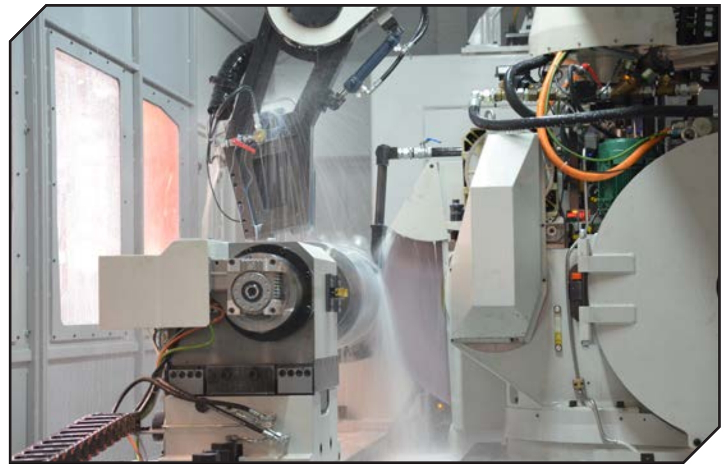
Doimak provides solutions for a wide range of cylindrical shaft grinding appli-



cations including extrusion screws and barrels, power generation, printing and more. Different disposition of wheels, including OD/ID solutions with multiple grinding heads mounted in a single swiveling base are available for any type of application requirement. Productivity is improved through the use of in-process measuring systems, steady rests and wheel contact sensors.

Gear Grinding

Doimak has also developed several machining solutions for the gear and transmission field. Based on the RER thread grinding platform, straight and helical involute gears can be ground using latest CNC technology which includes built-in drives and linear motors. Involute, as well as cycloidal gear profiles, are automati-



cally calculated according to standard gear parameters. These machines offer a higher degree of process automation thanks to different probing and component measuring solutions.

Automotive

Automotive components such as steering racks, engine and transmission components and crankshaft and camshafts require the latest machining advances. Doimak provides in-process measuring gauges and high performance tools in order to optimize productivity. Mass production machines can be equipped with robots or gantry-type automatic loaders. In most cases, these machines are equipped with hydrostatic drives in order to avoid wear in moving components minimizing production stops due to maintenance requirements.

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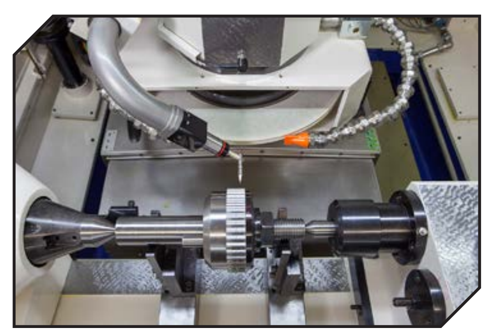

Saint-Gobain Abrasives

INTRODUCES NORTON CENTURY45 CENTERLESS GRINDING WHEELS

Saint-Gobain Abrasives has launched a new line of centerless grinding wheels to its bonded abrasives portfolio.

The newly developed Norton Century45 centerless bond platform features an exclusive chemistry that greatly improves grain retention in the wheel. Better grain retention means wheels are constructed with more porosity for a given hardness. This translates into wheels having a hard grade with the performance of a softer grade, providing a range of benefits.

Norton Century45 wheels are available with ceramic, aluminum oxide, silicon carbide grain and abrasive blends to maximize user grinding safety and efficiency. These wheels reduce cycle times by up to 50 percent, improve stock removal by over 30 percent and increase wheel life from 30-100 percent versus standard products currently on the market.

Norton Century45 provides a continually sharp wheel face that achieves over 30 percent more stock removal, reducing grinding times through fewer passes to achieve optimal results. Operators will generate more parts through reduced production cycle times when using Norton Century45 wheels.

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The Comprehensive Gear Grind

Samputensili Develops Alternatives to Conventional Gear Manufacturing Solutions

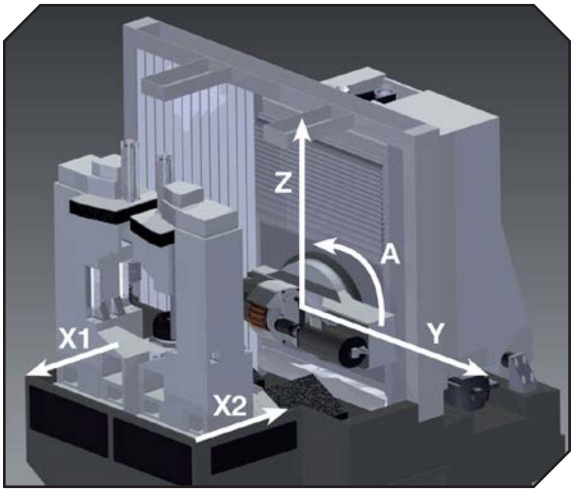
Matthew Jaster, Senior Editor

Looking for some simple yet useful advice heading into IMTS 2016? Never second guess your machine tool investment. Flexibility is a mandatory requirement in gear manufacturing today. Accuracy, reliability and efficiency must improve with each new machine tool purchase. Innovation is always the end game. So it comes as no surprise that IMTS 2016 attendees will have plenty of gear grinding technologies to consider this fall.

"There has been an increasing demand for noise reduction as nine and 10-speed automatic transmissions have become the norm," said Enrico Landi, CEO of Samputensili. "Gear manufacturers are challenged to develop new technologies to handle higher speed transmissions, noise reduction and provide solutions that meet all customer requirements while keeping production costs in mind."

Samputensili recently shared some of its machine tool innovations including the new SG 160 Sky Grind and the GP 500 HL (a combined machine allowing the user to grind on a long shaft, and in one set-up, a spline or gear, the OD diameters, and the related shoulders) with ***Gear Technology*** as well as a rundown of the machines available today through Star SU in the U.S. grinding market.

Double work spindles, driven by linear motors, make it possible to obtain a fast workpiece change and a chip-to-chip time under two seconds.



The G 160 is an innovative, patent-pending machine featuring a very stiff and unique architecture and only three stacking axis (Y, Z, A) granting the highest dynamic stiffness and a new virtual Y-axis.

Manufacturing Challenge Accepted

How are the latest gear grinding machines solving the manufacturing challenges that occur on today's shop floor? Samputensili is focused on a few key areas according to Roberto Bagni, product manager. "The main features for customers investing in the grinding process include the improved quality of 'silent' gears, a reduction in cycle times, a precise and flexible dressing unit for profiling the grinding worm wheel, a user-friendly and safe HMI and a total savings on investment, consumables, tools and energy."

Noise reduction

Bagni said that extremely high accuracies are the norm for today's hard-finishing technology. "There are several other aspects that help to improve noise characteristics including topological grinding, superfinishing and surface topography."

With topological grinding, the idea is to apply specific modifications to the grinding wheel in order to compensate the natural twist effect and to obtain the desired profile and lead.

Superfinishing divides the grinding wheel in two sections: grinding and polishing. In the grinding area, a standard ceramic bond is used for the roughing and finishing process. In the polishing area, a resinoid bond is used for the superfinishing operation. Roughness even below 0.1 Ra is achievable with this process.

Surface topography controls the surface pattern generated on the teeth during grinding, through the definition of proper dressing and working parameter, in order to avoid the generation of any malicious resonances that could negatively affect the noise level.

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Decreasing cycle times

In the last decade, the grinding cycle time has decreased significantly. "This drastic reduction is due to the new machine features which make it possible to reach a much higher cutting speed (from "old" 35 m/sec to the present, and also higher forecasted in the near future, 80 m/sec) and dress the worm wheel with a practically unlimited number of starts," Bagni said. "Another important role has to be attributed to increasing the coolant pressure up to 250 and more psi solving the problem of cleaning the grinding wheel faster, consequently granting a longer wheel life," he added.

Reducing idle time out of the grinding process

The goal of global machine tool manufacturers is to offer machines where the non-productive idle times are minimized. For example, dual work spindles are utilized to reduce part changeover time including alignment. "The dressing tool axis is located as close as possible to the working position. This not only grants a precise wheel calibration, but it also drastically reduces the dressing time," Bagni said.

The flexibility to use the same machine for various part sizes

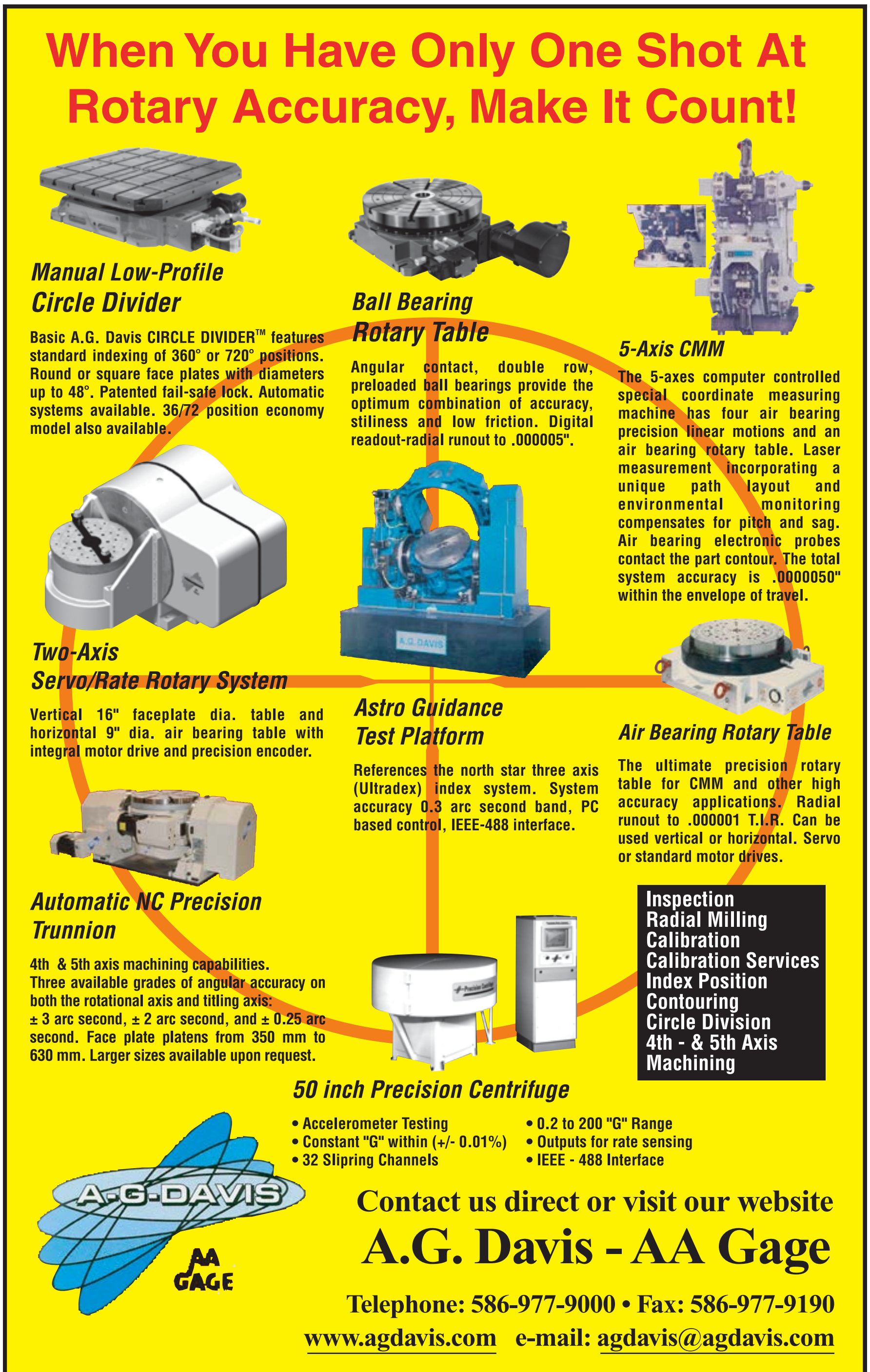
Samputensili grinders are ergonomically designed to allow ease of workpiece changeover. These grinders also have the ability to do gears and shafts on the same machine with easy changeover. As for tailstock set-up, Star SU provides a fitting taper morse-type while the clamping force can be changed and stored in the part program through the CNC. The use of quick-change tooling can save considerable changeover time.

Machine Considerations

So how are some of these grinding advancements applied to Samputensili's equipment? Through its relationship with Star SU, there are at least four machines available for the U.S. grinding market including the G 160, SG 160, GP 500 HL and the GW 3600 H.

G 160 "Wet Grind Version"

A new concept for high-productive grinding of gears up to 160 mm diameter with double work spindles, where



The option to grind on the same shaft and in the same setup is a feature of Samp's GP 500 HL "Combined."

Skive-hobbing did not succeed in producing transmission gears because the cutting edges created by the hob form a regular pattern (feed and profile scallops) on the gear flank. This is unacceptable as for durability and noise (left). This is one of the reasons why grinding has become almost mandatory as a finishing process. The smooth but irregular surface grants a high load capability, high durability, and quiet running (right).

separate X1 and X2 axes (driven by linear motors) replace the rotary turret and make it possible to obtain a fast workpiece change and a chip-to-chip time under two seconds.

The G 160 features a very stiff and unique architecture and only three stacking axes: Y, Z, A granting the highest dynamic stiffness and a new virtual Y-axis. It allows high thermal and mechanical stability due to the free swarf disposal area located underneath the machining area and to the transversal chute for oil and swarf return. No additional axis is needed to perform the dressing cycle. The dresser is mounted on the X1 axis slide for minimized interaxis errors. An acoustic emission sensor is offered for easy setup and multi-rib dressing capability.

SG 160 "Sky Grind"

The same concept as the G 160 is the SG 160 with a brand new, highly sophisticated dry-hard-finishing, better known as sky-grinding. "For decades in the transmission industry, the gear manufacturing process, starting from the raw material, has required the following steps: 1) soft-turning, 2) soft-hobbing the gear teeth, 3) deburring, 4) hardening, 5) hard-turning and lastly, grinding the gear teeth," Landi said. "The reasons why gear grinding has been expensive so far, is not just because of machinery and tooling costs. A major contributor to cost increase is the use of oil as a coolant in the process."

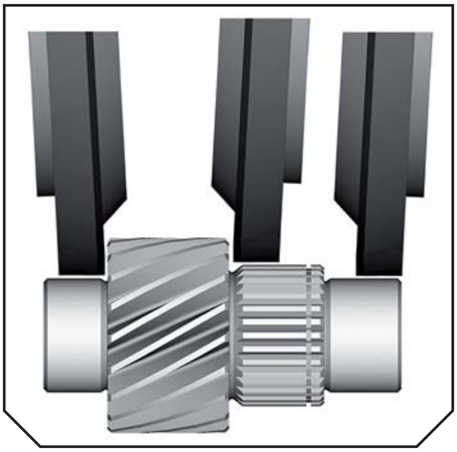
Aside from the production cost, the oil creates costs throughout its life cycle, starting with huge additional investments for the extra installation in and around the machine, automation to catch and gather dripping oil from components and the necessary handling systems and equipment to return the oil into the coolant circuit.

"All of these units consume valuable space," Landi said. "A typical installation for gear grinding requires less than half the footprint necessary for the grinding machine itself. Much more room is used for installation of all the additional equipment around."

Grinding automotive transmission gears are mostly done in two steps: roughing and finishing. During roughing, around 80 percent of the total material is removed and the gear flanks are cleaned by finishing. On the other hand, technologies exist that can remove a high amount of hardened material without any oil and without heat on the workpiece surface.

Hard turning is one example, and it has become a state-of-the-art in the bearing manufacturing industry. In gear production, hobbing of hardened gears with carbide tools (or skive-hobbing) is currently used without oil, even in mass production. Steering pinions are a typical application.

The logical next step was to combine the removal rate of the dry skive-hobbing with the geometric accuracy and surface quality of the dry finish grinding process. Samputensili has addressed this challenge by not only developing this dual technology but also by creating the SG 160, to run this process for automotive mass production.



Samputensili has introduced a fully automatic grinding wheel changing system complete with a grinding wheels magazine up to five stations.

GP 500 HL

Star SU, following up the strong demand for implementation of the OD grinding process, has made a decision to introduce the possibility to grind on the same shaft, and in same set-up, also the exter-

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nal diameters and the related shoulders as well with the GP 500 HL.

On the two spindles, now dedicated each to a different operation, are two grinding wheels, one for the toothed part of the job, and the other for the external grinding. Spindle variants with different power outputs and speeds are offered for different manufacturing tasks (ceramic or CBN), fast format changes via quick-change adapters and modular software. The machine can be supplied with an in-process Marposs control for both diameters and shoulders.

The wheel could be slightly angularly positioned and dressed to achieve a better finishing, while grinding both diameter and shoulders on one side of the shaft. "The big advantage is that the Samputensili wheel head can be rotated 180 degrees upwards thus allowing the same side of the wheel to grind both shoulders, on the right or on the left flank, and the head rotation takes only few seconds," Bagni said.

This combined machine could be the right solution for many job shops, specializing in grinding technology, giving them the possibility to completely finish the part after heat treatment. "This achieves a real cost reduction by having less machines involved in the final production process while reaching a superior quality level," Bagni added.

GW 3600 H "Wheel Magazine"

The GW 3600 H thread grinding machine is able to grind plastic extrusion screws, as well as any other type of screw, from solid, with a total length up to 3,000 mm. Built with the same concept of stiffness, precision and high rigidity common of all the smaller size Samputensili machines, this grinder includes: an oversized 35 kW motor spindle complete with a wheel automatic balancing unit, a Heidenhain direct measuring system for radial and axial movement on high precision linear guides with pre-loaded roller cages, a fixed steady rest, self-centering, three points, hydraulically-operated for automatic movement, with high accuracy

The GW 3600 includes an oversized motor spindle (35 kW), complete with a wheel automatic balancing unit integrated in the main spindle body, located in the machine column with axial and radial movement.

and repeatability down to 3 µm or an innovative migrating steady rest, moving on dedicated linear guides, that could follow the dressing wheel motion from the opposite site of the part.

In addition, the HMI includes a wide range of different processes carried out thanks to specific and reliable software able to perform variable pitch, taper and barrier screws in all possible configurations. "Up to now, the only possible limitation was the need to change the grinding wheel according to a completely different shape of the workpiece," Bagni said. "Samputensili has introduced a fully automatic grinding wheel changing system complete with a grinding wheel magazine offering up to five stations."

Next Stop IMTS 2016

The positive feedback received on these grinding concepts like combination machine technology and sky grinding provides a new way of thinking about machine tool purchasing decisions, according to Landi. "This confirms that these new processes will transform the production of transmission gears in the long run."

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Hail to the Quick-Change King

Quick-change capabilities are far and away the most demanded feature for workholding tools, and everyone's finding their own niche to fill.

Alex Cannella, News Editor

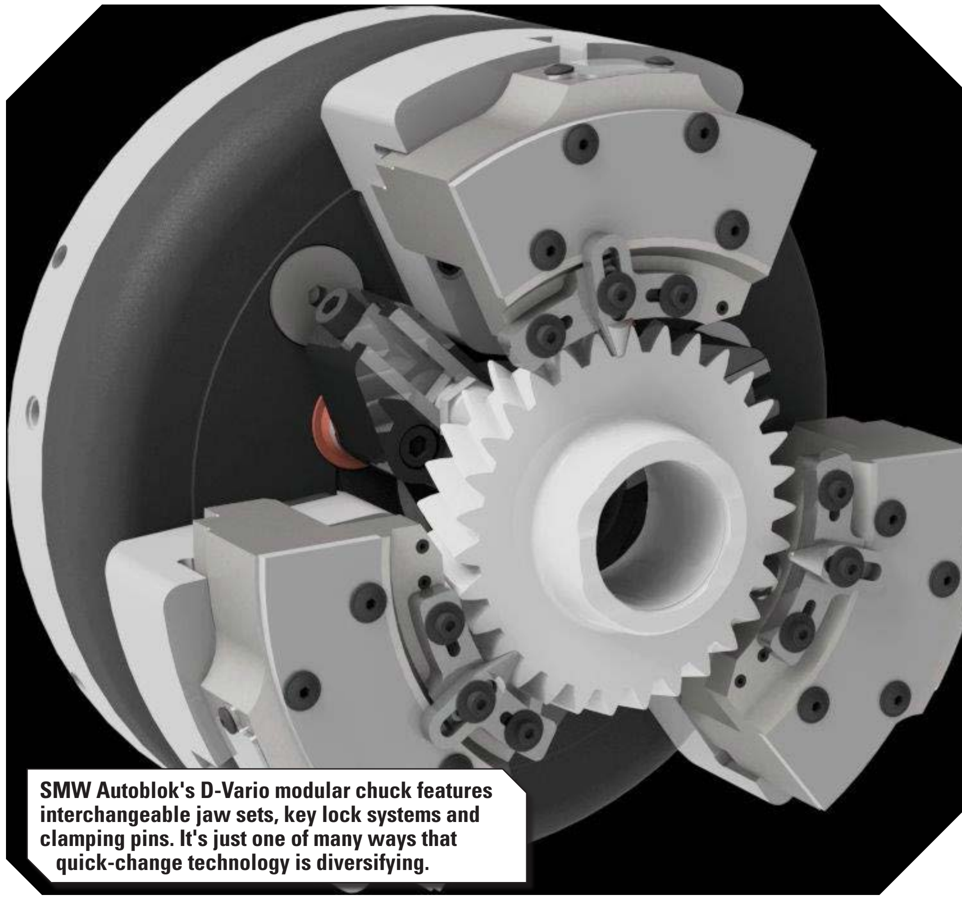
It's the year of the quick-change tool. From chucks to mandrels, workholding manufacturers across the industry are seeing a continuing trend from their customers: give us more quick-change. This year is no different. In fact, quick-change may be gathering even more steam, as manufacturers are seeing a universal spike in demand for quick-change capable products.

"The biggest thing our customers want is they want their spindles to stay running," Tim Zenoski, global product director for workholding at Gleason said. "And they want the workholding to be completely tool-less or something they can change over in minutes or seconds."

This isn't a new phenomenon. Quick-change has been gaining steam for some time, but now, bigger than ever, it's on everybody's lips. For everyone we talked to, it was the number one thing their customers were requesting. It's an increasingly common mantra these days to "do more with less," so it shouldn't come as much of a surprise that quick changeover solutions, which scratch that exact itch, are hot right now.

"It all comes down to how many dollars it costs to run a machine for a period of time, and how efficiently that machine can run/produce workpieces during this period," David Jones, precision workholding manager at Emuge, said. "In any light all companies look at this value, and machine uptime is utterly important to all of them. This is where quick-change, or even part family adaptability, come into play."

But there's more to quick changeover's current popularity than just natural appeal. Economic factors are also coming into play. With some industrial sectors taking hits (like, say, the energy sector), some companies are left in the lurch with a sudden lack of business, and many of them are turning to quick-change products to try and make up for losses caused by rough markets and economic conditions by streamlining their processes to cut expenses elsewhere.



SMW Autoblok's D-Vario modular chuck features interchangeable jaw sets, key lock systems and clamping pins. It's just one of many ways that quick-change technology is diversifying.

"Every time the economy takes a downturn, we see a renewed interest in 'how can we make it faster, better, and change over quicker?'" Larry Robbins, vice president of sales and marketing at SMW Autoblok, said. "Well, right now, there's certain shops that are in dire straits, and they're looking for any way to increase profitability...and that's where quick-change comes into play. Whether it be a chuck or an entire system, interest peaks in times like this."

While quick-change manufacturers are seeing increased demand for their products, they're also seeing more demanding requests. Customers are constantly asking for much the same of what's being demanded of them: better products that can do more with less. According to Robbins, customers are asking for products that are "better, faster, smarter."

"That's kind of hard with chucks," Robbins said. "Because there's really nothing smart about a piece of steel. A piece of steel is a piece of steel is a piece of steel, all day long."

It's a bit difficult to imagine how to reinvent something as simple as a chuck. Quick-change workholding has been around for decades now, and pretty much everyone manufactures a quick-change capable product of some kind,

> "It used to be there would be people coming in every time you change the workholding out who are just specialists. And the days of that are gone." **Tim Zenoski,** *Gleason*

Spline workholding is just one of the options provided by Positrol.

and with so many competent options already on the market, the question becomes: how do you innovate a piece of steel? How do manufacturers differentiate themselves and stick out from the crowd?

Companies are taking a number of different approaches in carving out their niches. SMW has put together several products with additional convenient features thrown in. Take their sealed chuck technology, for example, which is a feature on many of their products. SMW's sealed chucks do everything their other chucks do, but are also "permanently greased" and offer 2000 hours of labor without maintenance. While Robbins says that a lot of people are used to putting in grease every eight hours or so during production, they always get customers that are less familiar with the process, some of whom don't even realize they need to grease the chuck in the first place. SMW's sealed chuck feature eases the fuss of having to constantly grease your chucks while removing one potential way to meet with disaster.

SMW has also seen success with several of their Type D series diaphragm chucks, such as the D-Vario, a modular chuck. The chuck comes with extra jaw sets, key lock systems and clamping pins that can be swapped out with each other for different size projects. Also convenient is SMW's online D-Vario Configurator, which crunches the numbers to tell you which parts you need for a certain size gear.

