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JAN/FEB 2019

STATE OF THE GEAR INDUSTRY

ANNUAL SURVEY RESULTS TRENDS AND OPINIONS

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22

2019 STATE OF THE GEAR INDUSTRY SURVEY

features

technical

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VLC 200 GT

HARD TURNING, SCROLL-FREE TURNING AND GRINDING ON A SINGLE MACHINE

PRECISE DYNAMIC PRODUCTIVE COMPACT

HIGHLIGHTS

+ Reduced machining time: The combination of hard pre-turning and grinding reduces machining time and produces scroll-free surfaces.
+ Improved quality and productivity: The workpiece is hard pre-turned in a single clamping operation with only a few microns for the grinding that follows.
+ Minimum grinding wheel wear: Since only a small amount of material is removed when grinding, the grinding wheel wears more slowly and needs to be dressed less often leading to an increase in productivity.




Technical data for the VLC 200 GT: Chuck diameter, max. 210 mm (8 in) I Swing diameter, max. 270 mm (11 in) I Workpiece diameter, max. 160 mm (6 in) I Workpiece length, max. 100 mm (4 in) I Travel distances X (total stroke from pick-up to turret) / Z 1,700 / 250 mm (10 in) I Loading time (depending on clamping device) 6 – 10 sec. I Main spindle capacity: 40% duty cycle / 100% duty cycle, 22 / 18 kW I Main spindle torque: 250 / 202 Nm I Main spindle max. speed: 3,000 rpm I Spindle bearing dia., front: 110 mm (4 in)

www.emag.com

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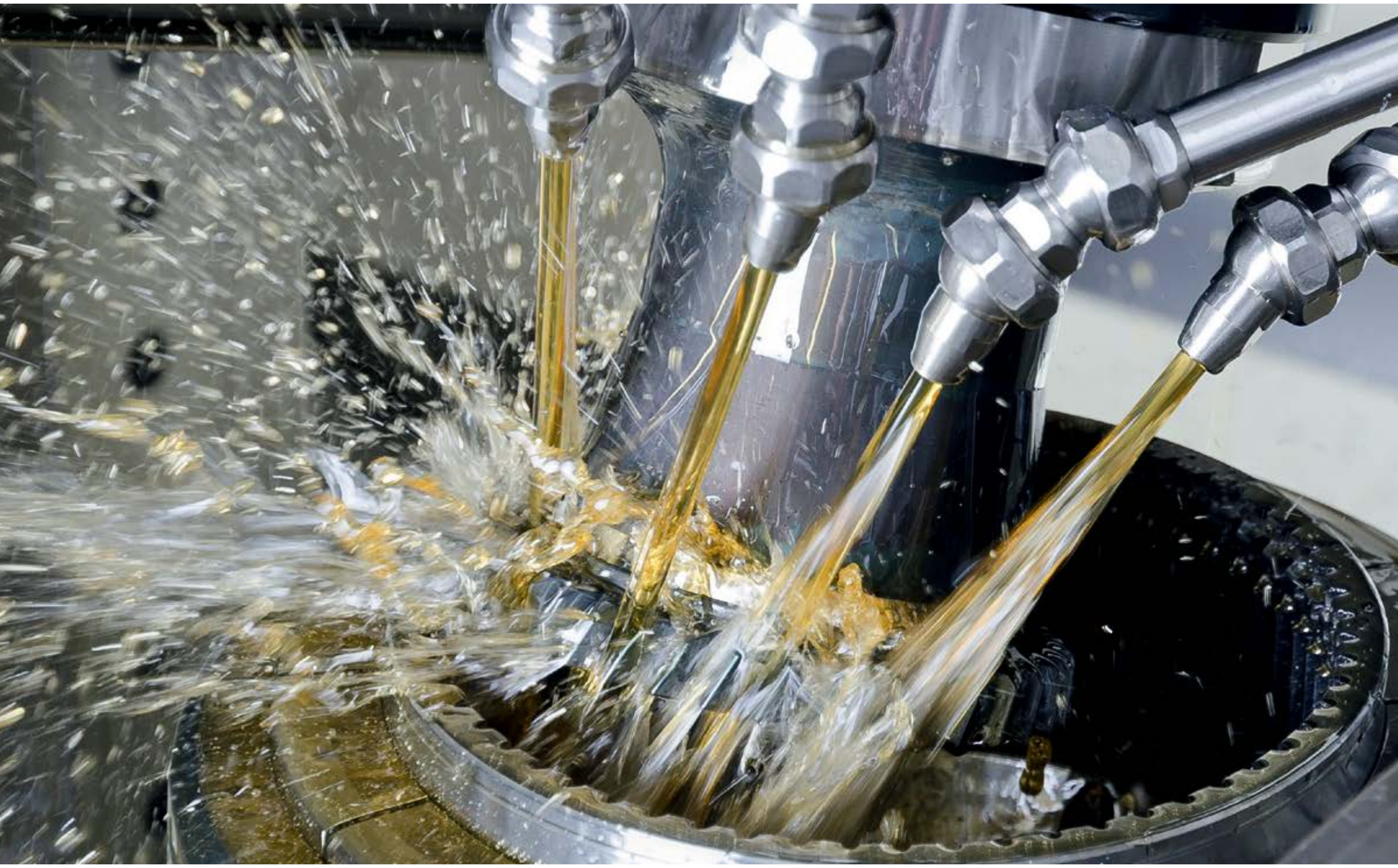
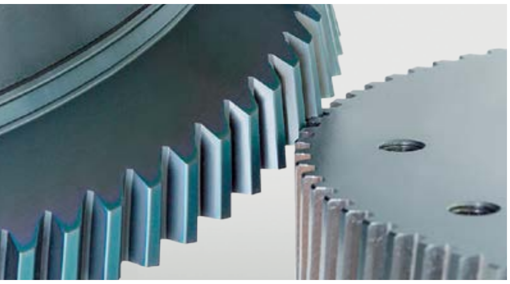
Vol. 36, No. 1

departments





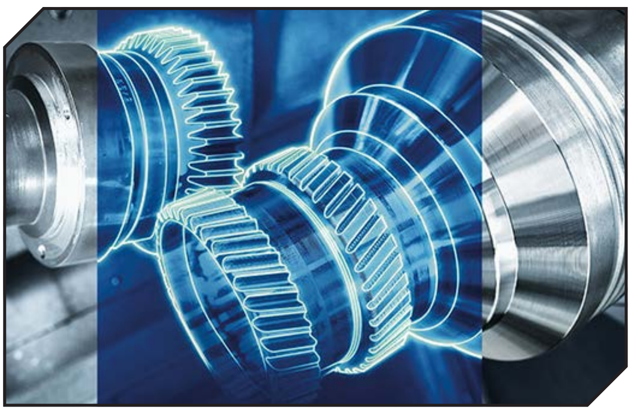
THE GEAR INDUSTRY'S INFORMATION SOURCE

www.geartechnology.com

Gleason Chamfer Hobbing

Gleason offers a hobbing machine with integrated chamfer hobbing. The machine is arranged with an integrated chamfer station which is