Gleason has doubled down on the faster part of the "better, faster, smarter" demands customers are making. The new Quik-Flex Plus workholding system allows for a changeover in less than 30 seconds. It's a modular product, with a base part permanently installed in the work spindle and different workholding upper parts that can be swapped in and out of the base almost like ratchet bits.

The process is fast and simple.

Simplicity is another factor Gleason has been focusing on, which according to Zenoski, is also appealing to their customers.

"A lot of our customers in the industry lack the experienced tool setup people they once employed," Zenoski said. "In the past workholding changes would be made by dedicated personnel that would cater the machine each time workholding changes had to be executed. But these days are long gone. Without setup specialists, a straightforward workholding system has become more appealing than ever. The lack of specialists, as well as the industry's dearth of young talent in general, makes it imperative that new systems can be easily picked up by untrained personnel. Hence, anything more user-friendly is welcome to get new hires up to speed faster."

Without those specialists, it's easy to see the appeal of a straightforward workholding system that can be easily picked up by untrained personnel. A lack of specialists, as well as the industry's current dearth of talent as a whole, means that making anything more user friendly can get new hires up to speed faster is always going to be appealing.

Positrol is a specialty manufacturer that's always working small orders across a high variety of industries, and they've diversified themselves accordingly. They have 25 different products (including, yes, quick-change options), and if none of those are what you're looking for, they regularly come up with custom solutions for any specialized tasks you need done. They use a six step process where they look at your needs and technical requirements, determine the best tool for the job, and then manufacture and test it upon approval.

"We specialize in 25 different areas," Eric Weber, VP of sales at Positrol said. "Which gives us a very high degree of confidence that we can tackle any job."

Hainbuch, meanwhile, has seen success with their line of mandrels.

"Most people for years thought [mandrels were] a weak workholding solution, and we've proven that you can

Hainbuch has seen success with their line of ID mandrels.

clamp IDs just as well as ODs," Larry McMillan, Great Lakes regional sales manager at Hainbuch, said.

Hainbuch's overcame the mandrel's reputation with a different, stronger design that combines different materials and a new clamping system. Where most competitors use spring steel for their mandrels, Hainbuch is utilizing vulcanized segments made of solid steel. They also have opted to use parallel clamps, which provide grip force down an entire piece and addresses one of mandrels' biggest weak points. The parallel clamp gives Hainbuch's mandrels an advantage over even OD chucks in some situations, as it allows the mandrel to provide a solid grip without clamping down on part of the outside of the product.

Hainbuch has also developed a system that allows you to not only swap out different size tools, but also switch between a mandrel, a collet and a three-jaw, giving their system extra versatility without compromising changeover time.

But even as they work to produce new solutions to make other companies operate more efficiently, workholding manufacturers are also finding new ways to improve their own processes. From new

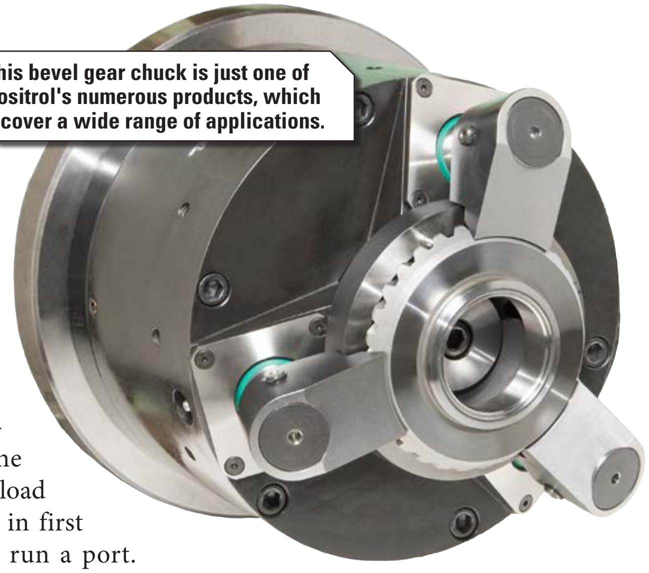
> "We're a designer and manufacturer, just like our customers. So we deal with the same issues that our customers deal with. So we live and breath their life, as well."
> **Eric Weber,** *Positrol*

software to equipment, workholding manufacturers are often looking for better ways to deal with many of the same issues their customers want solutions for.

"We're constantly reinventing ourselves, because we have to," Robbins said. "If we become complacent and we don't constantly innovate, then we're just another person in the game, we're just another person supplying a chuck. We want to supply a solution. We want to give a customer the ability to come to us, say 'here's the issues I have in my facility, here's the 15 ports we're having a problem with, what can you do to help us?'"

One upgrade SMW has incorporated is *Esprit*, a program that takes virtual prototypes and simulates the roughing and cutting process on them. The program allows SMW's engineers to directly upload a product and select the proper tool for the job, then shows a complete simulation of the manufacturing process. Once the simulation checks out, it's off to the cutting tools. For the particularly cautious, you can double check on the physical machine by using a "no touch" run to make sure the process is working as simulated.

"Adopting [*Esprit*] has taken our programming time and cut it at least in half," Robbins said. "It's allowed us to be proactive to customers' needs, so if a customer needed reduced delivery time, it allows us to create a program and program offline. And someone can program at night, download it, and someone can come in first thing in the morning and run a port. Before, somebody had to stand at the machine and program."



This bevel gear chuck is just one of Positrol's numerous products, which cover a wide range of applications.

Gleason, meanwhile, is working with modular systems for many of their standard product lines. Over the years Gleason has developed automated systems for design to manufacturing to ensure consistent execution.

"Rather than redesigning workholding every time for an application that is slightly different, we build from our modular solutions to perfectly fit customers' requirements. It's simplifying and perfecting the product to the point where our engineers can concentrate their efforts on the more complex tasks."

Some manufacturers, such as Positrol, are even designing their own equipment to improve their workflow, which makes sense when you think about it.

"We're a designer and manufacturer, just like our customers," Weber said. "So we deal with the same issues that our customers deal with. So we live and breath their life, as well."

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Workholding companies are essentially manufacturers that supply other manufacturers, and it's not much a surprise that they have many of the same needs and wrestle with the same issues as the people the sell to, including the need to become more streamlined and "do more with less." For Positrol, the answer to that problem is the same as it is for everyone else:

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Hainbuch touts mandrels that can compete with OD chucks without gripping the face of the gear.

"It's an increasingly common mantra these days to "do more with less," so it shouldn't come as much of a surprise that quick changeover solutions, which scratch that exact itch, are hot right now."

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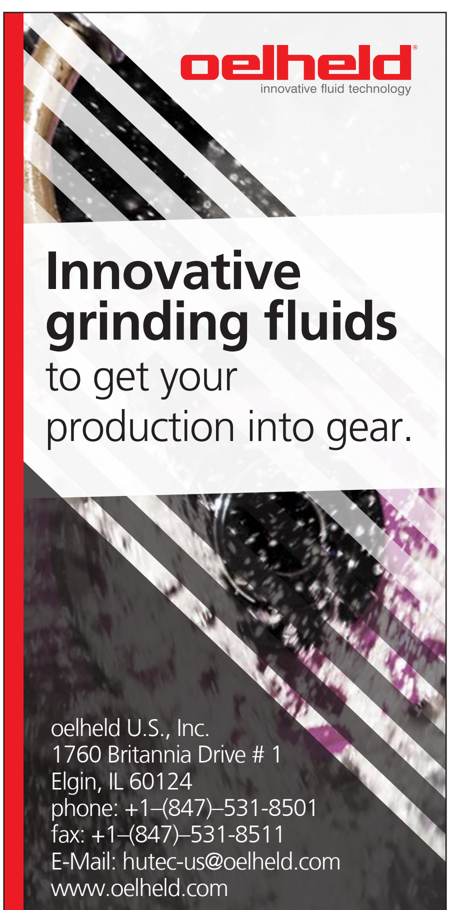
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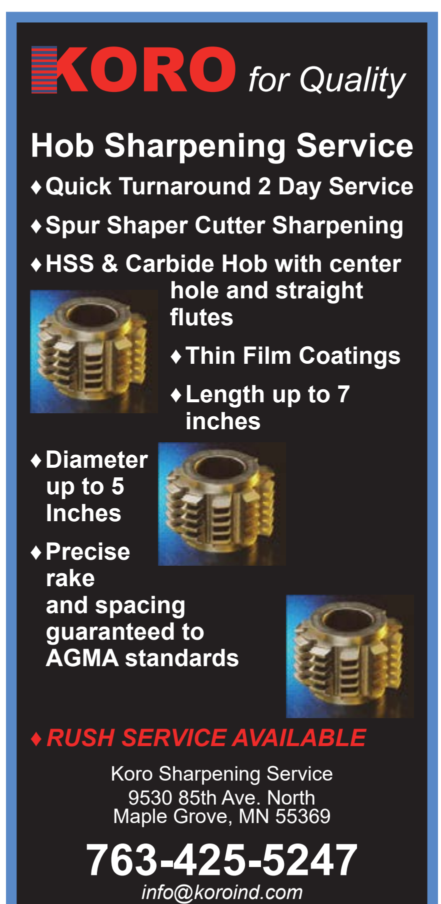
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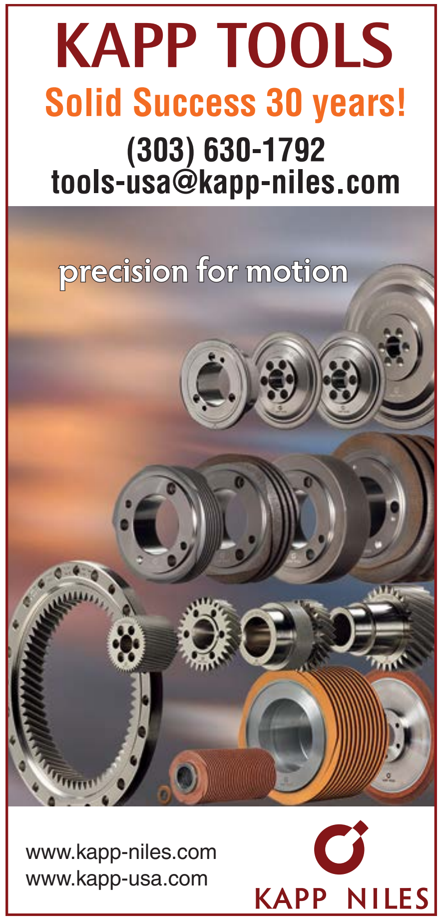
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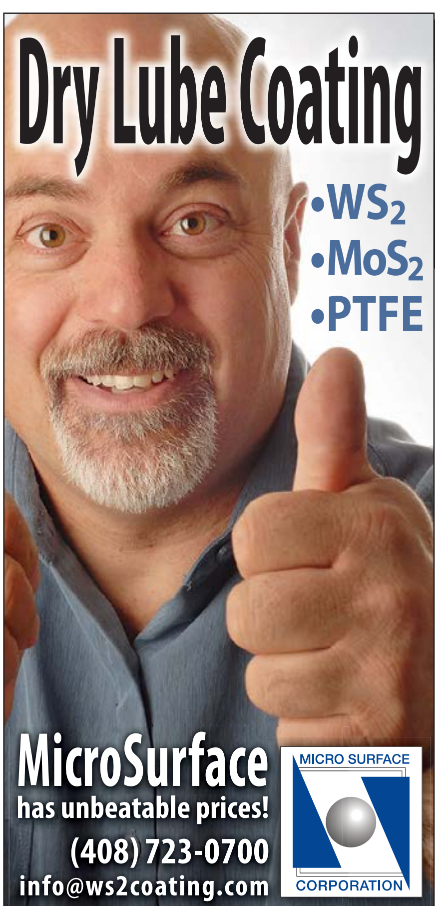
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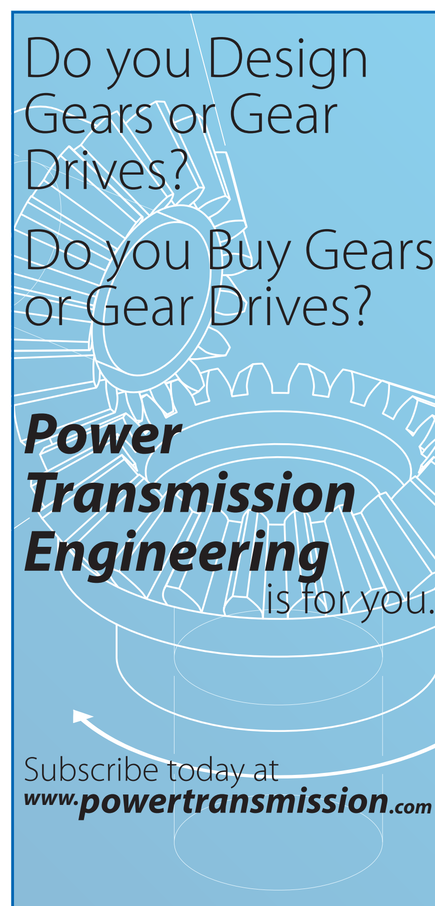
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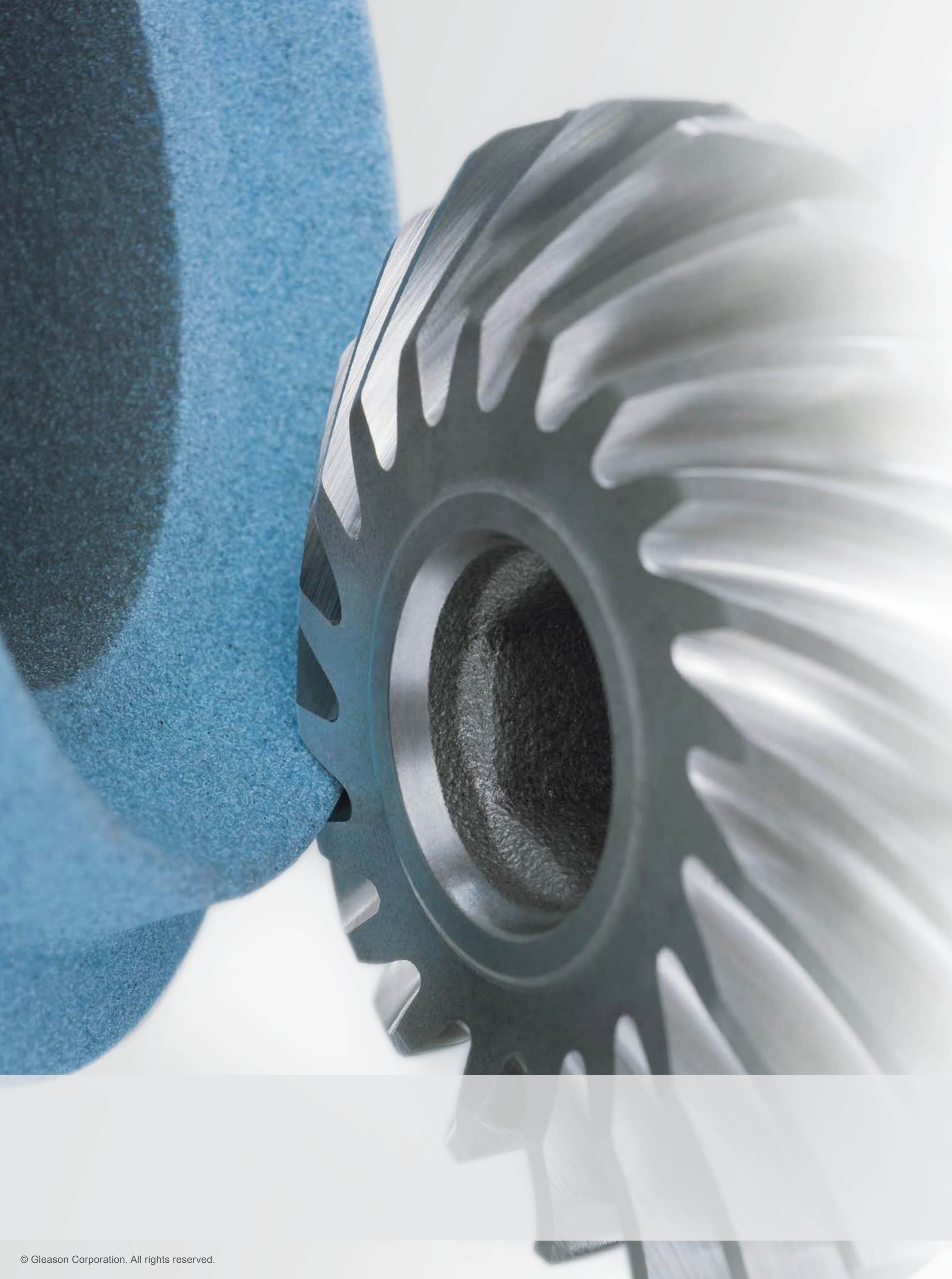

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Innovations for High Productivity Generating Grinding

Four Recent Developments Expand on Proven Technologies

Martin Witzsch

In comparison to the visionary Industry 4.0 — or the Fourth Industrial Revolution — the machine tool industry can appear rather down-to-earth.

But even in long-established technologies such as generating gear grinding, substantial improvements in terms of speed and quality have been made. Gear machine tools for generating grinding target high production volumes in industries that require large-lot, series production such as automotive. These industries are known for continuously growing demands in the areas of cost reduction, energy efficiency and environmental improvement. To serve these markets, machine and process developers react with solutions that cross technological boundaries. This article presents four developments by the company Kapp Niles that tap into new arenas using proven technologies, making them yet more efficient.

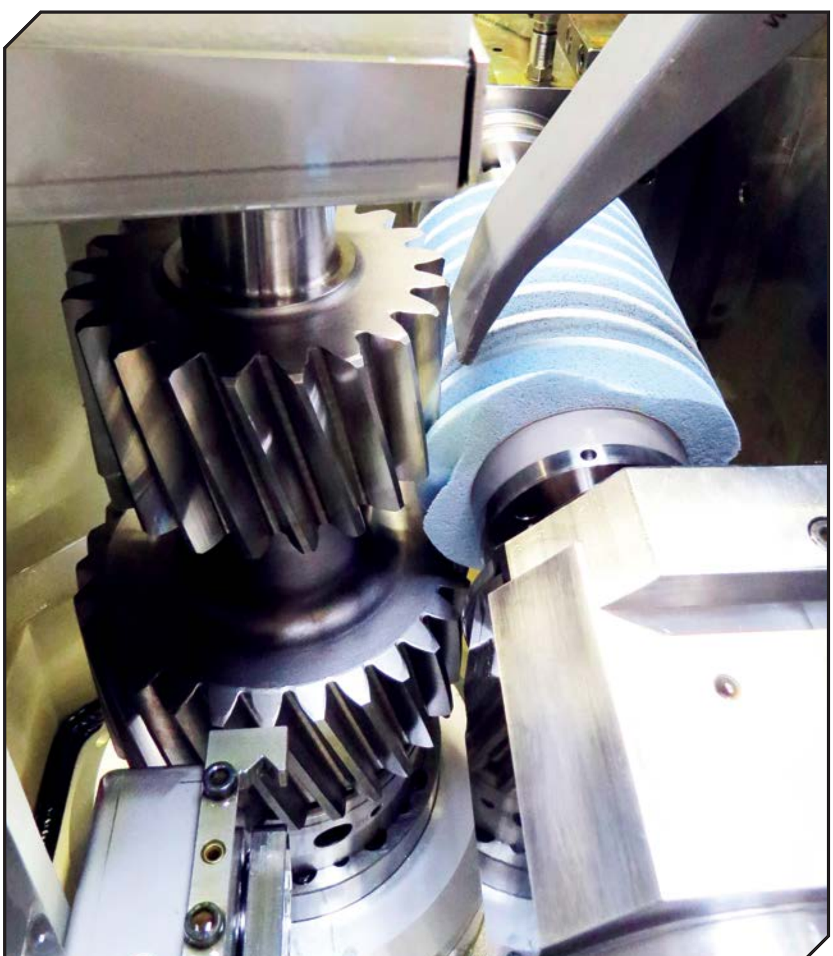


Figure 1 Generating grinding of a gear with interference contours.

Feasibility – Generating Grinding of Gears with Interference Contours

Cutting speeds for generating grinding between 63 and 80 meters per second yield huge productivities. This is accomplished with common tools — grinding worms with a typical diameter of 300 mm and with an rpm of 5,000 to 7,500. However, the large tool diameter presents a problem with interference contours because the tool requires room to finish its path on both ends of each grinding stroke. Typical examples are a bearing seat with a hob breakout, or a larger secondary gear close to the gear to be processed (Fig. 1).

Profile grinding of such workpieces would be very time intensive. Generating grinding technology is a viable alternative, but it requires a smaller grinding worm. However, smaller grinding worms require a higher rpm in order to reach the same cutting speed as that of a larger tool. Traditional gear grinding machines don't measure up to the task of meeting the dynamic requirements of tool and workpiece drives.

Modern grinding machines offer new alternatives. For example, the KX 160 Twin and KX 260 Twin from Kapp Niles now offer synchronization of dressing tool, grinding tool and machine in order to handle such complex tasks.

"Thanks to high speed grinding spindles, it is now possible to generate grind gears that require a tool diameter as small as 55 mm," says Dr. Sergiy Grinko, project manager at Kapp Niles. "In conjunction with the maximum possible width of 180 mm for the grinding worm, it is now possible to reach previously unattainable cycle times for critical gears with interference contours as well as cut production costs while still meeting the high quality requirements of series production."

The tool drives of the Kapp Niles KX 160 Twin and KX 260 Twin machines are able to run at a speed of up to 25,000 rpm. This necessitates the workpiece rotating at a faster speed as well. Kapp Niles standard machines offer a workpiece drive with 5,000 rpm.

To demonstrate the process improvement, Grinko calculated the cycle time for one workpiece for one of Kapp Niles' customers. The conclusion: non-dressable profile grinding with a CBN wheel results in a cycle time of 5.4 minutes. In contrast, dressable generating grinding of the same workpiece resulted in a cycle time of 2.9 minutes, with dressing intervals every 25 workpieces.

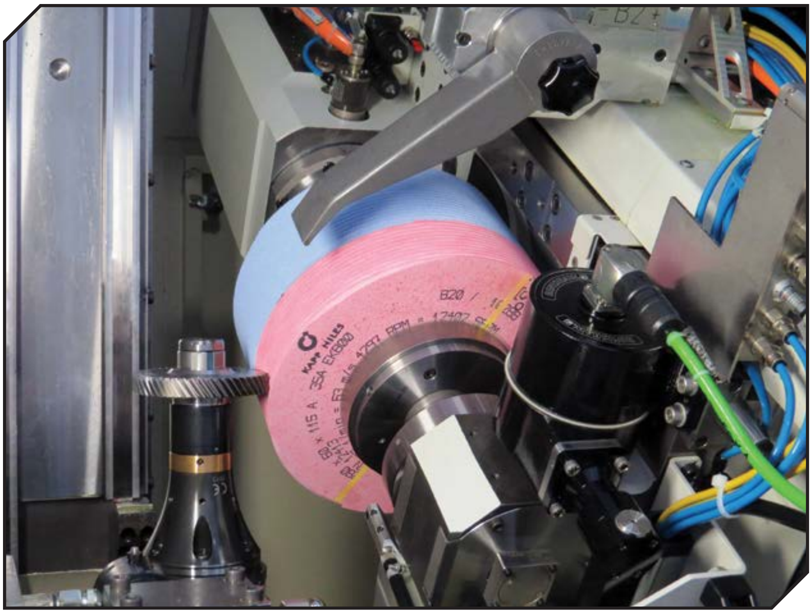


Figure 2 **Combined tool with conventional and superfinishing section.**

Quality in Micro-Geometry — Finish Grinding

Gear finishing, such as finish grinding, can considerably improve the characteristics of a workpiece. For example, with a better surface finish on the tooth flanks, it is possible to use transmission oils with lower viscosity. Consequently, the efficiency of the transmission improves, without the risk of reduced stability. This requires an 80–90 percent bearing ratio over the contact load area, which during the finish grinding process is obtained by mechanically removing the roughness peaks of the surface. This has so far been a challenge.

The required surface finish has traditionally been attained via time consuming processes, such as isotropic superfinishing (ISF). This process entails submerging the workpieces with small non-abrasive pellets into a vibration tub filled with a watery solution and an additive. While this process offers very good results, it could very well require several hours to complete, depending on the type of workpiece.

Compare that to a cycle time of one minute per gear that series manufacturers operate with.

"Series transmission manufacturers require automated process chains, ideally with a single-piece-flow," Grinko says. "Variable processing times are therefore not practical."

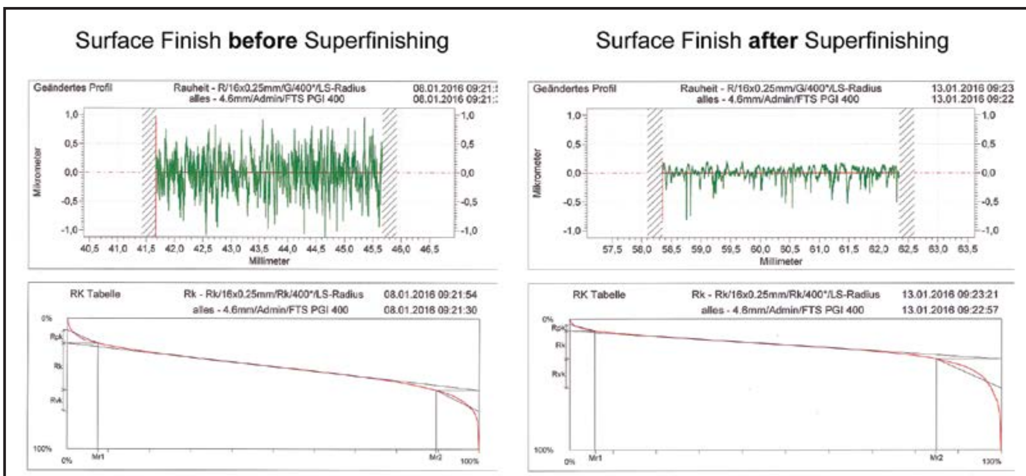
And he notes an additional problem: "ISF requires chemical additives that are subject to a number of regulations and safety measures, as well as recycling and disposal, all of which are a burden for the manufacturer to comply with. It is therefore more sensible to equip existing grinding machines with superfinishing capabilities to meet production requirements."

The German research association for drive technology (*Forschungsvereinigung Antriebstechnik, or FVA*) presented proof with the results of project 654 I: Finish grinding with conventional gear grinding machines produces surface finishes of Rz ≤ 1 µm. Kapp Niles offers special combination tools with two functional zones (Fig. 2). With these special tools, the newer generating gear grinders of the KX and ZX series are able to reach a surface finish of Rz 0.5–1 µm in one clamping setup (Fig. 3). With cutting speeds of up to 63 meters per second, the cycle time is higher but generally not more than 50% higher than the cycle time of conventional finish grinding.

"Generating grinding is substantially more efficient than profile grinding with a finishing wheel," Grinko says. "Our expertise allows us to make informed decisions concerning the most effective segmentation of the grinding zones on the combination grinding tool. Our software complements the set-up for optimal results."

Quality of the Macro-Geometry — Topological Generating Grinding

Gears rarely are manufactured without lead modifications. A simple involute exists only in textbooks, but not in reality. In the real world, engineers have to deal with tolerances such as misalignment of axes in the gear box. To address this issue, the tooth flank is designed to have a crown of several µm (0.001 mm). If a gear had no lead modification, the slightest deviation would result in a negative impact on load and noise behavior.



Rpk	0,2527	µm	Rk	0,8619	µm	Rvk	0,3916 µ
Mr1	7,59	%	Mr2	89,46	%	Rvk/Rk	0,4544
Rz	1,6263	µm	Rt	2,3716	µm		
Ra	0,2482	µm	Rsk	-0,2124		Rku	3,3138
R3z	0,9354	µm	R3y	1,2118	µm	Rz1max	2,2163 µ
Rmr(c) (1)	22,80	%	Schnitttiefe	-0,250	µm	mr%	5,00

Rpk	0,0513	µm	Rk	0,2263	µm	Rvk	0,2323
Mr1	5,85	%	Mr2	84,93	%	Rvk/Rk	1,0268
Rz	0,5434	µm	Rt	1,0163	µm		
Ra	0,0751	µm	Rsk	-1,6687		Rku	8,4048
R3z	0,2072	µm	R3y	0,5261	µm	Rz1max	0,9710
Rmr(c) (1)	89,84	%	Schnitttiefe	-0,250	µm	mr%	5,00

Figure 3 **Comparison of surface finish before and after superfinishing.**

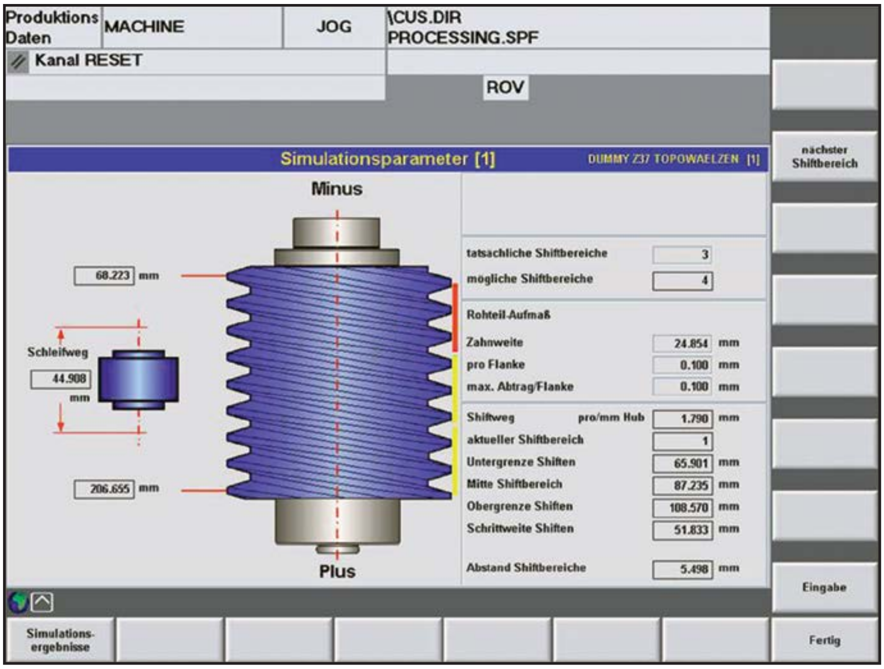


Figure 4 Input screen with illustration of possible shift area.

Processing such gears with generating grinding technology imposes special demands on the machine: the distance between tool axis and workpiece axis will have to be modified repeatedly throughout the process. However, this creates a bias error due to the position of the contact lines and the axes, which means instead of a symmetrical crown there could be a lead distortion.

"Generally, it is not the goal to simply eliminate bias but rather to manipulate it," Grinko says. "If the customer knows what the load will be and how the load will affect the behavior of the workpiece, it is possible to calculate the best generating contact for that application. Sometimes the noise behavior is better with minimal bias than having no bias at all."

So, such complex gears can be produced with generating grinding. This requires that during the grinding process, the tool shift position be interpolated with the axial feed position. Additionally, the process requires a modified tool: the grinding worm needs to have segments with different geometries specific to the requirements. Standard dressing tools can generate such varying geometries during the dressing cycle. It is apparent that such complex calculations of the worm geometry, the grinding and the dressing process require a highly sophisticated software. Some manufacturers do such calculations in-house and upload the data to the customer machines. However, this takes significant time. In prototype manufacturing or a test environment, this would mean substantial machine idle times for each slight modification.

"We have a user-friendly interface for topological generating grinding," Grinko says, "and calculations for geometry, dressing and grinding paths can be done in the machine control itself. Our customers are able to manipulate the lead modifications to their requirements all the way from simulation to final setup in 2D and 3D."

After the data is entered, the machine calculates the maximum possible number of shift areas for the specific worm width at hand (Fig. 4).

"For the topological generating grinding process, the goal is to have as many segments on the worm as possible for highest utilization of the grinding tool," Grinko says. "However, the segments have to be large enough to generate the desired geometry."

Once the number of segments is determined, the machine operator can monitor them in the simulations screen (Fig. 5). Should the machine operator notice tool wear and loss of quality during grinding due to a high number of shift areas, it is possible to reduce the number of shift areas to produce the best possible gear quality.

Speed — Multi-Rib Dressing

One primary advantage of generating grinding is time savings. A higher number of threads on the tool allows for an increase in feed rate and subsequently a reduction of processing time. The next natural step after processing time reduction is to reduce the dressing time. This is accomplished by dressing multiple threads with one tool simultaneously (Fig. 6). Kapp Niles investigated this process in detail in order to explore all possibilities for improvement.

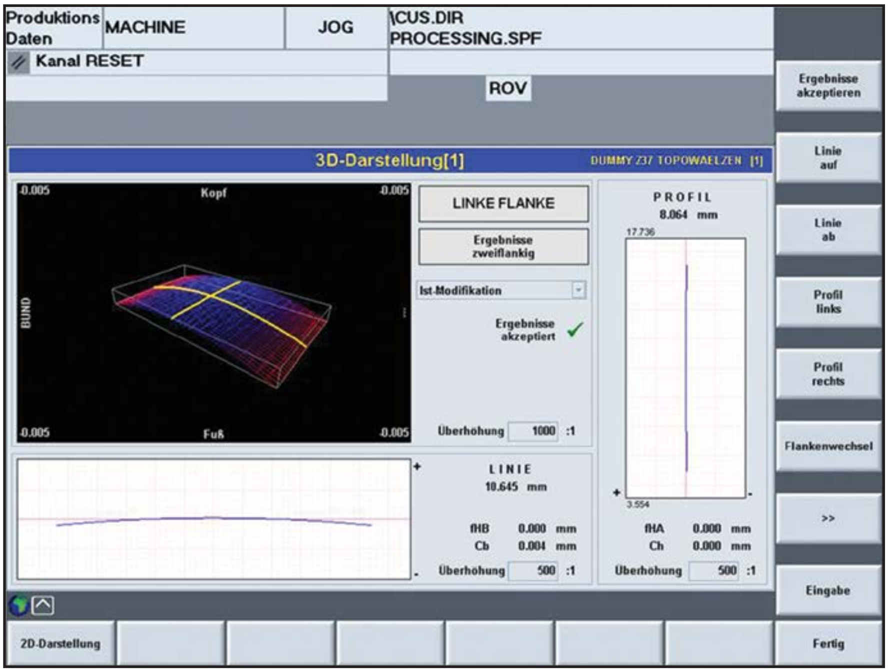


Figure 5 Simulation enables monitoring and controlling the topology before processing.

Figure 6 Multi-rib dressing of a sintered grinding worm saves time.

"Multi-rib dressing requires full-profile dressing rolls, which means they do not require a separate tip dresser," Grinko says. "Multi-rib dressing tools are manufactured by means of a negative-plating process."

This process does not place the diamond grains directly onto the steel body but rather into a negative form which then goes through the nickel-plating process. The negative form with diamond grains is then molded to the steel body.

In order to keep the dressing time to a minimum, it is necessary to coordinate the number of ribs on the dressing roll and the number of threads on the worm. The best scenario would be to have the same number of ribs and threads. That would result in all threads being dressed during each infeed pass. However, this is not always possible. A combination of five threads on the worm and three ribs on the dressing roll, however, would lead to the latter wearing more quickly. In order to avoid this and to increase the tool life of the dresser, Kapp Niles machines utilize an algorithm that guarantees uniform wear.

Conclusion

The examples prove that significant progress in productivity and quality is still possible even for a well-established technology such as generating grinding. Beyond faster drives, new tool concepts and intelligent controls, additional advances allow for further improvements such as fully automated clamping change and integrated automation solutions, as offered by the new pick-up generating grinding machine. All these factors allow for cycle times and process qualities that were inconceivable only a few years ago.

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Gear Backlash Analysis of Unloaded Gear Pairs in Transmissions

Carlos H. Wink

A best practice in gear design is to limit the amount of backlash to a minimum value needed to accommodate manufacturing tolerances, misalignments, and deflections, in order to prevent the non-driving side of the teeth to make contact and rattle. Industry standards, such as ANSI/AGMA 2002 and DIN3967, provide reference values of minimum backlash to be used in the gear design. However, increased customers' expectations in vehicle noise reduction have pushed backlash and allowable manufacturing tolerances to even lower limits. This is especially true in the truck market, where engines are quieter because they run at lower speeds to improve fuel economy, but they quite often run at high torsional vibration levels. Furthermore, gear and shaft arrangements in truck transmissions have become more complex due to increased number of speeds and to improve efficiency. Determining the minimum amount of backlash is quite a challenge. This paper presents an investigation of minimum backlash values of helical gear teeth applied to a light-duty pickup truck transmission. An analytical model was developed to calculate backlash limits of each gear pair when not transmitting load, and thus susceptible to generate rattle noise, through different transmission power paths. A statistical approach (Monte Carlo) was used since a significant number of factors affect backlash, such as tooth thickness variation; center distance variation; lead; runout and pitch variations; bearing clearances; spline clearances; and shaft deflections and misalignments. Analytical results identified the critical gear pair, and power path, which was confirmed experimentally on a transmission. The approach presented in this paper can be useful to design gear pairs with a minimum amount of backlash, to prevent double flank contact and to help reduce rattle noise to lowest levels.

Introduction

Many components inside a truck transmission, such as gears, synchronizers, and sliding sleeves, can move to a certain extent in the axial, radial, and circumferential directions. These components may rattle as excited by time-varying torsional vibration that comes from internal combustion engines, such as diesel-powered engines. Gears are susceptible to rattle and are a major contributor to the overall rattle noise level in transmissions. The meshing gears that are unloaded may often leave contact, moving freely back and forth within the backlash as torque fluctuates and causing repetitive impacts. The vibro-impact dynamics induced by gear backlash leads to vibration, rattle noise, and dynamic loads (Ref. 1). An effective approach to reduce rattle noise on transmissions is to lower the amount of gear backlash (Refs. 2–3).

Gear backlash is the clearance between a pair of teeth in mesh (Fig. 1), and can be described as the freedom of one gear to move around its axis while the mating gear is held stationary (Ref. 4). Backlash is required to ensure no contact of the non-driving side of the teeth, accommodate lubricating film on the teeth, and prevent tooth binding under running conditions (Ref. 5). When designing gear pairs, backlash is incorporated into the gear mesh by changing center distance between gears, or most commonly, by reducing tooth thickness of one or both gear members; this results in a tooth space width that exceeds the thickness of the engaging tooth on the operating pitch circles (Refs. 4 and 6). Industry standards, such as ANSI/AGMA 2002 and DIN 3967, and gear handbooks (Refs. 4–5), provide minimum values of design backlash as a function of gear module (or diametral pitch) and center distance. However, the actual backlash depends on other system elements and operating conditions. Manufacturing tolerances of gears, housings, shafts, bearing clearances, and other components cause the amount of backlash to vary considerably. Also, thermal expansions at operating temperatures, and elastic deflections caused by transmitted loads, result in additional backlash variation. This is difficult to predict in multispeed transmissions of numerous gear pairs, shafts, and bearings. Center distance of gears carrying load increases due to the radial component of force, resulting in larger backlash. However, a more complex shaft deflection shape and magnitude may cause tooth binding

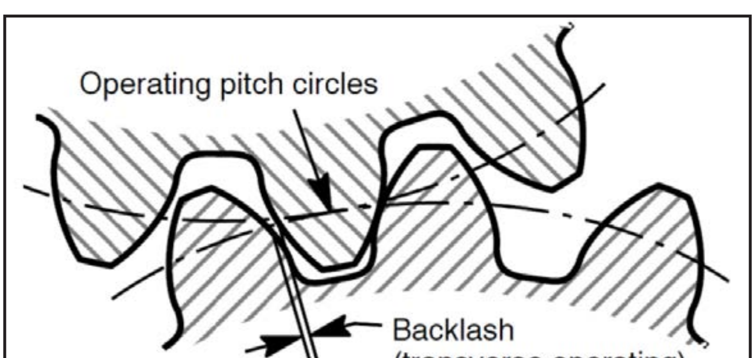

Figure 1 Backlash (ANSI/AGMA 1012-G05) (Ref. 7).

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of meshing gear pairs that are unloaded. This condition may be easily overlooked in the gear design and transmission development process.

Determining the dimensions and tolerances of gears and other system components that result in minimum amount of backlash and gears performing properly, while keeping reasonable cost in a production setting, is quite a challenge. This paper presents an investigation of actual backlash of unloaded meshing gear pairs of a pickup truck transmission with six forward speeds. An analytical model was developed to determine the actual backlash of each meshing gear pair not when transmitting torque, but when subject to shaft deflection effects of other gears in the power path. A statistical approach Monte Carlo was used, considering key factors that affect backlash, such as tooth thickness variation, center distance variation, runout, pitch and lead variations, bearing clearances, spline clearances, and shaft deflections. Analytical results were verified experimentally on a transmission for the critical gear pairs and 3 power paths. The approach presented in this paper can be useful to design gear pairs with minimum amount of backlash in order to prevent double flank contact and help reduce rattle noise to lowest levels.

Gear Backlash Calculation

Backlash in an assembled gear pair may be calculated in the transverse plane by taking the difference between the width of the tooth space and the tooth thickness of the engaging tooth on the operating pitch circles. Hence, backlash is governed by the center distance at which the gears are operated and by the effective tooth thickness of each of the gears (Ref. 6).

Operating pitch diameters are determined from the numbers of teeth, and the center distance at which gears operate and can be calculated as (Ref. 7):

$$d_{w1} = \frac{2a}{u+1}, d_{w1} = 2a - d_{w1} \tag{1}$$

where, d_{w1} and d_{w2} are the operating pitch diameter of the pinion and gear respectively, a is the center distance, and $u = z_2/z_1$ is the gear ratio.

Circular tooth thickness in the transverse plane at the operating pitch diameter is calculated from a given tooth thickness at pitch circle diameter, as follows:

$$s_{wt1,2} = d_{w1,2}\left[\frac{s_{t1,2}}{d_{1,2}} + (\text{inv}\,\alpha_t - \text{inv}\,\alpha_{wt})\right] \tag{2}$$

where s_{wt} is the circular tooth thickness in the transverse plane at the operating pitch diameter, subscripts 1 and 2 designate pinion and gear, respectively, s_t is the circular tooth thickness in the transverse plane at the generating pitch diameter, d, and are the involute angle at the generating pitch diameter and operating pitch diameter, respectively, and are calculated as $inv\ \alpha = tan\ (\alpha)\ \text{-}\alpha$. The transverse pressure angle at the operating pitch diameter is calculated as $cos(\alpha_{wt}) = d_b/d_w$, where d_b is the base circle diameter.

Transverse backlash at the operating pitch diameter can be calculated by Equation 3:

$$J_t = \frac{\pi d_{w1}}{z_1} - s_{wt1} - s_{wt2} \tag{3}$$

This same set of equations can be used to calculate the actual backlash when the center distance, a, and tooth thickness, s_t, are replaced by an effective center distance, a_e, and effective tooth thicknesses, S_{et}.

The effective center distance provides for:

- Deflections of housing, shafts, and bearings under load
- Displacements of shafts and bearings due to manufacturing deviations and bearing clearances
- Displacements of gear axes due to radial clearance of splined joints
- Differential expansion due to changes in temperature

In addition to the tooth thickness tolerances, the effective tooth thickness also provides for:

- Mesh misalignment of gears due to elastic deflections of housing, shafts, and bearings
- Skew of gear axes due to housing deviations and bearing clearances
- Gear tooth deviations, such as runout, profile, lead, and pitch deviations

The factors listed above are based on Appendix A of ANSI/AGMA 2002, which underlines the importance of good judgment and experience to assess minimum expected backlash requirements, since the worst-case tolerances are not likely to coincide (Ref. 6). Thus, a statistical analysis is a sound approach to determine the actual backlash range considering the significant number of factors involved.

Statistical Analysis

The backlash range can be statistically determined using the Monte Carlo method, which simulates thousands of variable combinations, and then averages the results and draws statistical conclusions. The combinations are generated from random numbers selected within the design allowable variation and a characteristic statistical distribution of each factor.

The simulation procedure can be broken down into these steps (Ref. 8):

i. Fit gear production data to an appropriate distribution function; goodness-of-fit statistics are used to determine an acceptable model
ii. Assign a distribution function to each variable in the backlash equation and upper and lower limits of each of the factors of interest
iii. Generate random variables from each of the distributions
iv. Calculate backlash using the random variables for each factor
v. Predict the estimation error and adjust sampling size, if needed

The acceptance criteria of the Monte Carlo simulation result are given by:

$$\frac{3\sigma}{\mu\sqrt{N}} \leq \varepsilon \tag{4}$$

where ε is an acceptable error, μ and σ are the mean and standard deviation of the backlash results, respectively, and N is the number of iterations.

Case Study: pick-up truck 6-speed transmission. As a case study the Monte Carlo model of backlash calculation was implemented into an *Excel* spreadsheet to determine the actual backlash range of a pick-up truck transmission with six forward speeds (Fig. 2).

This 6-speed transmission is rated to 440Nm input torque for 5.5-ton vehicles. The main shaft and countershaft are both supported by three bearings. All gears are helical, with helix angles from 19 to 33 degrees. Gear flanks are hard-finished, except for reverse gears.

A complete transmission model was built into *RomaxDESIGNER* software to calculate elastic deflections and mesh misalignments under load for each transmission power path. These include housing, shafts, and bearing deflections. The deflections and misalignments under different torque levels were transferred to the Monte Carlo model in the *Excel* spreadsheet.

Random numbers of each variable were generated, assuming normal distributions, in order to create 25,000 iterations. The estimation error of the Monte Carlo simulation was set to less than 1%.

The statistical backlash calculation was done at three torque levels and in two driving conditions — drive and coast. The latter simulates a truck going downhill using its engine brake.

The following factors were included in the backlash analysis:

- Circular tooth thickness tolerance
- Gear runout
- Lead variation (*fHb*)
- Index deviation (*fp*)
- Needle bearing clearance variation
- Spline radial clearance variation
- Gear mesh misalignment due to deflections
- Shaft deflections
- Housing deflections

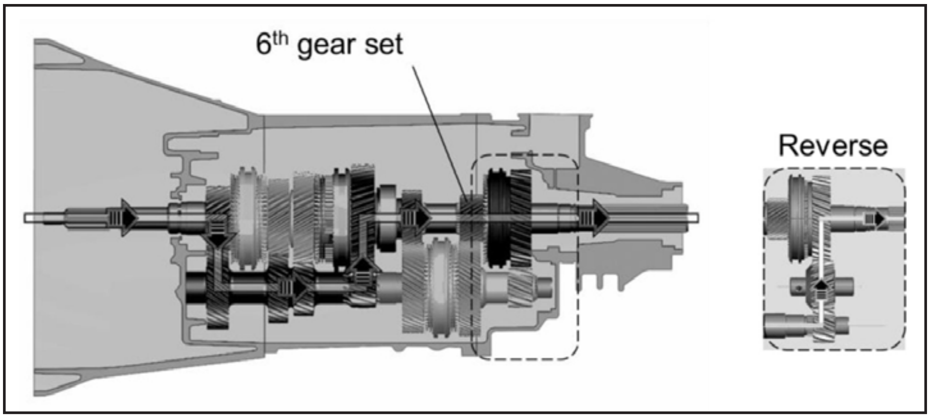

Figure 2 Pick-up truck transmission.

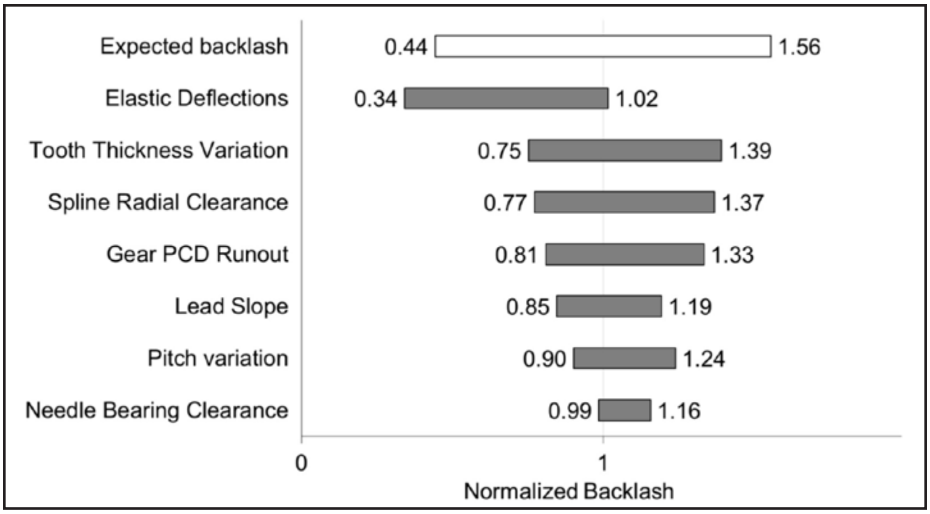

Figure 3 Sensitivity study results.

Bearing stiffness

Housing manufacturing variations, such as true position of housing bores, were assumed to have a minor effect on backlash because of their small magnitude over a large span between bearing supports; as such, they were not included in the analysis. Tapered roller bearing clearance variations were not considered, as countershaft bearings are pre-load-mounted. Gear profile slope variations were assumed as negligible compared to other factors. Thermal expansion effects were not included in the analysis.

After running the statistical analysis to each gear pair in all transmission gear speeds (power paths), results identified the reverse gear pair (when running in the sixth speed) and drive torque condition to be among the lowest-expected backlash results.

A sensitivity study was then carried out for that specific gear pair and condition in order to delineate the contribution of each individual parameter variance on backlash variability within the expected ranges of the parameters. The study was done by allowing one variable to vary according to its specified distribution, while holding all other variables constant.

The sensitivity study results are shown in Figure 3, using a tornado plot. The results are normalized to the mean value of expected backlash, which is shown at the top of the chart for reference.

The deflections of shafts, housings, and bearings play a significant role in the overall backlash result. For that particular gear pair, when in 6th speed and drive condition, the deflections bring reverse gears closer to each other, resulting in smaller effective center distance and, consequently — less backlash. As torque goes up, deflections increase, and backlash of reverse gears goes down.

The tooth thickness variation, followed by spline radial clearance and pitch circle diameter runout, also significantly affects the actual backlash for that particular condition.

Experimental Verification

To verify the calculation results a transmission unit was built with components made to the design dimensions. A special housing was prepared in which a small window was opened around the reverse idler gear location (Fig. 4). It was assumed that changes of housing stiffness due to the small windows are negligible.

The transmission unit was fixed to a test rig, where two specific static tests were performed in order to verify the critical gear pair and condition identified on the backlash study.

The transmission was shifted into sixth

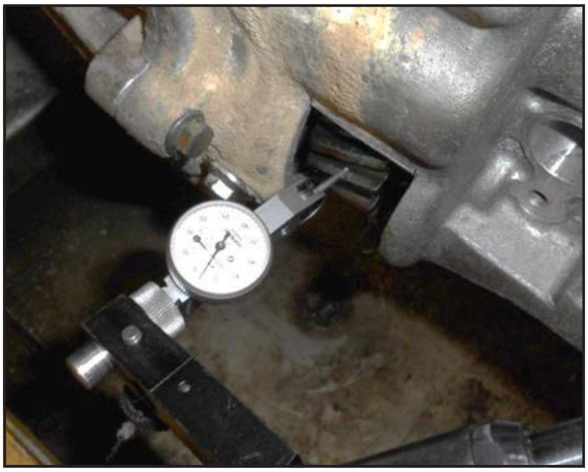

Figure 4 Backlash measurement of reverse idler gear.

gear speed, and torque was applied to the transmission input shaft. While holding the torque, gear backlash was measured using a dial test indicator with its tip positioned on a reverse idler gear tooth. This procedure was repeated at no load, half design load, and design load conditions.

Figure 5 shows a comparison of measured backlash results and expected results, using the Monte Carlo approach. All three data points fall within the expected distribution. Measured backlash at half design load and at the design load are close to the expected mean, with 69% and 68% of cumulative distribution, respectively. However, under no load, the measured backlash is closer to the upper limit of the normal distribution curve. The difference may be caused by clearances of other components in the sixth-speed power path, which may have allowed the reverse geartrain to slightly rotate during the backlash measurement process, causing that rotation to be captured as gear tooth backlash. Under torsional load condition those clearances are eliminated, thus making the backlash measurement process more consistent.

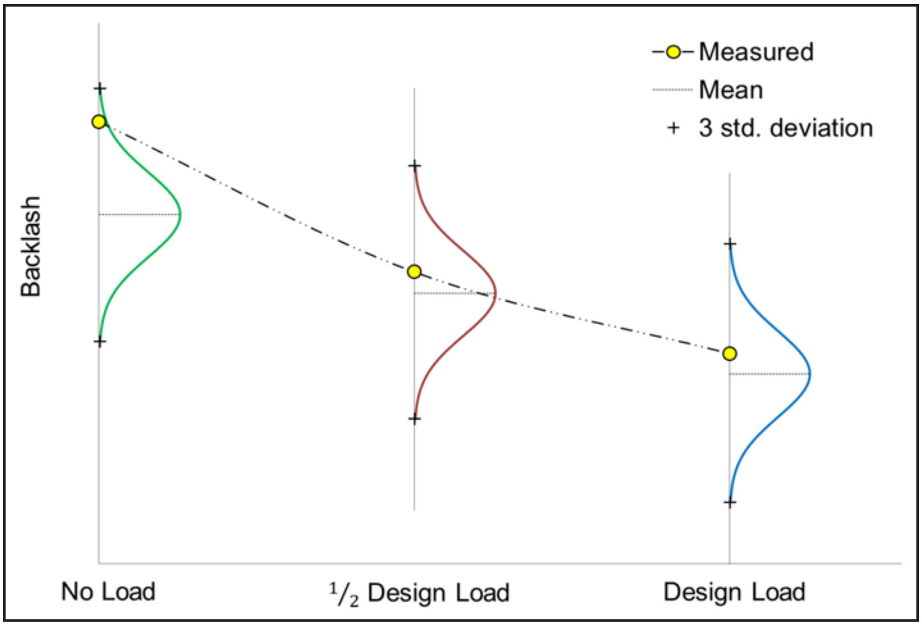

Figure 5 Measured backlash compared to expected values.

Discussion

The actual backlash of gear pairs is a result of the effective center distance at which the gears operate and the effective tooth thickness of each gear member. The effective center distance and the effective tooth thickness should be carefully determined at the system level, including important factors such as deflections of shafts; housing and bearings; misalignments and clearances of bearings and spline couplings; and tooth deviations, such as lead, runout and pitch variation. This is important when defining the right amount of tooth thickness reduction in the gear design that will attain reduced rattle noise levels while preventing the non-driving side of the teeth to make contact. Regarding adverse operating conditions, special attention should be given to the backlash of unloaded gear pairs when transferring power through other gear pairs, since the resulting deflections may lead to critical backlash results of gears that are unloaded, as shown in the case study. The approach using Monte Carlo simulation worked well to determine the expected gear tooth backlash and delineate the contribution of each individual parameter on backlash variability, which can be helpful to choose suitable manufacturing tolerances for gears and other parts in the assembly. The approach presented in this paper can be used to design gear pairs with minimum amounts of backlash to prevent double flank contact, and help reduce rattle noise to lowest levels.

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Worm Gear Efficiency Estimation and Optimization

Massimiliano Turci, Elena Ferramola, Fabiola Bisanti and Giampaolo Giacomozzi

This paper outlines the comparison of efficiencies for worm gearboxes with a center distance ranging from 28 – 150 mm that have single reduction from 5 to 100:1. Efficiencies are calculated using several standards (AGMA, ISO, DIN, BS) or by methods defined in other bibliographic references. It also deals with the measurement of torque and temperature on a test rig—required for the calibration of an analytical model to predict worm gearbox efficiency and temperature. And finally, there are examples of experimental activity (wear and friction measurements on a block-on-ring tribometer and the measurements of dynamic viscosity) regarding the effort of improving the efficiency for worm gear drivers by adding nanoparticles of fullerene shape to standard PEG lubricant.

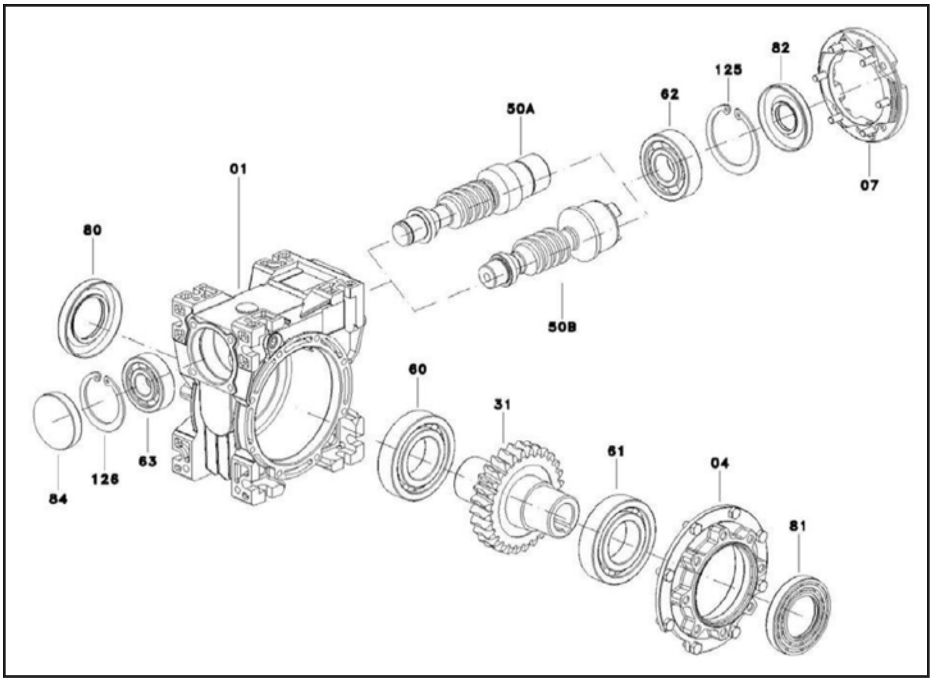

Figure 1 Typical worm gearbox components (Ref. 1)—aluminum housing; case-hardened steel worm with *ZI* profile; bronze wormgear molded on a cast iron shaft; four ball bearings with Seeger rings and oil seals; the lubricant is a synthetic PEG oil with viscosity grade 320 per AGMA 9005-E02 (Ref. 2)—tab B.5.

Introduction

The worm gearbox is widely used for high reduction ratios, because it can provide both "small cost" and "small size" by allowing a single reduction unit to be used for many applications.

Worm gearboxes are a strategic product for many Italian companies, constituting up to 50% of sales. For this reason, the paper presents some examples of factors affecting worm gearbox efficiency and investigates means of optimization, particularly on medium-sized worm gearboxes (with center distance between 28 and 150 mm).

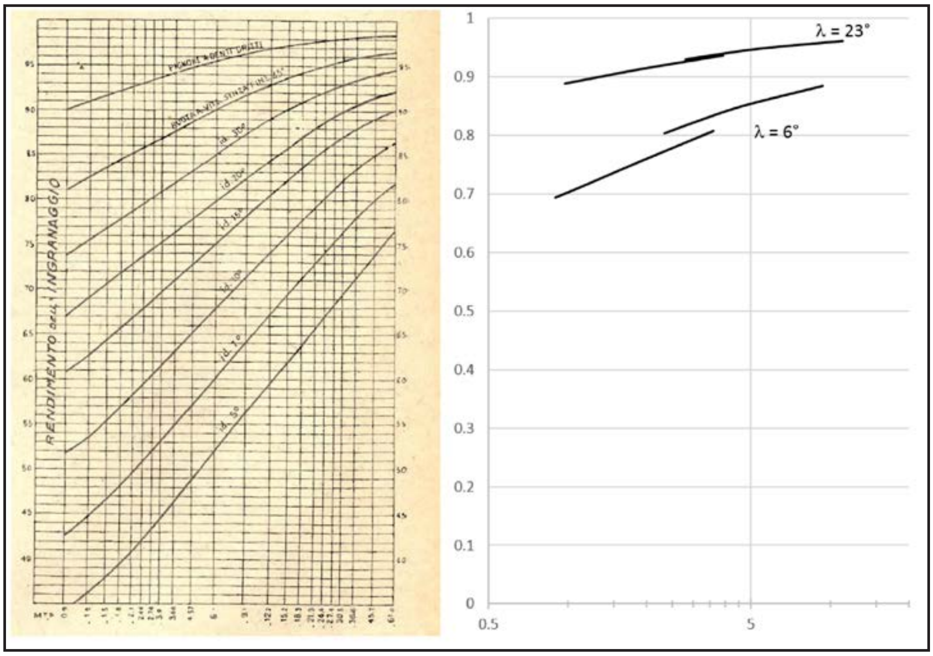

Figure 2 Worm gearbox efficiency vs. sliding velocity (m/s) for different lead angles: a) historical data (Ref. 4); b) AGMA 6034-B92 (Ref. 5) on current worm speed reducer (Ref. 1).

Efficiency Calculation According to Standards

Current Italian worm gearbox catalogues often show data calculated according to the old BS 721 (Ref. 3). Many companies are now evaluating which one of the latest standards they should adopt. For this reason, the Authors made a massive efficiency calculation on several size and ratio

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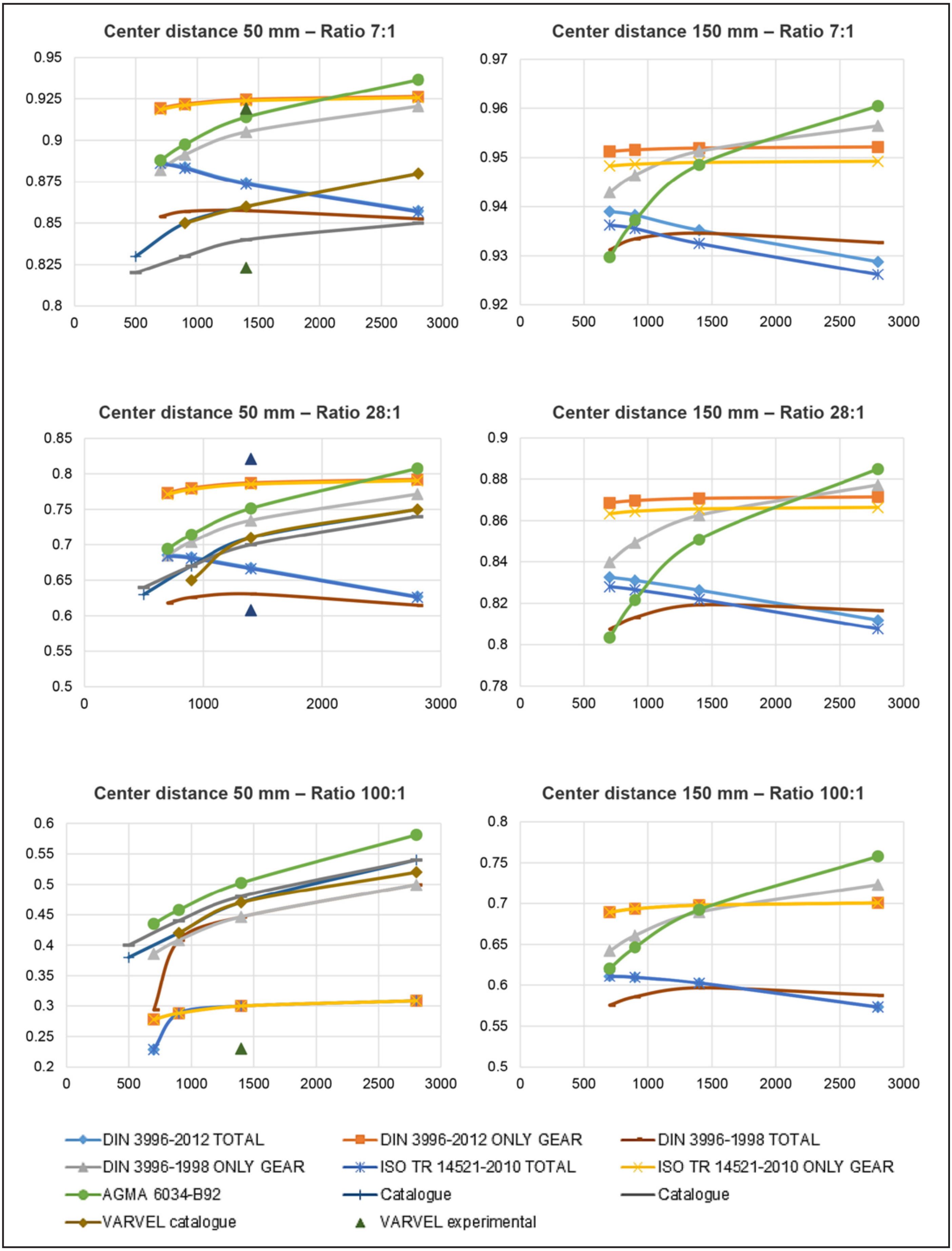

Figure 3 **Worm gearbox efficiency according to different standards and catalogues—*η* vs. *n* (rpm).**

configuration worm gearboxes, according to many standards, and also comparing results with values from catalogues of some companies.

The first studies of this kind in Italy date back to a century ago (1920s) as reported in (Ref. 4). A comparison between historical data (Fig. 2b) and the results obtained by the authors (Fig. 2a)

Figure 3 shows results applying the nominal output torque and according to DIN 3996-1998 (Ref. 6), DIN 3996-2012 (Ref. 7), ISO/TR 14521 (Ref. 8), and AGMA 6034-B92 (Ref. 5). When it is possible, the plot shows both meshing and total efficiency.

There are not any results about smaller gearboxes ($a = 28$ mm) because they are out of the range of ISO and DIN standards.

Figure 3 also shows efficiency from competitor catalogues. Note that often in the catalogues there is an indication that the efficiency settles after the running-in period, but the indication of time ranges from "a few hours" to "200 – 800 h."

In the plot there are also some points experimentally detected in the tests described below.

For the calculation of the friction coefficient, the authors used the method C for the DIN and ISO standards, and the oil temperature does not influence the efficiency.

Looking at the plots in Figure 3, note that:

- For the same input speed and ratio, the efficiency changes as a function of size (center distance), especially because there is the friction coefficient variation as a function of absolute speed in the reference diameter, which changes with the gearbox size
- DIN 3996-2012 and ISO/TR 14521 have similar plots
- AGMA 6034-B92 is quite similar to the old version of DIN 3996
- AGMA 6034-B92 has only the mesh efficiency

Experimental Definition of Temperature and Efficiency; Calibration of the Model for Their Prediction

Varvel SpA R&D and sales departments usually work with *KISSsys* (software that allows users to model drivetrains, based on *KISSsoft*, the popular program for sizing, optimizing, and recalculating designs

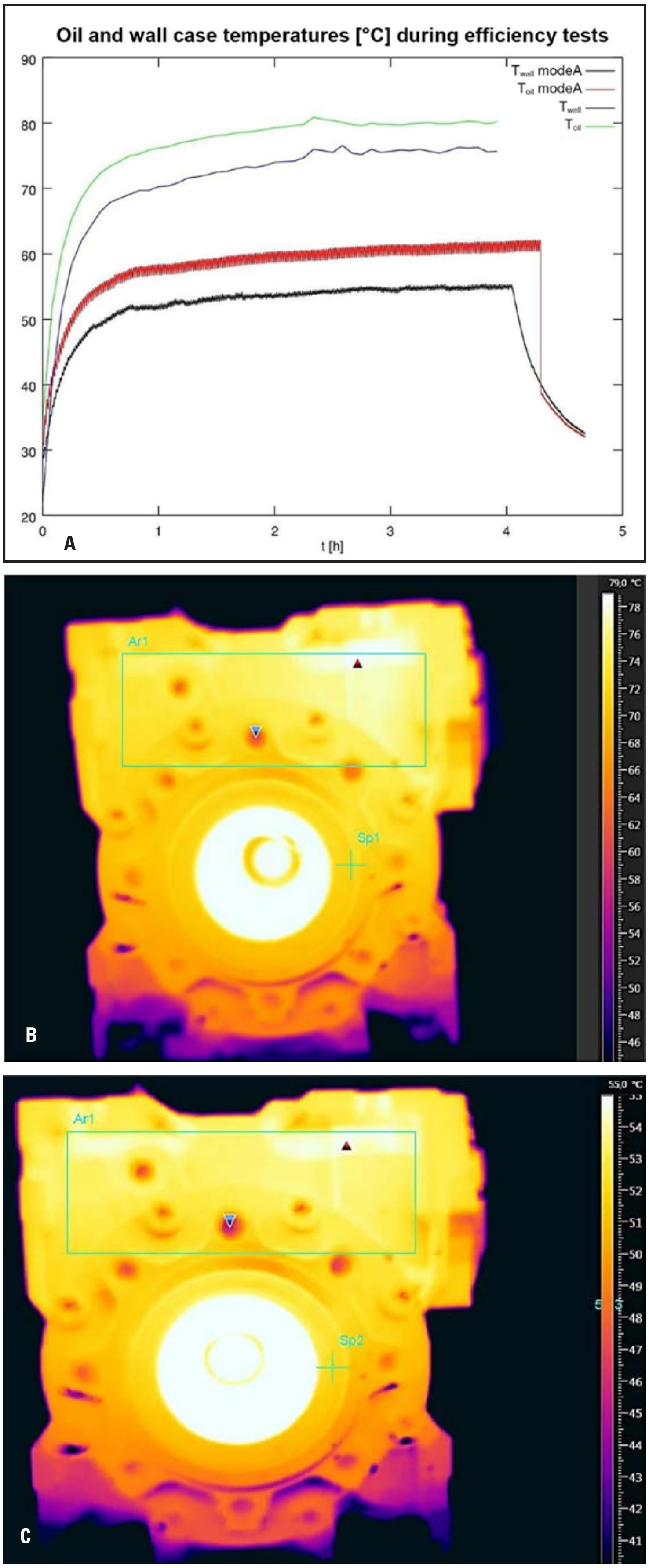

Figure 4 Comparison between T_{oil} and T_{wall} for continuous vs. alternating operating modes — a) temperature trend during efficiency tests; b) infrared frame after 4h in continuous operating mode; c) infrared frame after 4h in alternating mode.

Table 1 Experimental results of efficiency η and temperature tests compared with calculated values

Ratio	Input rotation	Output Torque measured [Nm]	Input Power measured [KW]	Input Power KISSsys [KW]	η measured [%]	η KISSsys [%]	T_{wall} measured [°C]	T_{oil} measured [°C]	T_{oil} KISSsys [°C]	T_{wall} KISSsys [°C]
7	CW	68.07±0.18	1.559±0.005	1.6	91.9±0.3	89.1	75.2±0.4	79.2±0.5	73.3	68.9
7	CCW	72.8±0.2	1.863±0.006	1.7	82.3±0.2	89.2	78.8±0.5	85.1±0.3	75.1	70.6
28	CW	75±0.4	0.481±0.007	0.53	82.1±0.2	73.9	74.5±1.5	78.8±1.4	71.4	67.1
28	CCW	76.6±0.4	0.663±0.009	0.542	60.8±0.9	74.0	78.4±1.1	82.1±0.7	70.9	66.6

for machine components such as gears, shafts and bearings (Ref. 9)), to help customers with the right gearbox choice from the catalogue for their application. With a single model they can calculate lifetime or safeties for gearboxes of the same type with different size and ratio.

When a customer is looking for a worm gearbox, often he enquires about the efficiency and housing temperature for its application — especially in non-steady operating conditions. And so the model has been enhanced with this feature.

But to do this, initially, an accurate experimental campaign was conducted in order to define worm gearboxes' performance in terms of efficiency and temperature. Shown (in this presentation) are some results obtained on gearboxes with center distance 50 mm and ratios 28:1 and 7:1; these data will be used to calibrate the model for efficiency prediction.

The gearboxes were test-rigged with an input speed of 1,400 rpm and output torques listed in the catalogue for continuous operating mode. Each housing was monitored with an infrared camera (Figs. 4b and 4c) while a thermocouple inserted from the top acquired the inner oil temperature. Table 1 summarizes results for both clockwise and counter-clockwise rotations of the input shaft; it is clear how performances of the CCW are worse than that of the CW. Changing the rotation, the axial reaction force moves from one bearing to the other in the input shaft. Because the two bearings have different sizes, the power loss is different.

Although the total efficiency calculation is already in the software (as seen previously), the authors improved the possibility of better controlling each parameter of the efficiency calculation in the model, adding all power losses — according to many standards or references — chosen by the user:

- Bearing P_{VL}
- Churning P_{VZP}
- Meshing P_{V0}
- Seals P_{VD}

The equations used in the model are similar to those in ISO/TR 14179 (Refs. 10 – 11) for cylindrical and bevel gears:

$$T_{wall} = (\varepsilon_{thermal})(T_{oil}) \text{ is the definition of the } \varepsilon_{thermal} \text{ (not present in any standards)} \quad (1)$$

$$P_V = P_{VZP} + P_{V0} + P_{VLP} + P_{VD} \text{ total power losses} \quad (2)$$

$$P_V = k(A_{ca})(T_{wall} - T_\infty) \text{ total heat flow} \quad (3)$$

Unlike the thermal capacity calculation for cylindrical and bevel gearboxes, here the oil temperature has no influence on Equation 2 factors, so Equation 1 is not needed and the T_{wall} is easily calculated from Equation 3.

Nevertheless, the factor $\varepsilon_{thermal}$, experimentally measured, was included in the model: $\varepsilon_{thermal}$ medium values T_{wall}/T_{oil} is 0.94 (from Table 1).

The calculation model validation required two steps.

Step one: after entering the input speed and output torque of each experimental case, choose the right equations so the model calculates the same input power measured in the test rig. The better mix of standards is this:

- ***Bearing*** P_{VL}: formulas from SKF catalogue (Ref. 12) (where there are new formulas compared to old catalogue editions)
- ***Churning*** P_{VZP}: ISO/TR 14521 (Ref. 8); (the other choice was ISO 14179)
- ***Meshing*** P_{V0}: ISO/TR 14521 (the same as DIN 3996:2012 (Ref. 7))
- ***Seals*** P_{VD}: ISO/TR 14179-2 (Ref.11) based on a German proposal

Note that the analytical model does not show a true efficiency variation when changing the rotation direction, as shown before in the test rig.

Step two: set the value of the global thermal coefficient k to obtain (in the model) the same housing temperature measured by the infrared camera.

$k = 31\ W/(m^2 °C)$: similar to vales in Table 7 of ISO/TR 14179-1 (Ref. 10) — based on an American proposal.

The authors already calculated, using ISO/TR 14521, the same (within an acceptable range of ±15%) oil temperature measured by the thermocouple (Table 1), without any other calculation. Therefore Step 1 and Step 2 are independent, and T_{wall} is calculated from this value of T_{oil} from Equation 1.

So the model, validated for ratios 7:1 and 28:1, is quite ready to calculate efficiency (power losses) for all other ratios or load cases (torque and speed), and to

Table 2 Alternate operating modes and DOE parameters *A* and *B*, ΔT_{wall} measured values, $\Delta T_{wall}M$ medium between values with the same *A*, $\Delta T_{wall}C$ calculated from Equation 4

Operating Mode	Start Frequency *A* [min^{-1}]	Operating percentage *B* [%]	$\Delta T_{wall} + \sigma$ [°C]	$\Delta T_{wall}M + \sigma M$ [°C]	$\Delta T_{wall}C$ Equation 4 [°C]
G	30	25	29.6±0.8	42.4±0.6	40.75
H	60	25	49.9±0.5		
I	180	25	47.75±0.54		
C	30	50	17.5±0.9	19.5±0.7	22.75
A	60	50	20.4±0.6		
B	180	50	20.69±0.57		
E	30	75	5.4±1.2	7±1	4.75
D	60	75	7.4±0.9		
F	180	75	6.6±1		

calculate the housing temperature in continuous operating mode — as required. Perhaps, however, it should be modified a bit to allow for different gearbox sizes.

But note that the model does not yet enable calculation of efficiency and housing temperature for alternate operating mode of worm gearboxes. In order to define an empirical law to estimate such performances from the theoretical evaluation, further tests were conducted on a worm gear speed reducer with center distance 50 mm and ratio 7:1, with start frequencies "*A*" and operating percentages "*B*" summarized in Table 2, and with clockwise input shaft rotation. *A* and *B* values were chosen by a DOE 3^2 approach, which, with an optimized number of tests, allows one to define the variables with statistical effectiveness on temperature, together with an eventual, combined effect.

Figure 4 shows a comparison of temperature trends for continuous and alternate operating mode; in both ways housing and oil temperatures stabilize after almost 3 hours, but for the alternate one, lower values are reached. All the alternate modes show the same behavior. Table 2 shows ΔT_{wall}, the housing temperature difference, between alternate and continuous operating mode. From the statistical analysis of the DOE results pattern, only *B* effects seem to be significant (*P* value lower than 1), so it's possible to record linear Equation 4 for ΔT_{wall} housing:

$$\Delta T_{wall} = 58.75 - 0.72B \tag{4}$$

Figure 5 compares measured values (from Table 2 with the same *A*) with calculated values of ΔT_{wall} from Equation 4. The experimental trend shows a good correspondence with the theoretical one, also considering the relative σ, and confirms the strength of DOE approach. Regardless, this is just a first step in dealing with an empirical law, and further tests must be done to make it more accurate and applicable to other sizes of worm gearboxes.

Equation 4 was not added to the model because it required more validations, but it is starting to help R&D and sales departments to better answer customer requests, giving them indications that are more precise about the real temperature they should expect on worm gearboxes.

Besides having a strong computational tool to predict and define gearbox behavior in terms of efficiency and temperature, the R&D department frequently needs to answer customer requests for improved efficiency for the worm gearboxes. In order to fulfill this target, while also avoiding strong geometrical modifications, the authors studied the effects of adding on fullerene-shaped WS_2 nanoparticles to standard PEG lubricant.

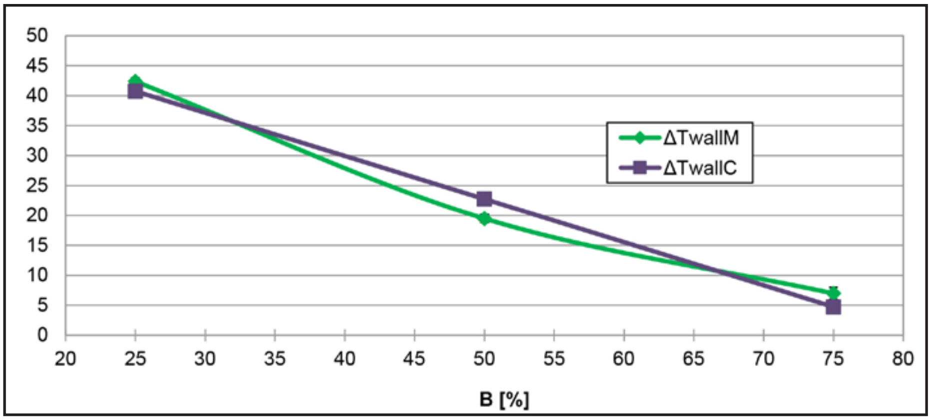

Figure 5 **Difference of temperature between housing (wall) and oil for worm gearbox with center distance 50 mm and ratio 7:1, rotation CW — comparison between measured ($\Delta T_{wall}M$) and calculated ($\Delta T_{wall}C$) values.**

Table 3 Rheological properties of the three lubricants tested

Rheological Properties	PEG	ESTER	PEG + WS_2
Viscosity 40°C [mm^2/s]	320	295	320
Viscosity Index	230	174	-

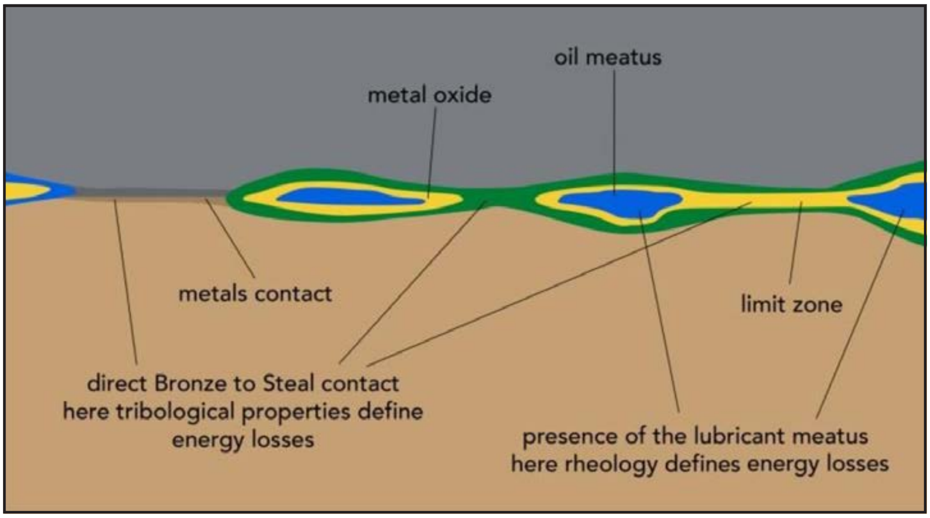

Figure 6 **EHL mixed lubrication, influence of tribology between contact surfaces and rheology of lubricant.**

Commercial PEG rheological properties are listed in Table 3; the additive is made of WS_2 nanoparticles of fullerene shape (diameter 13 Nm) added on the lubricant for a 4% WT. These particles are only supposed to improve tribological properties of the lubricant by flaking and going to attach to the sliding counterpart, reducing wear and facilitating the reciprocal motion.

WS_2 fullerene nanoparticles should not influence the rheology of the PEG lubricant — which is quite essential in order to guarantee constant performance of the worm gearboxes — while the oil temperature increases during operations. Such a high value of the PEG lubricant viscosity index, 230, is the expression of this aspect and guarantees that the viscosity does not drop too much with the temperature, constantly providing the right combination of controlled power losses due to shear stress and hydrodynamic lift between the teeth coupling.

Both tribology and rheology aspects are involved in the contact area on an EHL mixed regime, such as the one associated with the high Hertzian pressure experienced by worm gearboxes (Fig. 6). Friction

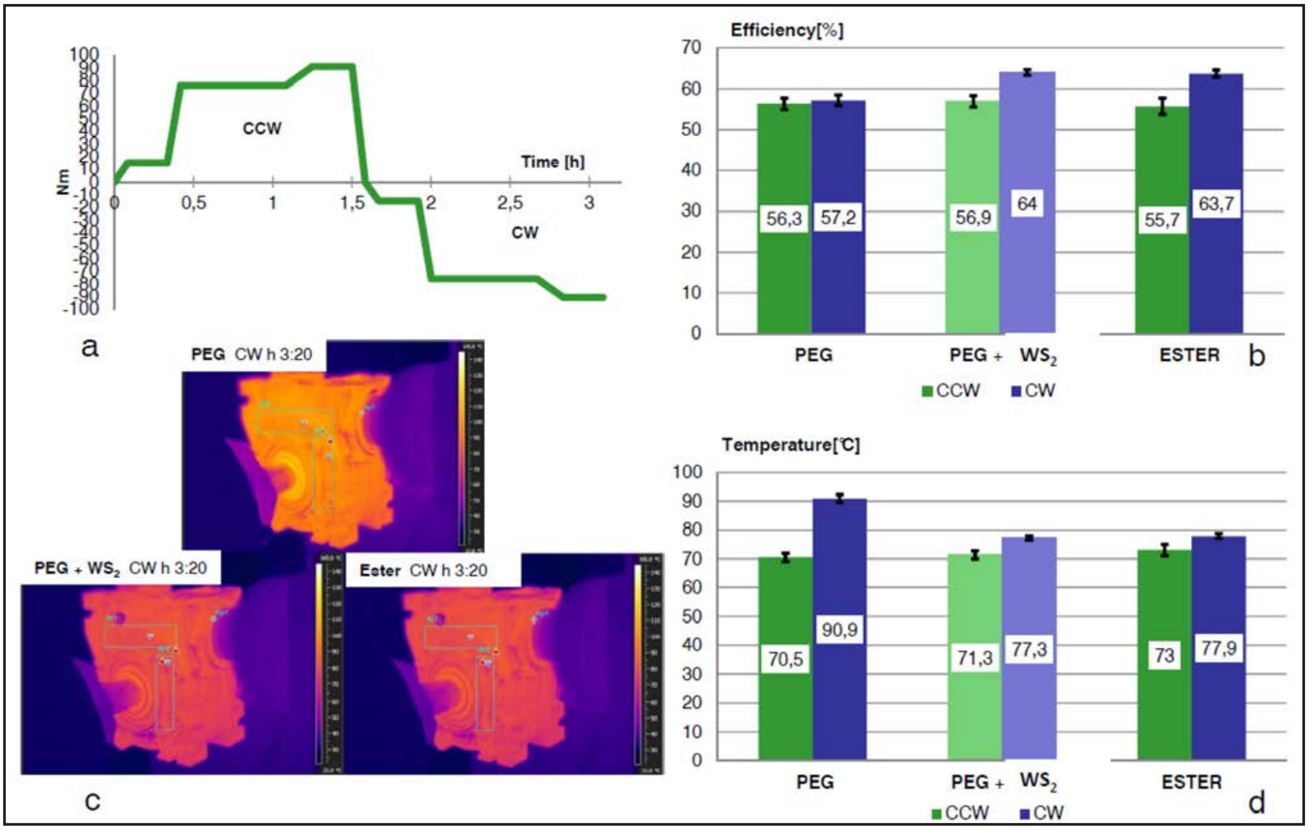

Figure 7 Efficiency and temperature tests on worm gearbox with center distance 50 mm and ratio 1:49 with PEG, PEG + WS_2, and ester lubricants — a) output torque trend during test; b) efficiency results; c) infrared picture of the gearboxes at the end of the efficiency tests; and d) temperature results, meaning maximum *T* value acquired.

and wear are related to the limit zone, where the metallic counterparts come in direct contact. Here the fullerene WS_2 nanoparticles flake and facilitate the reciprocal sliding, attaching themselves to the counterparts. Instead, rheology is related to the contact areas where the meatus is still present; here the energy losses are related to the shear stress of the lubricant, which needs to be won while sliding.

Efficiency tests were run on a worm gearbox with center distance 50 mm and ratio 49:1, after a proper running-in, with 1,400 rpm as input speed and an output torque following the trend in Figure 7a.

Rotation of the input shaft switched from counterclockwise to clockwise without cooling; the temperature of the housing was collected with an infrared camera during all tests (Fig. 7c).

Figures 7b and 7d show the comparison of efficiencies and temperatures of RT50 PEG lubricated with and without WS_2 nanoparticles. The filler brings an increase of almost 12% between the counterclockwise efficiency and the clockwise one, which is not present with the only PEG. This improved efficiency is also clear in the temperature confrontation; for the WS_2 nanoparticles the temperature reached during the clockwise phase is comparable to the counterclockwise one, while for the only PEG it's almost 20° C higher. A similar behavior was observed for the same gearbox, while using an ester-based lubricant (Table 3) with a viscosity index lower than the PEG one — i.e., 174.

This third lubricant showed a positive effect on gearbox efficiency, but even the small increase in temperature it goes through means a decrease of the cinematic viscosity to 55 mm^2/s from the 320 mm^2/s at 25° C. As explained above, a decrease in viscosity is good to limit energy losses in the EHL mixed regime contact, but it should not run too low, in order to avoid seizing of the gearbox system. To exclude any unexpected influence of the WS_2 nanoparticles on the rheology of PEG, further tribological and rheological testing on the three lubricants was conducted.

Figure 8a shows the effect of oil temperature on the dynamic viscosity of the PEG — with and without fullerene particles. Measurements were run by a rotational viscometer according to the ISO 2555 (Ref. 13) standard. The measured parameter is the dynamic viscosity, which is related to the cinematic one by the fluid density.

Values of dynamic viscosity are comparable, as well as temperature trends; this first result excludes the effects of WS_2 on rheology.

The effect of fullerene nanoparticles was better understood by performing wear tests for the three oils using a block-on-ring (BOD) tribometer (Fig. 14a). In the BOD configuration a sample block rests on a rotating 100Cr6 ring (HRC 62) half-plunged in a small tank of sample lubricant. While rotating, the ring picks up the oil that goes to lubricate the contact area, with the same operating principle of lubrication in worm gearboxes. The tested contact geometry is comparable to the one of worm-wheel teeth; in this way one can observe wear resistance of the bronze counterpart in a much shorter time than on the driver itself. Bronze blocks (HRB 130) are obtained directly from a worm wheel trough-wire EDM.

The ISO/TR 14521 (Ref. 8) wear intensity J_{OT} was used to evaluate the amount of wear on the bronze block. In Equation

5 the wear depth P of each sample was measured by a 3-D profilometer (Fig. 9). In Equation 6 the wear path length L is calculated from BOD test parameters (Fig. 14b). Values of normal loads on the bronze block correspond to Hertzian pressure equivalent to the values experienced by the teeth at the output torques that were used at the test rig during the efficiency tests.

$$J_{OT} = \frac{P}{L}\left[\frac{mmWear}{mmPath}\right] \quad (5)$$

$$L = (t)(\omega)(R_{ring})\ [mm] \quad (6)$$

In Figure 8b the J_{OT} values measured for each lubricant are compared. PEG plus WS_2 showed the lowest value of J_{OT} — proving the effects on bronze wear as described above. Ester lubricant had the worst performance in terms of wear — probably because in BOD tests the viscosity decreases while the temperature rises; thus the bronze wears out against the harder 100Cr6 roughness.

This result explains the efficiency performances (Fig. 7) in terms of two different causes for the same effect. Ester lubricant improves efficiency, reducing energy shear losses in the meatus zone of the EHL contact area due to its rheological properties. PEG plus WS_2 fullerene nanoparticles act upon the metal contact zone, thereby reducing losses due to bronze wear and friction. In other words, the additive has effect only on the tribology of the system, as expected. This one is definitely the best solution for improved efficiency requests of final customers, guaranteeing constant temperature performances in terms of hydrodynamic lift, while introducing a solution focused for the metal contact area. It is also a cheaper solution because total cost of the gearbox increases by just 2%.

Conclusions

Although wormgear speed reducers are less efficient than other gearboxes with equal ratio and size (e.g., orthogonal ones), they are still very popular — especially for occasional or intermittent service per day — because they are simple and inexpensive. The improvement of their efficiency over the years, along with the continuous evolution of the standards, bears this out.

The low efficiency of these gearboxes can even be an advantage because it avoids the introduction of the brake when irreversibility is required. Because of this, it is important to provide a reliable value of the efficiency. If specifically requested, it can still be increased without any geometric changes, but only while acting on the lubricant additive composition.

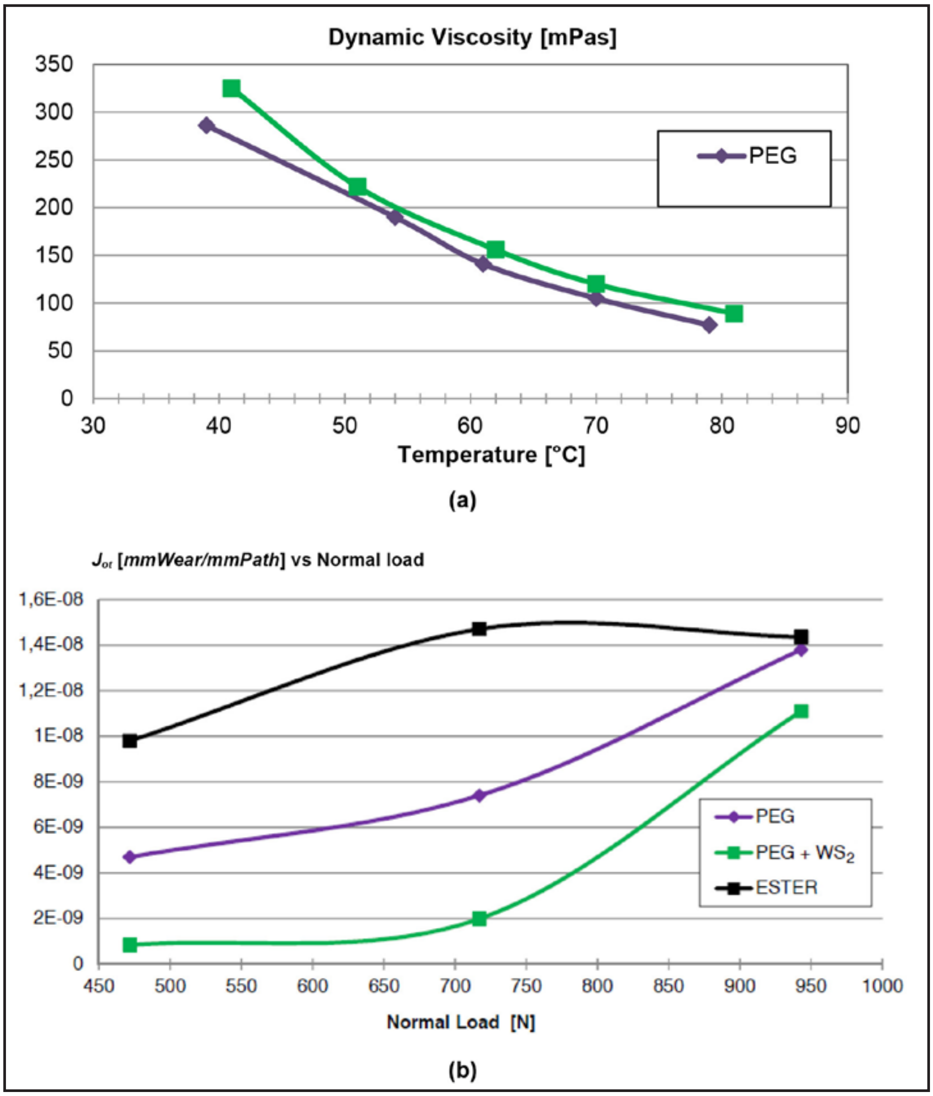

Figure 8 **(a) Dynamic viscosity vs. lubricant temperature for PEG with and without fullerene WS_2 nanoparticles, ISO 2555; (b) wear coefficient J_{OT} vs. normal load after BOD tests on bronze with three different lubricants.**

Acknowledgements. The authors would like to thank KISSsoft AG for the support and the development; Varvel SpA for the tests; the AGMA WG06a committee for the ideas; Tec Star Srl for Fullerene nanoparticles; Dr. Alessio Passalacqua for DOE; and the reviewers for their comments that helped to improve the paper.

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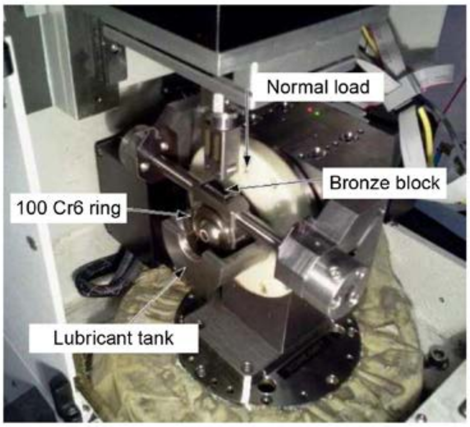
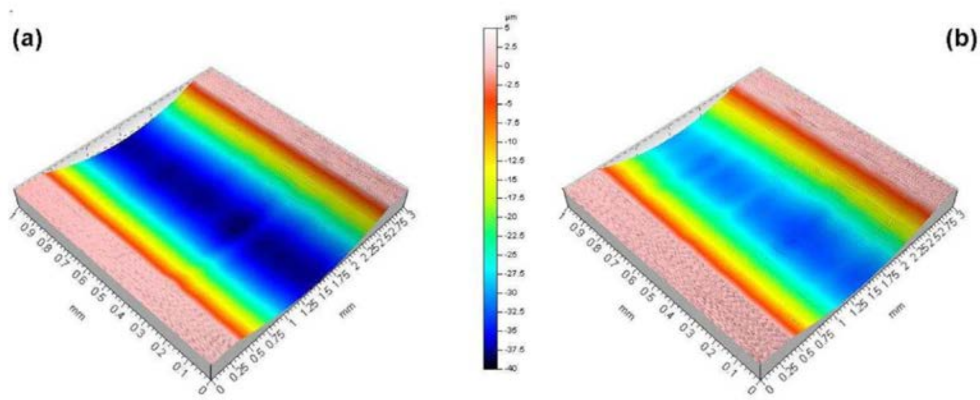


A

BOD parameter	Values
Normal load	471.5 N 717 N 943 N
Ring Speed ω	867 rpm
Period *T*	30 minutes
Ring radius Ruing	17.49 mm
Ambient temperature	25°C

B



C

Figure 9 Tribological BOD tests on bronze block with PEG, PEG+ WS_2, and ester lubricants. (a) BOD tribometer configuration; (b) test parameters; (c) 3-D maps of wear tracks on bronze block — *a* with ester, *b* with PEG + WS_2 lubricant.

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Fabiola Bisanti has a master's degree in industrial engineering — specializing in production and logistics. In 2011 she worked at Caterpillar Global Paving in collaboration to implement a health & safety management system — in accordance with OHSAS 18001 — to align standards work production with safety law. In 2012 she completed a post-master's degree in vibro-acoustic engineering and began work with Bologna, Italy-based Varvel SpA as technical collaborator for an R&D project focused on development of a diagnostics method for detecting gear and gearbox defects via vibration analysis and test bench. Since 2013 Bisanti has worked in Varvel's R&D department, her principal responsibility being the diagnostic and quality control of Varvel's products via vibration and acoustic signals analysis.

Elena Ferramola has a master's degree in physics, specializing in condensed matter. Her collaboration with Bologna, Italy-based Varvel SpA began in 2009 with a 2-year R&D project intended to define alternative solutions to traditional lubricants. In so doing she developed an expertise in polymers for metal replacement, and tribological and mechanical solutions for gear materials issues. Ferramola's collaboration continues today in research and development, where she focuses on with new products feasibility studies and continues her research for innovative tribological solutions.

Giampaolo Giacomozzi has since 2012 held the position of Research & Development manager at Varvel SpA in Bologna, Italy. A 1995 graduate in mechanical engineering at the University of Bologna, for the first five years he worked in the packaging industry as a mechanical designer in the technical department at CAM SpA. He next (2001) worked as a Quality Assurance manager and head of the Prevention and Protection service for Bottazzi SpA, before moving on to Varvel SpA in 2002 where — until 2005 — he was Quality and Environment manager and head of the Prevention and Protection Service. In 2005 Giacomozzi was named assistant technical manager — and from 2007–2012 — technical manager.

Massimiliano Turci is a consultant in gear technology and the design of cam mechanisms. Upon earning his master's degree in mechanical engineering at Studiorum University of Bologna, Italy he began his career as a CAD expert. He then developed X-Camme — a CAM design software used in the packaging and beverage machinery industry. He is a member of the Italian KISSsoft staff for training and engineering — especially for industrial gearboxes. His professional experience is now primarily in gearbox model calculations. Turci is a member of the AGMA worm gear committee.

Bevel Gear Cutting Methods

Dr. Hermann J. Stadtfeld

Bevel Gear Technology

Chapter 9

THE FINAL CHAPTER

This is the last in the series of chapters excerpted from Dr. Hermann J. Stadtfeld's *Gleason Bevel Gear Technology* — a book written for specialists in planning, engineering, gear design and manufacturing. The work also addresses the technical information needs of researchers, scientists and students who deal with the theory and practice of bevel gears and other angular gear systems. While all of the above groups are of course of invaluable importance to the gear industry, it is surely the students who hold the key to its future. And with that knowledge it is reassuring to hear from Dr. Stadtfeld of the enthusiastic response he has received from younger readers of these chapter installments.

Gear Technology would like to thank Dr. Stadtfeld for his peerless scholarship, as well as Gleason Corp. for not only allowing the series to publish, but more importantly, for providing the kind of positive and nurturing work environment that enables such needed work as this to flourish.

— The Editors

Introduction

At the beginning of the twentieth century, motion and torque were transmitted to the driving wheels of the first automobiles with straight bevel gears. With slightly curved (episinoid) teeth, bevel gears were an improved alternative. Both straight and curved bevel gear teeth were cut with several different types of two-tool shaping generators. These cutting methods worked in a single-indexing mode. In 1913 The Gleason Works developed a single-indexing face cutter head method. At the same time, Gleason acquired the patents of Paul Boettcher from Hamburg, Germany, which were also based on face cutter heads. Although the subject of the Boettcher patents was the manufacture of bevel gears in single-indexing as well as in continuous indexing methods, company founder James S. Gleason made the strategic decision to concentrate on the single-indexing method only. The American and Asian automotive industry soon adopted this new method for all automotive and truck axles. The "Gleason method" also spread to Europe — although the European market was shared between Gleason and several local manufacturers with different methods (Ref. 1).

In the mid-1920s the German company Klingelnberg introduced the continuous working "Palloid" cutting method, using a tapered hob that was applied by many European automotive manufacturers until the late 1940s. It is interesting to note that some companies had their own developed bevel gear cutting methods, like Fiat ("Mamano method") and Renault ("Rochat method") (Ref. 2).

After World War II, the special methods from Fiat and Renault disappeared, along with the Palloid method from the automotive and truck industry. Mass-produced bevel and hypoid gear transmissions were now being produced, with a few exceptions, by single-indexing methods on Gleason machines. Many of the bevel gears that have been produced in Europe after 1945 on non-Gleason machines were manufactured with newly developed methods from the Swiss company Oerlikon-Bührle. The so-called "N" and "G" methods from Oerlikon were continuous indexing cutting methods (Refs. 2–4).

The first modern face hobbing process based on machines with cutter head tilt and cutters with HSS stick blades was developed by Oerlikon-Bührle in the 1970s, and caught the interest of European and American manufacturers of heavy trucks. More than 10 years went by before the first face hobbing machines were installed in U.S. automotive gear labs to try out this "new process."

In the meantime, Gleason had also developed a version of the face hobbing process. The Gleason method was also based on stick blade cutter heads and was offered together with the world's first CNC-controlled bevel gear cutting machines (G-MAXX). What started out very slowly in some gear labs in Detroit gained in popularity during the following decade. Desirable attributes like low cutting times, good tooth spacing, and an

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easy to lap surface structure helped face hobbing break through to the U.S. market. It must be mentioned that—without exception—all face hobbing methods are completing processes that reduce cutting times even further.

In Europe, on the other hand, the old face milling, five-cut was replaced by the Gleason face milling completing. The single-indexing completing method also uses cutter heads with stick blades, which in connection with fast indexing CNC machines achieves a similar productivity as the face hobbing process. The reason for European manufacturers to change to this new single-indexing method was the possibility to grind the manufactured bevel gears after heat treatment. The grinding tools are cup wheels that are dressed so that they duplicate the enveloping surface of the face mill completing cutter blades used in the cutting operation. All attempts to find ways to also grind the face hobbed gears in a completing cycle failed, which is the reason why most face hobbed bevel gears are lapped, or sometimes skived, and in very few cases ground in two single side setups.

The Trend in the United States and Europe

Bevel gear grinding in fixed setting mode (single flank grinding) was already introduced by the 1920s for the hard finishing of aircraft gears. However, the stable grinding of automotive bevel gears in a cost-effective completing mode has evolved in production and as a commonly used process only during the past 15 to 20 years. European manufacturers turned away from traditional lapping and converted more and more bevel gear designs to face milling completing. These manufacturers liked the small variations in the finish geometry of the manufactured bevel gears, which is nearly independent from the varying heat treat distortions. The scrap rates for grinding production are lower than that for lapping. Further advantages of grinding are the simplified manufacturing logistics, higher efficiency in operation, and less cleaning effort. Lapped bevel gearsets show lower efficiency (higher operating temperatures) and in some cases more wear because of the lapping grit that can embed in the flank surfaces.

At the same time, the bevel gear manufacturers in the U.S. converted more than 90% of their five-cut face milling applications to face hobbing completing. The American vehicles with bevel, i.e.—hypoid gearsets—are mostly pick-up trucks and sport utility vehicles (SUVs). This category of vehicle with the consumer requirements of the 1980s and 1990s was particularly well suited for the application of face hobbed and lapped hypoid gears.

The Asian automotive industry didn't adopt either of the two trends. The same company might apply the five-cut method on 40-year-old (well maintained) Gleason No. 116 machines, practice completing wet cutting with grinding after the heat treatment, or apply face hobbing dry power cutting with lapping as a hard finishing operation. This variety enables the Asian manufacturer to choose the optimal manufacturing scenario for every batch size and each application case.

Which of the two camps—face hobbing and hard finishing by lapping or face milling and hard finishing by grinding—will establish itself in the future will depend on the technological developments of the next years (Ref. 5). One thing is certain, however—a compromise between face hobbing and face milling is obviously not possible.

Continuous Indexing (Face Milling) with Lapping or Single-Indexing (Face Hobbing) with Grinding

The question as to which method delivers the better rolling performance and higher strength of the manufactured bevel gearsets has often been asked. The answers are as different as the people asking the question, and the answers have changed over time. The most significant influence upon the changing properties of the two methods was the development of bevel gear grinding. Today's bevel gear grinding improves, in general, all important properties such as strength, noise characteristics and efficiency. A global rating of the strength of bevel gearsets that have been manufactured with various combinations of manufacturing methods can be rated using the following grades (1→excellent, 4→poor):

1. → Face milling completing and hard finishing by grinding
2. → Face hobbing and hard finishing by lapping
3. → Face milling with five-cut and hard finishing by lapping
4. → Face milling completing and hard finishing by lapping

A rating regarding noise emission and efficiency is basically the same. The rating list makes it clear that the real question is not face hobbing or face milling, but rather lapping or grinding. A ground gearset with an epicycloid flank line might have achieved the best rating—if it were possible to manufacture. The mathematical function of the flank form, the taper of slot width and tooth thickness in face width direction, as well as the tooth depth taper (parallel or conical), play an important role, which makes it important to clarify the following parameters:

- Macrogeometry
- Flank surface topology
- Ease-Off topography
- Root fillet geometry
- Microstructure of surface

These parameters and their influence on the rolling performance and strength of a bevel gearset are discussed in the following sections. This leads to head-to-head comparisons of the functionality and economy of the two methods, which will finally lead to a recommendation for the method best suited for a certain manufacturing environment, i.e.—which geometry best fulfills the requirements of the mechanical gear properties. The analytical explanations concentrate on the most commonly used method combinations, with the ratings 1 and 2 in the list from the previous page.

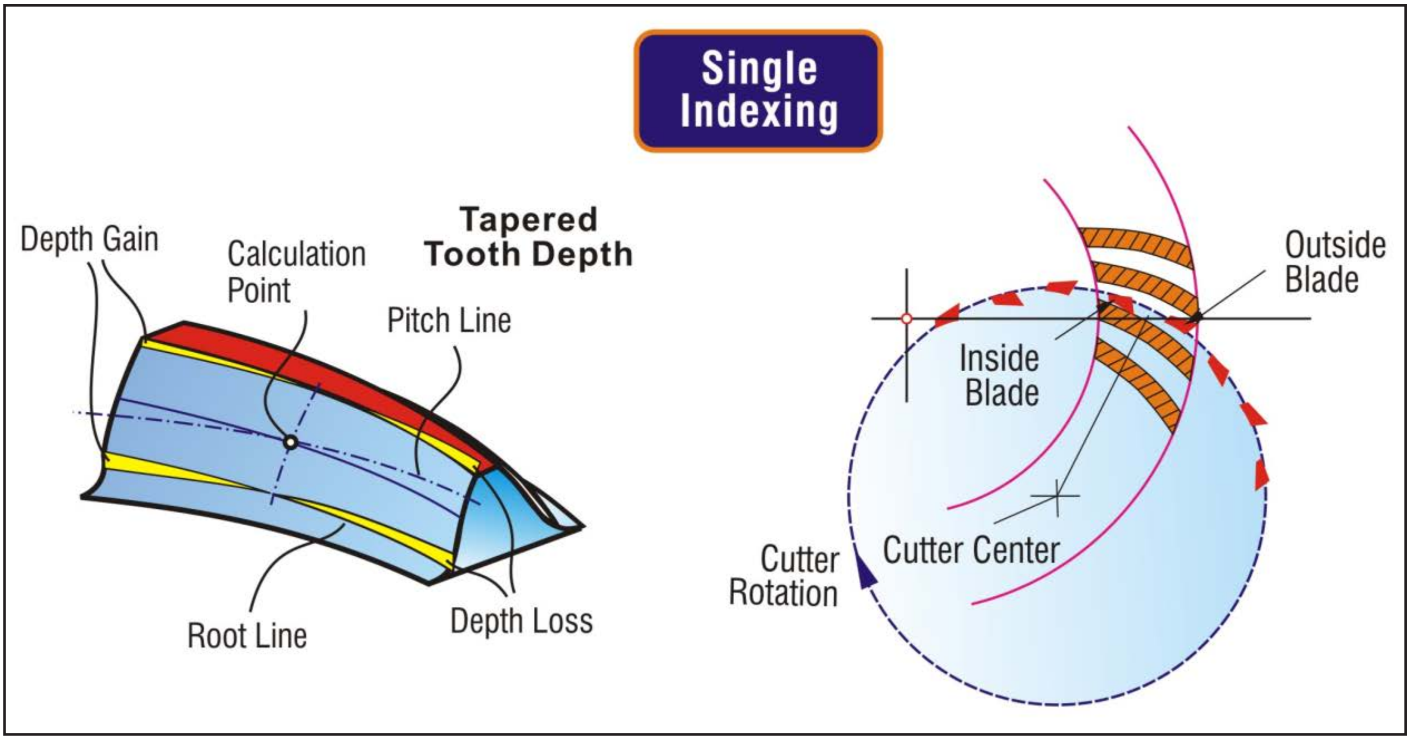

Figure 1 Single-indexing (face milling) Formate.

Observation of Differences in Macrogeometry

Macrogeometry of face milled bevel gears. Face milled gearsets are manufactured in single-indexing — one slot at a time. The right side of Figure 1 shows how all the inside and outside blades of a face mill cutter head pass through one slot of a plane gear, while the cutter moves perpendicular to the drawing plane until the full depth position is reached. For a simple explanation, it is assumed that the manufactured bevel gear is cut in Formate. In this case there is no additional motion and the cutter rotates around it's center, while the center is also fixed relative to the generating gear axis. The flank line's mathematical function is a circle. The distance between the cutter center and the gear center results from the desired mean spiral angle in connection with the cutter diameter. In the case of bevel or hypoid pinions and gears, the circular flank lines wind around a conical or hyperbolic pitch element, similar to the straight flank lines that wind around the pitch cylinder of a helical gear.

The curvature of the teeth, as well as the relative curvature of the meshing teeth, is constant along the face width of the teeth. The slot width, equidistant to the root, is also constant. Consequently if both flanks are cut with the same cutter simultaneously (completing), the radius of the convex flank is about the amount of the slot width smaller than the radius of the concave flank. Figure 2 shows a schematic of the unrolled flank lines for a pinion.

The difference in outer and inner circumference of the generating gear causes, as seen in Figure 2, an extreme tooth thickness taper that leads to an un-proportionally thin and high tooth in the toe region, and to a short and thick tooth at the heel. Other than the fact that a pointed topland can occur on the toe, the teeth of the one member will not fit and roll in the slots of the other member if both members are manufactured in a completing process. This is why a certain tooth depth taper is applied in all face milled completing bevel gears. The tooth depth taper is calculated in such a way that it generates a slot width taper that splits the difference in circumference between toe and heel in an equal slot width and tooth thickness taper (in the height of the generating gear pitch plane). Figure 3 illustrates this principle using a ring gear as an example. This assures also that the tooth profile changes it's size between toe and heel proportionally and, in turn, that

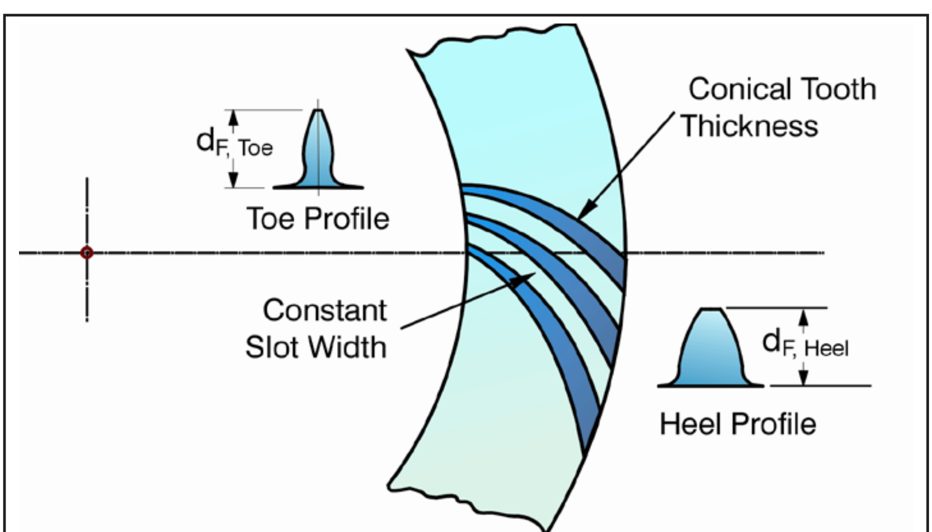

Figure 2 Flank lines in generating gear plane of parallel depth face milling; profiles of resulting pinion tooth.

the teeth of a member fit in the slots of the mating member with a controllable amount of backlash. Given this explanation it becomes obvious that the proportions of tooth depth and slot width for face milled completing bevel gears is not a freedom to be chosen, but a given relationship necessary for establishing a functional gearset.

Macrogeometry of face hobbed bevel gears. Face hobbed gearsets are manufactured as continuous indexing; while the outside blade and following inside blade of one blade group cut one slot, the following blade group will enter the next slot (Fig. 4, right). This is accomplished by the simultaneous rotation of the cutter and workpiece, where the work rotates per cutter revolution for as many pitches as the cutter has starts. The resulting mathematical function of the flank lines of a plane generating gear is an extended epicycloid. In this case the curvature radius of the flank line is increasing from toe to heel and the average curvature depends not only on the cutter radius, but also on the number of starts of the cutter head (*see also original text chapters 2.3 and 2.4*).

The constant relative indexing motion between cutter and work results in an equal split of the inner and outer circumference on the toe and heel — as well as an equal split between toe and heel along the entire face width. This leads to a "natural" slot width taper and equal tooth thickness taper. If the tooth depth along the face width is designed constant (parallel depth), then the pitch cone is equidistant to the root cone, which with no Ease-Off corrections results in a perfectly conjugate geometry between produced pinions and gears.

The fact that face milled gears have no slot width taper — but a large tooth thickness taper — and face hobbed gears have an equal slot width and tooth thickness taper, is the one reason why it is impossible to grind face hobbed gears (using a cup-shaped grinding wheel) simultaneously on both flanks of a slot in a completing process. And, the reason why face hobbed gears cannot even be ground on even *one* side of a slot at a time with a cup-shaped wheel is demonstrated in Figure 5. The difference between an epicycloid and a circle has a nearly sinusoidal appearance. Single side grinding

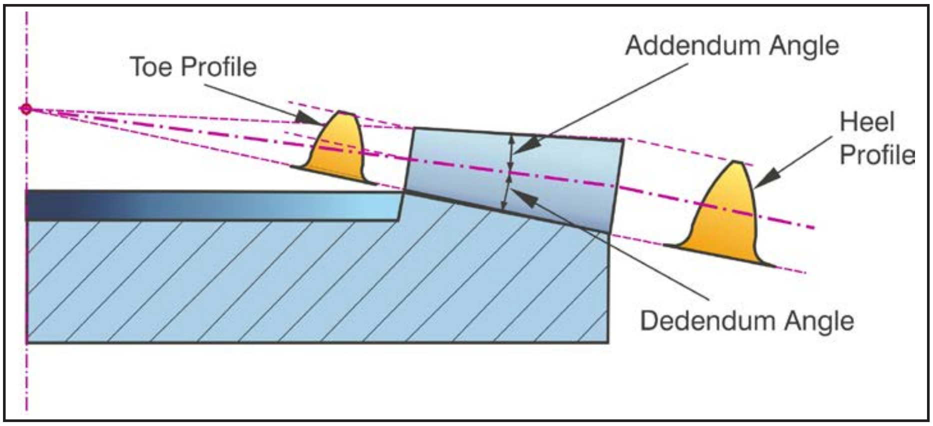

Figure 3 Tooth proportions — tapered depth face milling completing.

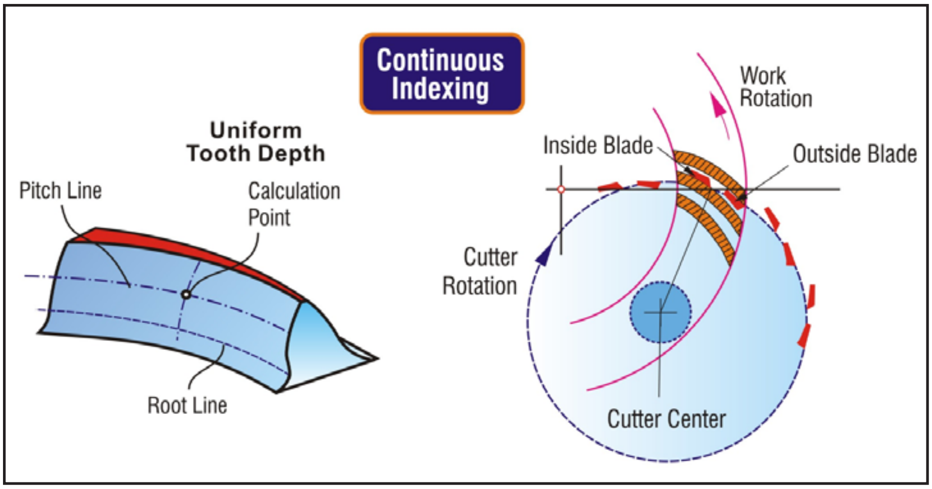

Figure 4 Continuous indexing (face hobbing) Formate.

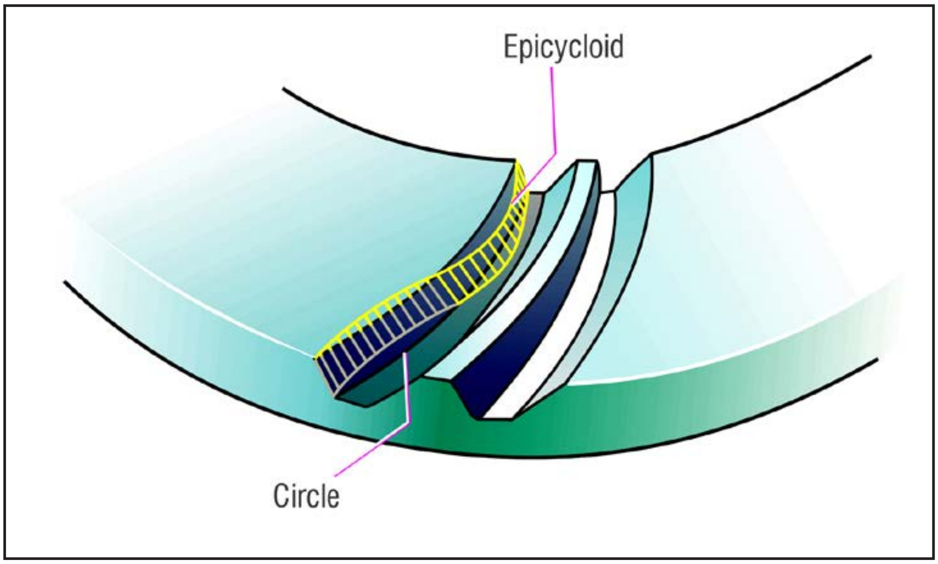

Figure 5 Circular arc vs. extended epicycloid.

might be possible with big variations in stock removal along the face width, but a change in the properties of the ground gearset must be expected because it will destroy the epicycloid and replace it with a circle. The specifically favorable displacement properties of the face hobbed, soft manufactured geometry will be removed due to the grinding.

The longitudinal macrocurvature is constant in face milling and changes along the face in face hobbing. However, an interesting longitudinal shape for a flank line is an involute. Teeth with such a shape would be insensitive to longitudinal displacement between pinion and gear flank, similar to the insensitivity of regular cylindrical gears with respect to a center distance change. For example, Klingelnberg Palloid gearsets have an involute flank line function. Neither face hobbing nor face milling is able to produce involute flank lines; nevertheless, there is always one point along every curved flank line that fulfills the so-called involute conditions.

Figure 6 shows the curvature required to achieve involute conditions at different points along the flank line. Independent from the mathematical flank line function of the bevel gears discussed in this paper, which are epicyclic or circular, the position of the involute point relative to the center of the flank or relative to the initial contact position is significant for noise and load behavior. It is perceived as ideal if the initial contact for light load is positioned towards the toe and moves under increasing load to the heel, while the contact spreads. Under 100% nominal load the contact area should use the entire flank — without hard contact at the teeth boundaries. The positioning of the involute point allows control of the contact movement under load. It is recommended to choose an involute point location between the flank center and the heel. If only small displacements are expected, the involute point should be positioned at the heel border. Large displacements require an involute point between center and heel. However, the involute point should not be positioned at the center of the face width because this would prevent contact movement and therefore cause surface fatigue at the flank center. The contact pattern tends to move under load towards the involute point; this movement becomes smaller as the contact pattern approaches the involute point. No contact movement will occur, even under severe overload due to matching locations of contact pattern and involute point. In spite of the significance of the involute point, an involute-shaped flank line is not desirable.

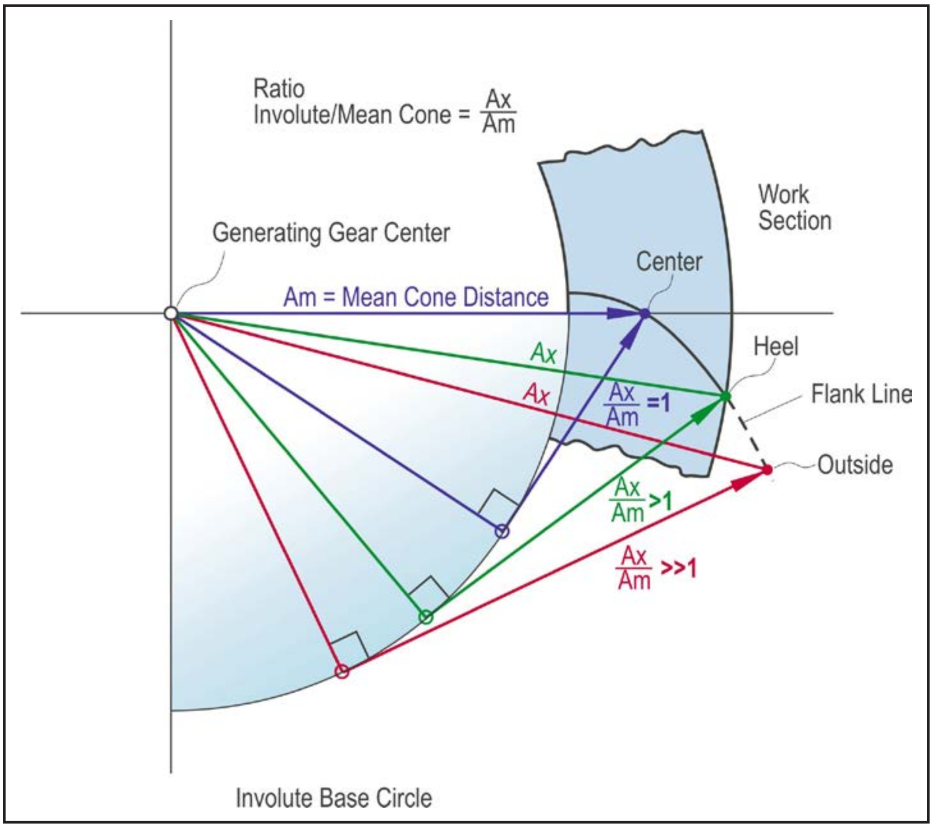

Figure 6 Involute-shaped flank line and relationship between involute and cutter radius.

Face hobbed bevel gearsets tend to have their involute point location between the flank center and the heel, which gives them the reputation of being forgiving with respect to gearbox and gearset deflections. The design practice for modern face milling completing gearsets takes advantage of the relationship described in Figure 6 and has adopted smaller cutter radii than were used until some years ago (with the five-cut process), in order to achieve a predetermined position of the involute point. The so-called ratio of invoute-to-mean-cone (*Ax*/*Am*, Fig. 6) should be above 1.0, while the ratio of involute-to-outer-cone has to be below one, or should at least not exceed 1.0. Face milling bevel gearsets designed according to this rule achieve the same forgiveness for high deflections as face hobbed gearsets.

Surface Topology

Surface topology of face milled bevel gears. Face milled gearsets have machining marks (generating flats) that are parallel to the lines of contact between pinion and gear. In other words, the cutter blades cause traces on the flank surfaces during the cutting process with a spacing that depends on the roll rate and angular distances of the blades in the cutter head; the contact lines between pinion and gear flanks are parallel to those machining marks. Figure 7 offers a simplified visualization of the relationship between the generating flats and a contact line. Case 1 (Fig. 7, left) shows a plane as a simplified ring gear flank and a pinion flank, simplified to a cylinder. The contact line between cylinder and plane is parallel to the machining marks of both surfaces; this is typical for two flank surfaces machined in a single indexing generating process. The surface combination in case 1 leads to a "rough" rolling of the cylinder on the plane. There is a high risk that lapping compound between the two surfaces will be pressed out and wiped away from the contacting zone; smoothness of rolling and lappability are not good in case 1.

The smooth surface in case 2 represents a Formate ring gear flank that does not show any generating flats. The contact line between cylinder and plane is, as with case 1, oriented in the direction of the generating flats of the cylinder. This resembles the surface analogy to a bevel gear pair of a generated pinion and a Formate ring gear. Also in case 2, the result is a "rough" rolling of the cylinder; however, lapping compound between the surfaces has a better chance of remaining in the contact zone. Case 2 leads therefore to poor rolling performance but has better lappability than case 1. In order to achieve good lapping results in face milling, the surface waviness (flat amplitudes) is required to have only about 10% of the surface waviness of face hobbed gearsets after cutting. While here the surface roughness is basically non-critical, the opposite is true regarding ground face milled gearsets. Flank form and surface condition of semi-finished face milled gears is less critical than with face hobbed gearsets prepared for lapping.

Surface topology of face hobbed bevel gears. Case 3 (Fig. 8, left) is a model of a generated face hobbed flank pair. The contact line between cylinder and plane crosses the generating flats under an angle. This configuration causes a gradual, soft rolling of the cylinder and provides a pumping of the lapping compound through the contacting zone (when the lapping process applies). The result is a high rolling smoothness and good lappability in case 3 (Ref. 6).

The smooth plane in case 4 represents a Formate ring gear flank surface with no generating flats. The contact line between cylinder and plane crosses the generating flats of the cylinder, as in case 3 — under an angle. This is analogous to the surfaces of a face hobbed and form generated bevel gear pair. Also in case 4, the result is a smooth rolling of the cylinder. Lapping compound placed between the two surfaces will be pumped through the contact zone, similar to case 3. Case 4 provides the best rolling quality of the 4 discussed cases, and shows equal lappability to case 3.

The observations in this section lead to the conclusion that face milled gearsets are not suited for hard finishing by lapping. However face hobbed gearsets, in contrast, show excellent suitability for lapping as a hard finishing process.

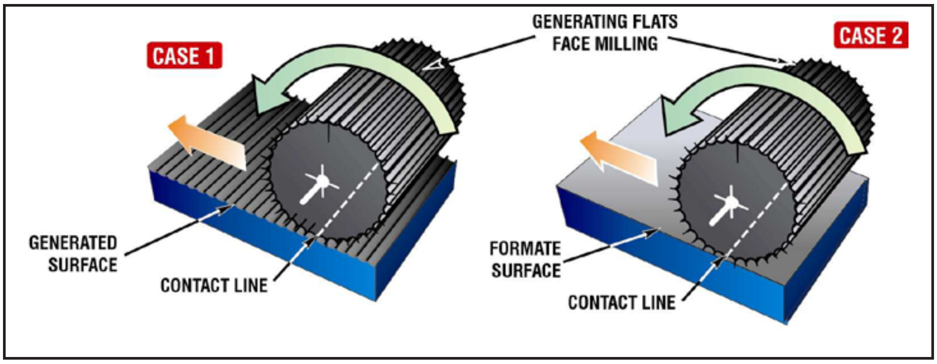

Figure 7 Principal roll condition for face milled gearsets.

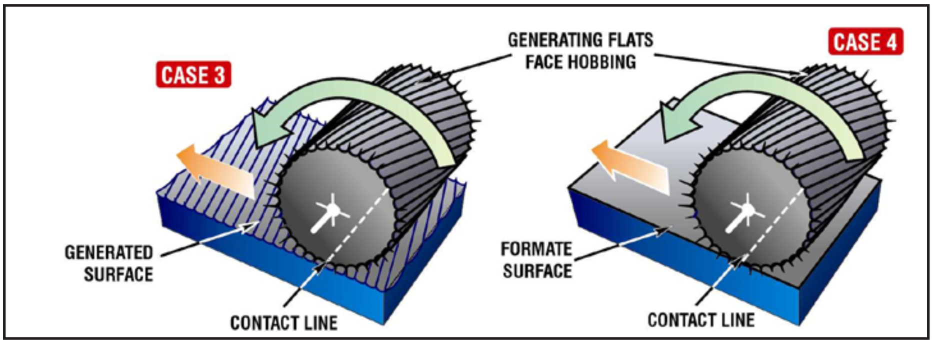

Figure 8 Principal roll condition for face hobbed gearsets.

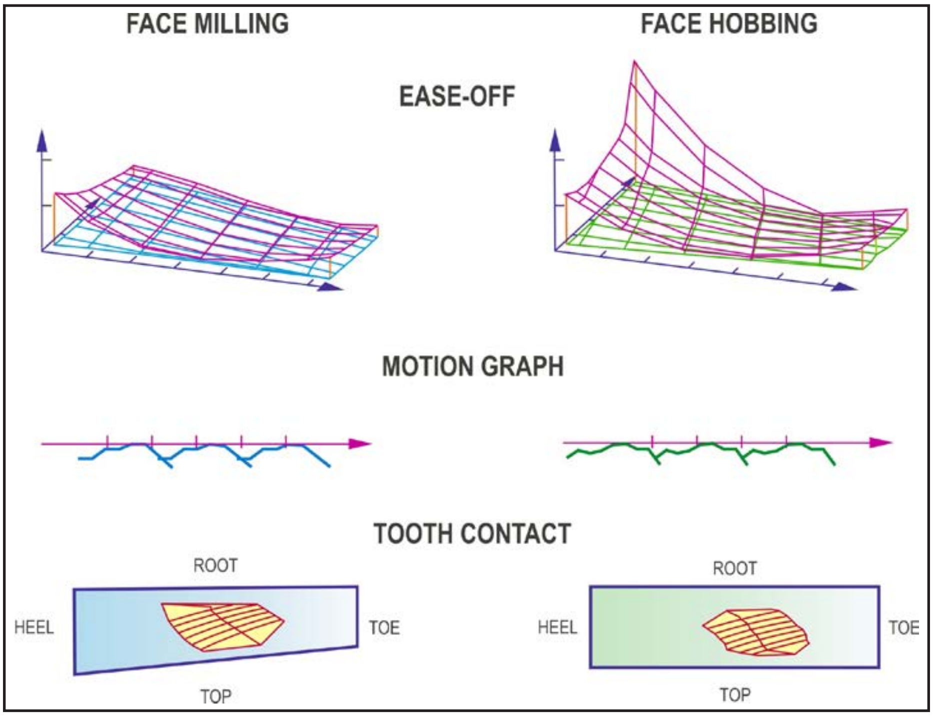

Figure 9 Analysis results of modern designs — left, face milling; right, face hobbing.

Ease-Off Topology of Face Milled and Face Hobbed Bevel Gearsets

The usual design calculation practice applies different tooth contact pattern and Ease-Off topographies for face hobbed vs. face milled designs. This was based in part on the large cutter radii recommended in the past for face milled gears and the small recommended cutter radii in face hobbing. Additional reasons for the design of different contact patterns included the conjugate basis with only simple optimization freedoms of face hobbed gearsets vs. the non-conjugate basis of face milling that offered a variety of geometric and kinematic optimizations.

Today's modern bevel gear design defines the cutter radii independent of the cutting method in order to achieve an optimal displacement characteristic. The shape and size of the contact pattern can be chosen nearly independent of the cutting method. Additional *UMC-Motions* and cutter blades with "blended Toprem" and "blended Flankrem" can be equally applied to face hobbed and face milled gearsets (Ref. 7). Figure 9 (left) shows the exotic-appearing Ease-Off of a face milled bevel gear pair. The contact pattern, which only a couple of years back was typical only for face hobbed gearsets, has been calculated using *UMC-Motions*. The complex Ease-Off function of the face milled gearset is realized with excellent repeatability after heat treatment, by grinding.

Ease-Off and contact pattern of the face hobbed bevel gear pair (Fig. 9, right) have also been designed using *UMC-Motions;* cutter blades with blended Toprem were also applied. Modern flank optimizations adapt very well to face hobbed bevel gearsets if a heat treatment with low distortions is possible, and if high-speed, short-time lapping is applied as a hard finishing operation. High-quality, ground bevel gearsets have to be rolled as individual pairs in order to measure single flank error or structure-borne noise in different pinion cone positions. The final pinion mounting distance, i.e. — the required shim rings — are determined on the roll tester. The logistical cost of ground gearsets is therefore only lower prior to the roll testing.

A lapped surface finish still depends today on the interaction between pinion and gear; it is impossible to achieve the precise mathematical target surface. Heat treat distortion and inconsistent lap removal in different zones of the flank surface result in a final contact appearance that differs significantly from the tooth contact analysis at the stage of the design calculation. Contact patterns of lapped gearsets have a very soft transition to the flank areas without contact and allow realization of excellent, low-motion error. Nevertheless, the variation in one manufacturing batch is high, and every gearset is matched after lapping; yet there still needs to be roll testing, with the possibility of finding an optimal build position that requires individual pinion shimming. The roll testing also serves of course to find and eliminate reject pairs.

This section about Ease-Off and tooth contact optimization has, in summary, four messages to convey:

1. There are Ease-Off limitations in face milled gearsets caused by the tapered tooth depth and the smaller cutter radii, as they are used today. They can be eliminated with *UMC-Motions* (and three flank sections).
2. The nominal geometry of face milled bevel gearsets can be reproduced by grinding with high accuracy.
3. There are limitations regarding the final Ease-Off for face hobbed and lapped bevel gearsets due to heat treatment distortions and non-uniform material removal of the lapping process.
4. Resulting Ease-Offs and tooth contact patterns look unconventional and exotic from a conventional viewpoint, but are more application-oriented than tooth contacts of the past.

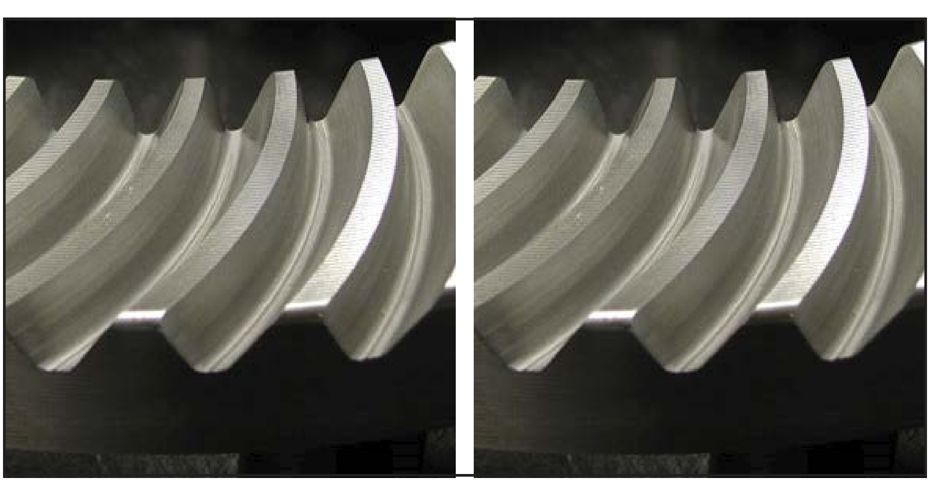

Figure 10 Ring gear root fillet — left → face milling; right → face hobbing.

Root Fillet Geometry of Face Milled and Face Hobbed Bevel Gearsets

The face hobbing macrogeometry has a conical slotwidth along the face, which is also true of the root bottom. The blade edge radii and the blade point width must be calculated from the smallest root width on the toe of the slots. Not only are the edge radii and blade points of inside and outside blades limited by the conditions of the smaller slotwidth at the toe, the movement of outside and inside blades along non-concentric tracks causes cross-over between outside and inside blades and leaves a fin — or step — on the root fillet bottom (Ref. 8). Although a step in the root can be averaged out between toe and heel by axial stepping of the blades, a fully rounded root fillet is not possible for a continuous indexing process utilizing face cutter heads (Fig. 10, right).

The strength advantages of face hobbing experienced in the past are based, to a larger extent, on the insensitivity to deflections and tolerances. This insensitivity has its origin in the central location of the involute point due to a small cutter radius and a high number of cutter starts. The subsequent reduction of the load concentration at the heel allows higher loads with reduced risk of tooth fracture. A non-optimized, standard face hobbing design today still delivers a stronger appearing gearset compared to a non-optimized face milling gearset.

The face milling root geometry can be optimized to a stepless, smooth root fillet and, in many cases, even a fully rounded root fillet is possible. Optimized, face milled bevel gearsets gain a definite strength advantage compared to optimized, face hobbed gearsets due to the possibility of a more optimal root design (Fig. 10, left).

Face milled bevel gearsets must be relieved with protuberance blades at the flank-root transition areas on the pinion and gear flanks in order to keep the grinding removal in these areas low and in order to achieve a soft flank-root transition.

Lapping of flank surfaces utilizes the top of the one member to lap the root of the mating member, and vice versa. The transition between flank and root must be relieved in the cutting operation by using protuberance in the pinion blades, whereas the ring gear flanks do not require this relief. This feature accounts for the lap removal that is on the pinion flanks because of the higher number of pinion revolutions , a multiple of the ring gear lap removal. The high material removal on the pinion would cause a lapping step between flank and root. The protuberance relief differs along the face width as a result of the generating process and the changing pinion diameter between toe and heel. Small protuberances will leave a partial lapping step along the face width, where in a case of too much protuberance some relieved section will not be lapped out. Both cases require a compromise in the design of the transition area between flank and root that either causes interference (lapping step) or weakening of the root. Interferences are often not recognized in the roll tester, and result in unexpected noise phenomenon under load. Good pre-corrections for heat treatment distortions and the use of pinion and ring gear blades with blended Toprem instead of protuberance limited to the pinion can eliminate the disadvantages of the conventional protuberance — if lapping time is kept short.

The message regarding strength in this section is that a more optimized root fillet can be machined by grinding. Also, interferences that can cause noise as well as strength problems can be avoided by grinding.

Surface Roughness, Waviness and Texture

Microsurface topology and microsurface structure are related properties of a surface characteristic. The generating flats that are crossed to the contact lines between pinion and gear in face hobbing have been mentioned in (*original text, chapter/section 9.5.2*). The characteristic of the generating flats in face hobbing helps to reduce excitations of higher multiple tooth mesh frequencies in the operation of a bevel gearset. The sources of those excitations are low because of the crossed arrangement, i.e. — contact line→ generating flat; the generation of additional high frequency excitations is reduced and the flat structure (Fig. 11, left) is eliminated with lapping. The remaining structure after lapping is generated by the lapping grit and the relative motion between pinion and gear. The relative motion can be captured by the relative sliding velocity, shown for a hypoid gearset (Fig. 11, right). The surface texture generated by lapping is consistent with the vector map of the sliding velocities, which shows a different orientation than the contact lines between the pinion and gear flanks. This also reduces the excitation of higher harmonic frequencies during operation of a gearset; but this excitation is not completely eliminated, as the flank surface structure between pinion and gear match exactly due to the manufacturing process, where the pinion is the finishing tool of the gear, and vice versa. The lapping motion can also induce long wave surface modulations. Further modulations that have a shorter wave length are leftovers from the generating flats caused during the cutting process. If all the mentioned possible imperfections are considered — and can possibly be avoided — the result is a remarkably quiet, lapped gearset.

In face milling the generating flat structure is removed by the grinding operation, but the traces from the grinding wheel grit are left. On the pinion and gear flanks those traces are parallel to the root and extend along the entire face width (see "Track of Blade Point," Fig. 11). Although the traces have an inclination to the contact lines, the valleys and crests of the longitudinally oriented roughness of pinion and gear are almost a match in their direction. The sliding component in profile generates a higher order excitation that presents a scoring risk. The goal is to achieve surface roughness values of $Ra \leq 0.8\mu m$ and $Rz \leq 5\mu m$; the roughness values of lapped surfaces are smaller. Certain imperfections, e.g., in the grinding wheel profile, repeat with high accuracy from flank to flank on all teeth of a ground gear. If the number of imperfections is, say, three, even though the magnitude of the imperfection might be below one micron, the likelihood of an excitation of a third harmonic frequency will be high. Gleason has developed a package in order to improve the surface texture of ground bevel gear surfaces. Under the trade name MicroPulse — a combination of dressing parameters, machine motions and dynamic effects are utilized to generate a surface texture during a "regular" grinding operation that gives the pinion and gear surfaces different, non-matching surface textures that in the past could only be realized via honing processes.

In concluding this section, it can be stated that the surfaces of lapped bevel gears are more optimized regarding roughness and rolling performance than the surfaces of ground gearsets. In contrast, measurement results seem to prove

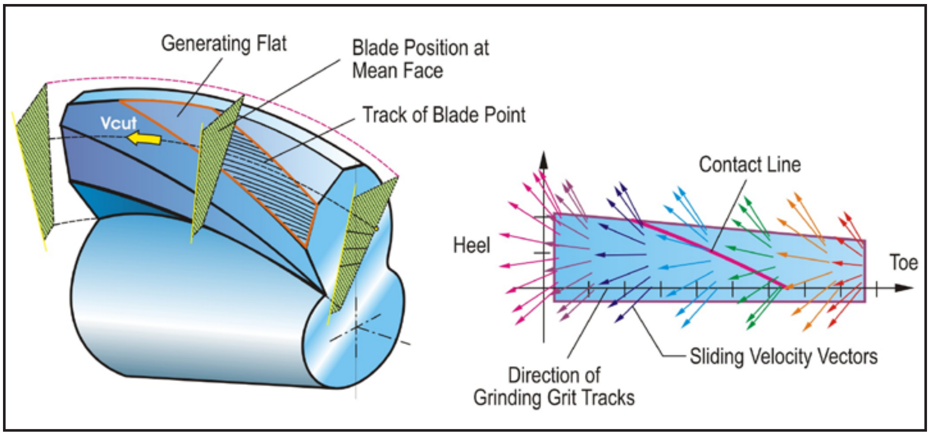

Figure 11 Generating flats and blade roughness traces, sliding velocity vectors, and contact line.

that the efficiency of a broken-in, ground bevel gearset is higher than the efficiency of comparable lapped pairs.

Global Strength Considerations

When face hobbing and face milling designs are compared, finite element calculations and strain gauge measurements prove that idealized teeth and root fillets with no or little surface roughness, optimal blend between flank and root, and optimal rounded root fillet without steps and fins in the root bottom, both deliver identical results.

The higher precision of the flank form and the more favorable root fillet of the face milled and ground gearset are therefore compared to the advantage gained from the more optimal surface structure of the face hobbed flank surfaces. Some of the possible advantages of the face hobbed flanks cannot always be realized due to variations in the lapped flank surfaces. Consistency in the grinding process is obtained through a strong effort regarding grinding cycles, grinding oil filtering, condition of the grinding machine, dynamically sound machine placement on the shop floor, etc.

In a highly consistent grinding production, it is possible to make gears that correspond in both surface durability and root bending strength — and extremely close to predictions calculated with sophisticated finite element programs. It is also possible to address single properties, such as sub-surface stress, in order to reduce them without sacrificing other properties.

Fine-Tuning and Optimization During a Lifecycle

During initial prototype testing, and also during the following lifetime of a gear design, it is often necessary to address specific parameters or features in order to eliminate a certain problem without having negative side effects on other features. At the beginning of the lifetime of a new design, the field of attention might be tooth fracture, pitting, or case crushing. For ground gearsets it is possible to change the root fillet radius, eliminate an interference with blended Toprem, change the contact size or position, modify the displacement characteristic, or add a *UMC* heel section in order to eliminate edge contact under high load, without a cross influence of the one optimization on all other features of the flank and root geometry.

The face hobbing finish geometry (including the flank > root blend) still depends in today's lapping to a large extent in the inconsistencies of the lapping process, and also is a result of the difficulty in controlling the material removal mechanism of lapping in general. Making small changes to the lapped tooth contact on the drive side may also cause some change on the coast side and could generate an unwanted change in the high load contact pattern. The transition between flank and root (lapping step) can also be influenced because the lapping process connects all the geometrical features of flank and root transition together. Changing the contact displacement characteristic by optimizing the lapping motions is almost impossible. In such a case a slightly modified new design calculation is required. This also means that most of the development that had been conducted to get from the theoretical design to a functional bevel gear or hypoid transmission will be scrapped and the development work will have to start all over again.

The advantage of ground bevel gear designs during the lifecycle of the gearset becomes obvious, due to the possibility of controlling nearly every single parameter independently without the risk of destroying other positive features of the gearset.

Manufacturing Cost Comparison

So far this chapter might seem to some readers as a "white paper" dedicated to grinding. However, the diligent, conscientious reader will have noticed that the last sections presented many facts that were not known or considered in the context of the evolution that grinding has experienced during the past 15 years, and particularly during the past five years. Some time ago, the manufacturing stability of automotive and truck production grinding was not at an acceptable level, which made in the comparison with lapping, face hobbing lapping the winner not only in manufacturing cost but also in noise and strength.

The progress in grinding, some of which has been reported in this chapter, is significant. It begins with a grinding friendly basic geometry with suitable parameters for a good displacement characteristic and a low noise excitation. The development of the Ease-Off is targeted today at conjugate flank center and sufficient crowning towards the boundaries of the teeth. The result is a highly effective contact ratio for high strength and smooth rolling, yet sufficiently robust to accept manufacturing variations and deflections. The right semi-finish strategy and heat treat pre-corrections are also important to guarantee good input for an efficient grinding operation. That does not at all mean grinding is the better process; it might only emphasize that grinding today is comparable with lapping regarding process stability and noise quality. To out-perform good, lapped gearsets regarding low noise emission, for ground bevel gearsets it is not yet possible — or at least very difficult. The strength of ground bevel gears is only better if the latest rules with respect to flank form and transition between flank and root are followed. Lapping can also benefit from the advancements made in grinding. *UMC Motions*, with three sections as well as a more advanced root relief, has been tried successfully in combination with short-term lapping and low heat treat distortions.

An attempt at a cost comparison between lapping and grinding was made (Fig. 12). Continuous face hobbing under comparable conditions is somewhat faster than the single indexing face milling. In spite of this, face milling is a semi-finish operation while face hobbing in preparation for lapping is considered a finishing process, and the reason the cost of the soft cutting operations for both scenarios can be estimated as equal. This also applies to heat treatment and grinding, or hard turning journals and seating shoulders. The cost estimations (Fig. 12) are therefore limited to hard finishing operations, including final measurement and roll testing. The hourly machine rates were calculated using a depreciation period of five years with a one-shift, 5-day operation.

Manufacturing cost of lapping. It has been assumed that one operator handles two lapping machines, and one operator attends to one testing machine for a 100% testing. The lapped gears are handled in pairs after lapping. The scenario in the (Fig. 12) spreadsheet assumes that all

Item	Lapping	Part Cleaning	Testing	Log of Manufacturing Pairs	Log of transporting from Lapping to testing in pairs	Quality
Machine Rate / Hour	$62.50		$60.00			
Operator / Hour	$17.50 (=35.00/2)		$40.00			
Door to door time / part	0.07		0.05			
Rate per part	$5.28	$1.50	$5.00	$2.00	$0.50	
Warranty resulting of skipped oil change						$1.25
Cost of 3.5% reject / $45.00 per set						$1.58
					Total Finishing Cost	$17.11

Item	Pinion Grinding	Gear Grinding	Testing	Coordinate Measurement		Quality
Machine Rate / Hour	$88.50	$88.50	$62.50	$50.00		
Operator / Hour	$17.50 (=35.00/2)	$17.50	$40.00	$40.00		
Door to door time / part	0.07	0.03	0.05	0.03 (=.25/10)		
Rate per part	$7.00	$3.50	$5.13	$2.25		
Warranty resulting of skipped oil change						
Cost of 0.5% reject / $45.00 per set						$0.23
					Total Finishing Cost	$18.09

Figure 12 Cost estimation spreadsheets—top → lapping; bottom → grinding.

lapped pairs have to pass a pinion cone search, with structure-borne noise analysis on a roll tester, in order to determine optimal shim position. (Coordinate measurement after lapping was not included in the spreadsheet.) The reject rate was estimated at 3.5%. For scrapped parts the entire value added, including the material cost, was used to multiply with 3.5% and the result was added to the cost of one pair. The calculation of the cost of scrap is based upon an estimated average cost for one pair at $45. Because of the difficulties in removing all the lapping grit from the lapped parts, the cost of an excessive washing cycle was added. Today nearly all manufacturers skip an oil change after 1,000 miles. The remaining lapping grit (some of which is in the surface of the parts, which will either work it's way out of the surface into the oil) or the grit that extends partially outside of the flanks, is crushed due to the flank sliding and rolling under load, and eventually end up floating in the oil filling. This leads in any number of documented cases to the destruction of bearings and/or seal rings. The cost of the warranty repair (in some cases this requires the change of an entire axle unit) has been estimated based on a 0.25% occurrence.

Manufacturing cost of grinding. It has been assumed that one operator handles two grinding machines and one operator attends to one testing machine for a 100% testing. The ground gears are not handled in pairs after grinding. The scenario in the spreadsheet assumes that all ground pairs have to pass a pinion cone search with a structure-borne noise analysis on a roll tester in order to find the individual roll-optimal axial pinion position in the gearbox. The pairs are mated after testing, which leads to the same transportation, storage and assembly logistics for ground parts as for lapped parts. Coordinate measurement is performed for every 10th part; reject rate was estimated with 0.5%. For scrapped parts the entire value added, including the material cost, was used to multiply with 0.5% and the result was added to the cost of one pair. In order to compare the cost of scrap in grinding with lapping, an estimated average cost of one pair at $45 (equal for lapping and grinding) was used.

Summary of the cost comparison. The resulting manufacturing cost per set in the two tables (Fig. 12) is very similar, which is not well suited in the presented form as a basis for a decision of one method over the other. However, there are many factors that have not been addressed, and both scenarios might change based on these factors. A bevel gear manufacturer wanting to re-evaluate the choice between "lapping or grinding" can expand the tables with certain cost for the non-considered factors, and also use different rates and amounts for the costs listed in Figure 12, which may be deemed more suitable for his present manufacturing environment.

Typical Applications of Ground and Lapped Bevel Gearsets

All major industries where bevel and hypoid gearsets are applied are listed in this section. An effort has been made to find a realistic estimation of the kind of hard finishing installations as they are practiced by the different industries, e.g., manufacturing branches.

Aircraft transmissions. Based on national regulations, are ground in all western countries.

Industrial gearboxes. Production stability for smaller batch sizes led in this industry to the grinding of face milled bevel gears and to the hard skiving of face hobbed bevel gears. Lapping is only used by a few manufacturers. Bevel gears with low requirements regarding their transmission function are sometimes not finished after heat treatment.

Agricultural equipment and small tractors.Ninety percent of the manufactured bevel gears are not hard finished after heat treatment.

Medium and large farm tractors. Twenty percent of the bevel gears are lapped; 80% are ground.

Construction equipment. Eighty-five percent of the applied bevel gears are not hard finished; 15% of the applied bevel gears are either lapped or ground.

Power tools. Forged or sintered powder metal bevel gears are used in non-professional grade products. Premium contractor grade tools use mostly face milled cut bevel gears, which are not finished after heat treatment.

Railroad. Product safety and high reliability requirements with small batch sizes led in this industry generally to the hard skiving of face hobbed bevel gearsets. There is also some face milling with grinding after heat treatment applied.

Large bevel gears above 1,000mm ring gear diameter. Low quantities and high-cost-per-piece led in this industry to the skiving of heat treated, face hobbed bevel gears.

Heavy trucks (class 8, semi). In the U.S., 90% of all heavy truck axles are lapped. In Europe and Asia a mix of 60% lapped and 40% ground bevel gears are built in heavy trucks.

Light trucks, pick-ups, sport utility vehicles. Seventy percent of all produced bevel gearsets are lapped; 20% are ground.

Passenger cars with all-wheel-drive. Almost 100% of all-wheel-drive passenger cars manufactured in Europe are ground; in the U.S. and Asia, 65% are lapped and 35% are ground.

Passenger cars with front- or rear-wheel-drive. Seventy-five percent of the bevel gearsets applied are ground; 25% are lapped.

Motorcycles. The three manufacturers who build motor cycles with a propeller shaft between transmission and rear wheel (instead of chain) use lapped bevel gearsets between the propeller shaft and the rear wheel.

The question of which combination of processes is best suited for a certain application (i.e.—an existing infrastructure) is discussed in a different light in the following two sections:

When are face hobbing and lapping the best process combination?

- Good for small manufacturer with continuously changing jobs
- Design calculation in-house, but complex optimizations are not practical
- Lowest investment in machines and tools is more important than production in a closed loop
- Manufacture of heavy truck axles
- Short development times, but must produce above-average bevel gearsets

When is face milling and grinding the best process combination?

- High numbers of equal bevel gearsets
- Bevel gearsets for premium passenger cars and SUVs
- Large numbers of different but repeated small batches
- Manufacturing of aircraft bevel gearsets
- Large high-precision bevel gears; e.g.—for marine applications (below 1,000 mm OD)
- If the efficiency of bevel gears is a particularly important factor

Summary

It is obvious that both process combination—face milling/grinding and face hobbing/lapping—have their unique strengths and weaknesses, and that both have a future in the modern manufacturing of bevel gearsets.

Lapping is a process used for certain kinds of fittings, like valve seats, in order to achieve a highly individual fitting accuracy between two functional machine elements. Lapping had its breakthrough in the hard finishing of bevel gears, at a time when highly qualified workmanship and manual labor in industrial production was available, as well as acceptable. The closed control loops desired in today's production are not applicable to lapping, as the quality of lapping production is only verified by rolling on a testing machine. Coordinate measurement against theoretical target data is without much meaning, because the flank form errors of the single members can only be judged in connection with the flank form errors of the mating member. Even if such an error consolidation was realized, the result could only be noticed because of the absence of a determined correction of flank form errors by corrective lapping (*see also original text, chapter 11.1.6*).

Grinding enables measurement against theoretical flank surface data and the correction of the found errors in a closed loop between coordinate measurement machine and manufacturing machine. The cost difference in the manufacture of ground gearsets vs. that of lapped pairs is negligible, as reflected in the tables of Figure 12. Grinding is therefore justifiable economically, and more suitable for modern bevel gear production than lapping regarding repeatability as well as AGMA, DIN, JIS or ISO quality.

Rear-wheel drive, premium-class passenger cars have made a comeback, and cars with all-wheel drive have enjoyed increasing popularity. Because these automobiles are considered to be high-tech products, ground bevel gearsets can be well justified, just as in aviation equipment.

What does this all mean?

It means that there are a number of reasons why ground bevel gearsets have become more desirable during the past years. Companies that specialize in the manufacture of lapped bevel gears are undoubtedly positioned to match ground bevel gearsets regarding strength and acoustic and NVH (noise-vibration-harshness).

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Dr. Hermann J. Stadtfeld received in 1978 his B.S. and in 1982 his M.S. degrees in mechanical engineering at the Technical University in Aachen, Germany; upon receiving his Doctorate, he remained as a research scientist at the University's Machine Tool Laboratory. In 1987, he accepted the position of head of engineering and R&D of the Bevel Gear Machine Tool Division of Oerlikon Buehrle AG in Zurich and, in 1992, returned to academia as visiting professor at the Rochester Institute of Technology. Dr. Stadtfeld returned to the commercial workplace in 1994—joining The Gleason Works—also in Rochester—first as director of R&D, and, in 1996, as vice president R&D. During a three-year hiatus (2002–2005) from Gleason, he established a gear research company in Germany while simultaneously accepting a professorship to teach gear technology courses at the University of Ilmenau. Stadtfeld subsequently returned to the Gleason Corporation in 2005, where he currently holds the position of vice president, bevel gear technology and R&D. A prolific author (and frequent contributor to Gear Technology), Dr. Stadtfeld has published more than 200 technical papers and 10 books on bevel gear technology; he also controls more than 50 international patents on gear design, gear process, tools and machinery.

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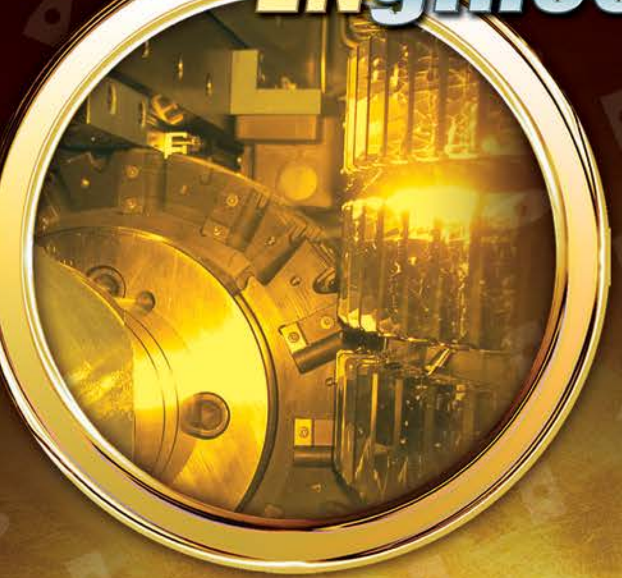

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Forest City Gear

ADDS CONTINUOUS GENERATING GRINDING CAPABILITY FOR HIGH VOLUME PRODUCTION

Forest City Gear has expanded its high volume gear production capabilities with the addition of a Reishauer RZ 160 Gear Grinding Machine and high-speed load/unload automation. The system is part of a new 8,500 sq. ft. facility, located in close proximity to Forest City Gear's main plant, dedicated to the high volume production of eight different gears for a robotics application.

The new Reishauer offers a highly productive, and extremely accurate, continuous generating grinding process, as well as dual workspindles to further increase productivity by enabling workpiece setup, and synchronization, on the idle workspindle while simultaneously machining on the other spindle. As a result, Forest City Gear has added significantly to its capacity for hard finishing gears in volumes much higher than what was possible before, and with exceptional quality, according to Forest City Gear Production Manager Jared Lyford. "Previously, we were using our hobbers to perform the finishing operation after heat treat using the carbide re-hobbing process, commonly known as skiving," says Lyford. "But with volume levels now four times what they were at the start of this project in early 2015, we needed a process that would greatly increase hard finishing throughput and free up more spindle time on the hobbers for rough cutting. The RZ 160 is delivering these benefits, and more."

Lyford estimates that at current part volumes, some 13,000 hours of machining time would have been necessary to finish the gears using the carbide re-hobbing process; the new Reishauer can finish the same number of gears in just 2,400 hours. In addition, the annual cost for tooling has been reduced from around $300,000 for the solid carbide hobs used in the carbide re-hobbing process to an estimated $25,000 for the multi-start grinding wheels used in the continuous generating grinding process.

Forest City Gear has also invested in several system enhancements that will add even more productivity to the system, according to Lyford. "At these volumes wheel dressing takes place frequently, about once an hour, so we've invested in a 'multi-rib' dressing diamond tool that dresses all five of the starts on the grinding wheel in a single pass, versus the usual process of dressing each start one by one," Lyford explains. "We're also awaiting delivery of a Felsomat 30-station, dual-pallet parts conveyor with a high-speed FANUC robot to automate workpiece load/unload for greater efficiency.

"For those in the global marketplace that have always known Forest City Gear as a low volume, high-precision manufacturer of one-off gears – guess again," Lyford says. "Today, we're prototyping, qualifying and producing gears at volumes no one would have expected here a year or two ago."

Bohler-Uddeholm

OPENS JOINT SERVICE CENTER WITH EIFELER

Bohler-Uddeholm has announced that the new joint Bohler-Uddeholm Service Center and Eifeler Coatings Technology PVD Coating Center are open for business. This Service Center of Excellence will strengthen Bohler-Uddeholm's tool steel and coatings offer and enhance the material processing capabilities and service in the Eastern Region of the United States.

In an effort to strengthen their overall position and value-added offerings in the marketplace, providing their customers and business partners with cost effective specialty tool steel material solutions, Bohler-Uddeholm Corporation has undertaken a project to enhance their material processing technologies focusing on better efficiencies and capabilities in the Eastern United States.

"This action has allowed us to increase our material saw cutting capabilities and capacity, along with adding larger material handling capabilities (seven MT cranes) and a machining center that has milling and Blanchard grinding capabilities," Jeff Albee, sales manager of region east at Bohler-Uddeholm, said. "This enhances our value-added product offering of square blocks and ground pieces to our valued customers. Our customers can expect same-day/one-day service for most orders. Combined with our extensive specialty tool steel grade offerings, Bohler-Uddeholm Corporation value proposition is second to none!"

"This new Coating Center offers primarily high quality PVD coatings to the metalforming industry in Ohio and neighboring states," Michael Reardanz, quality manager at Bohler-

Uddeholm said. "The Duplex-Tigral and Duplex-Variantic coatings will offer many benefits for our customers."

Exsys Tool

OPENS NEW FACILITY IN MEXICO

Exsys Tool, Inc. has opened a larger, all-inclusive facility in Monterrey, Mexico. The new Exsys Mexico S DE R.L. DE C.V combines a previous sales office and an off-site warehouse and repair facility under one roof. The facility will serve as a hub for meeting the growing demands of manufacturers throughout the country and will provide them innovative modular toolholding systems.

The facility's location allows Exsys to work more closely with customers and all major machine tool OEMs having a presence in Mexico. Customers will benefit from enhanced sales, service and applications support. The facility will also provide those repair services that were previously exported to the U.S. or Europe, and with its abundant warehouse space, Exsys will boost its Mexico inventory of most frequently ordered products to expedite delivery times to customers.

Cesar Vela, general manager of Exsys Mexico, will manage the new facility. He has extensive industry-related experience and a strong background in engineering, sales and the manufacturing sector in Mexico.

Kyocera

ACQUIRES SGS TOOL COMPANY

Kyocera Corporation announced that it has completed a share purchase agreement regarding the U.S.-based solid tool manufacturing and sales company, SGS Tool Company and its group companies (herein "SGS Tool"). Effective May 2, Kyocera will acquire 100% ownership of SGS Tool, and will rename the company as Kyocera SGS Precision Tools, Inc. By incorporating SGS Tool, Kyocera plans to increase sales of cutting tool business in North America by 2.5 times by fiscal year ending March 31, 2019.

Currently, Kyocera is expanding its cutting tool business globally with its main lineup of indexable cutting tool products.

June 5-8–Powdermet 2016 Boston, MA. Powdermet will be coming to Boston in conjunction with Additive Manufacturing with Powder Metallurgy. The technical program will feature over 200 worldwide industry experts presenting the latest in powder metallurgy, particulate materials and metal additive manufacturing. A keynote presentation will be delivered by Jim Carroll, world-renowned author, futurist and trends and innovation expert, who will address delegates on the new face of modern manufacturing. Over 100 companies representing leading suppliers of powder metallurgy and particulate materials processing equipment, powders and metal additive manufacturing will attend the trade exhibition. Other special conference events include special guest speakers, luncheons, Sunday evening's welcome event and Tuesday evening's dinner at the John F. Kennedy Presidential Library & Museum. For more information, visit *www.mpif.org*.

June 6-10–ESPRIT World Conference 2016 Naples, Florida. Attendees are updated on the latest technology advancements for manufacturing that DP Technology provides to its customers, resellers and partners. The general sessions offer an insightful look into the trends and technologies shaping the future of manufacturing. Classroom sessions cover topics including high speed machining, automation, 3D machining, 5-axis machining, mill turn, wire EDM, swiss machining and post processing. Comprehensive training in practical programming skills is at the core of this conference. For more information, visit *www.espritworldconference.com*.

June 14-16–MDM East Jacob K. Javits Convention Center, New York City. For 33 years, Medical Design and Manufacturing (MDM) East has offered a comprehensive medical manufacturing exhibition and conference focusing on the latest product developments from more than 900 leading suppliers. Attendees can network with peers, discuss the latest medical trends or take part in MDM's red carpet awards ceremony celebrating medtech innovations. Keynote speakers include Leroy Chiao, astronaut and pioneer in commercial spaceflight as well as Martin McCourt, former CEO of Dyson. Conference topics include trends in medical devices, 3D printing, healthcare cybersecurity, an IoT business workshop and material selection for medical devices. For more information, visit *mdmeast.mddionline.com*.

June 14-16–Rapid Tech 2016 Erfurt, Germany. Rapid Tech, the international trade show and conference for additive manufacturing is squarely aimed at users and developers of additive manufacturing technologies. With participants from over 20 countries, Rapid Tech combines a world-class convention and user conference for new technologies with specialist forums covering areas such as science, tools, aerospace and medical technology, making it a truly unique event. In addition, the Rapid Tech user conference and exhibition offers a platform for knowledge exchange between researchers, developers, designers and users. Presentations include Industry 4.0, 15 years of 3D printing, industrial additives, AM technology challenges and more. The 3D Pioneers Challenge seeks to discover specialists from around the world who are thinking outside the box and pushing boundaries on all major disciplines in 3D printing, such as fashion, automotive, medicine, architecture and design. For more information, visit *www.rapidtech.de*.

June 19-23–CCAI and PCI Annual Meeting 2016 Westin Riverfront Beaver Creek, Vail, Colorado. The Chemical Coaters Association International (CCAI) and the Powder Coating Institute (PCI) will host a joint annual meeting for networking, education and association business. CCAI conduct their annual social activities, committee meetings and business meetings to start the week followed by several events held in conjunction with PCI including a welcome reception, joint general sessions and a golf outing. PCI will round out the week with their association committee meetings and PCI business. This concept has been under consideration for the past two years as both the CCAI & PCI boards have been looking for ways that members can reduce the number of meetings they attend each year and also reduce the costs of attending various meetings. While there is some slight deviation from past annual meetings, members will enjoy all the regular annual meeting traditions and events while gaining the opportunity to meet new industry peers. For more information, visit *www.ccaiweb.com*.

June 21-23–2016 Gear Manufacturing & Inspection Cleveland, Ohio. This seminar provides the gear design engineer with a broad understanding of the methods used to manufacture and inspect gears and how the resultant information can be applied and interpreted in the design process. Please note: This seminar is not a tutorial in the mechanics of machine operation; rather, the content addresses the relation between the manufacturing/inspection sequence and the detailed gear design process. Gear design engineers, management involved with the design and manufacture of gearing type components, laboratory technicians, quality assurance technicians, and gear designers should attend this course. Raymond Drago is the instructor. For more information, visit *www.agma.org*.

June 27-29–Made by Klingelnberg Gear Seminar Series and WZL Gear Conference Ann Arbor, Michigan. The Klingelnberg Gear Seminar will keep customers abreast of current technologies and innovations in bevel gear, cylindrical and gear measuring technology. Presenters will include the head of the respective specialist departments at Klingelnberg. Evening meals will provide opportunities for discussions and exchanges in a relaxed atmosphere. In addition, Klingelnberg will host the 6th WZL Gear Conference on June 28, 2016. The Laboratory for Machine Tools and Production Engineering (WZL) at RWTH Aachen University will present the latest research results and developments in the gear industry. "Last year we held seminars in selected national markets in cooperation with partners from the gearing industry; now we are conducting the seminars under our own name," says Dr. Hartmuth Müller, chief technical officer at Klingelnberg, who is also in charge of organizing the seminars. The Gear Seminar Series is free and the WZL Gear Conference is $260 per participant. For more information, visit *www.getriebekreis.de*.

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Making Music Via Marbles

Sound and Mechanical Engineering Combine on the Wintergatan Marble Machine

Matthew Jaster, Senior Editor

According to his official biography, Martin Molin specializes in vibraphone and music box as the ringleader of the band Wintergatan (Swedish for The Milky Way). The band's unique low-tech, homemade instrumental moxie could easily work as a steampunk film score or set off an entirely new musical genre altogether (electronic folklore comes to mind). There's magic here, ambitious and creative, the kind of musical experimentation lacking in most playlists today.

Wintergatan (*www.wintergartan.net*) is a Swedish instrumental group that provides an array of low-fi noises and sound effects through bells, glockenspiels, projectors, music boxes and various drum beats. While Molin and his bandmates seem eager to bend, break and alter the rules of music production, it's evident there's an engineer or two within the band just dying to get out.

After touring with the band for 18 straight months, Molin found his 'inner-engineer' in November 2014 when he started building a programmable marble machine. "Shortly after visiting a fantastic museum with mechanical instruments (The Spielklook Museum in Utrecht, Holland), I stumbled across a computer program online to produce templates for wooden gears," Molin said in a recent interview with *Gear Technology*. "I always loved the marble machine subculture and once I learned how to cut wooden gears, I wanted to build one."

14 grueling months later, the dream of building a programmable marble machine became a reality. The finished product is a giant musical instrument that utilizes pulleys and funnels to move 2,000 marbles around via a hand crank. There's also a kick drum, a bass and other instruments thrown in for good measure.

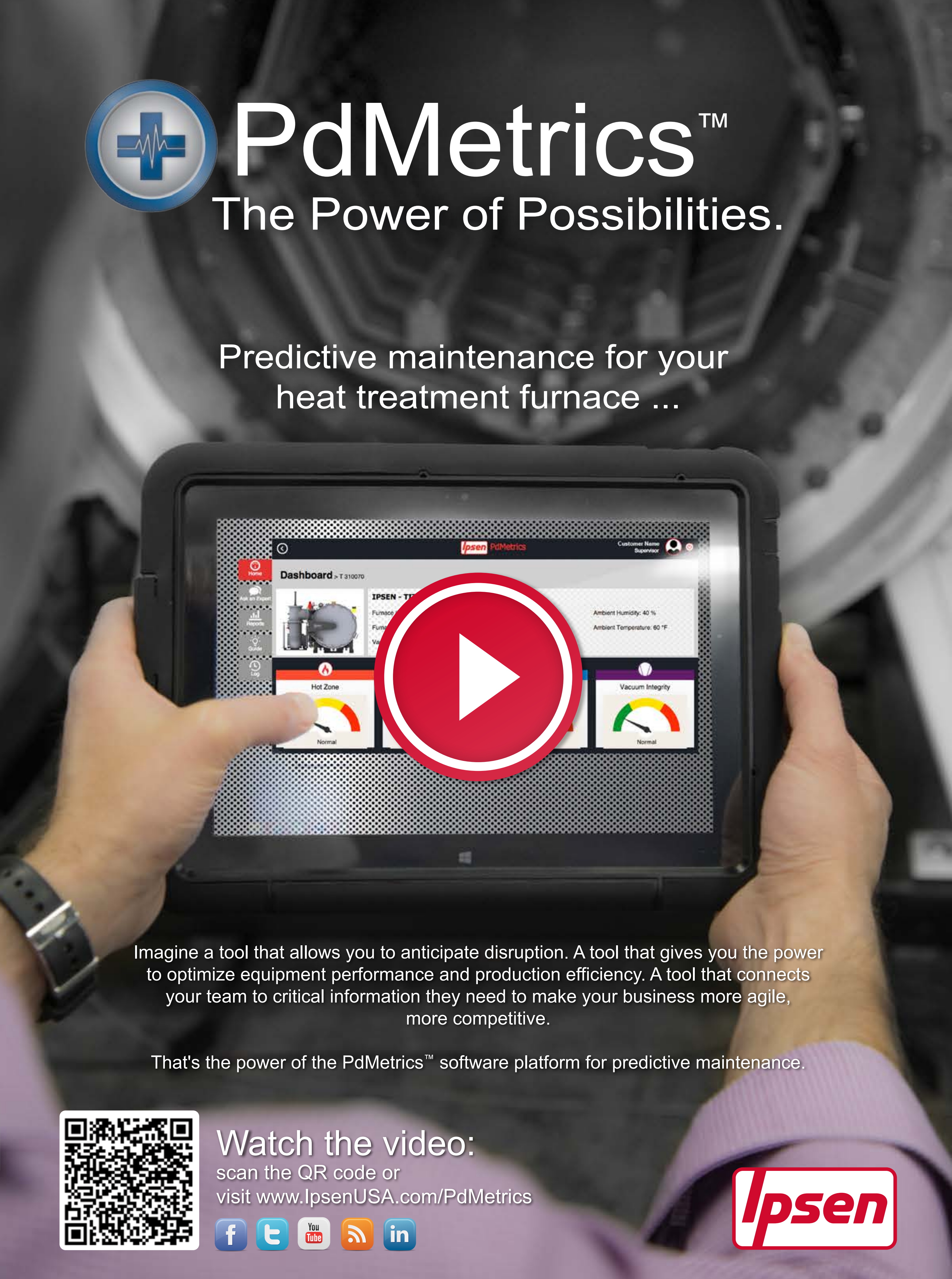
Unfortunately for this journalist, words don't exactly do the Wintergatan Marble Machine justice. But a quick click on the following link will give you an idea of what this young man put together without a traditional background in engineering, (*www.youtube.com/watch?v=IvUU8joBb1Q*).

The Wintergatan Marble Machine video has generated more than 19+ million views since he uploaded in March 2016. Molin believes, especially in the music business, people are more concerned with searching for the perfect advertising or promotional strategy. "They pay less attention to the quality of the work itself. While it's easy to fall into this trap particularly in our digital social media landscape, I think searching for the best art is the greatest promotional strategy."

For his part, Molin is thrilled so many people on the planet share the same kind of imagination and vision he does. "I knew the video and the machine were going to be good, but I couldn't believe that my love for this project would be shared by so many," Molin added.

Molin plans to build a smaller, motorized music box that he will take on tour that will acts as a 5th member of the band. After that, he plans to redesign some of the elements of the Wintergatan Marble Machine so the band can utilize the large version during live performances. "There is so much interest in the machine now, I have found some new energy to perfect it," Molin said. "I know there are more people than myself that want to see it on a live stage."

And where did all this ingenuity come from exactly? "Problem solving is very addictive," Molin said. "It puts me in a place where earthly, existential and emotional problems don't exist. When the idea first came to me to build the machine, it was so strong and it would not leave me alone."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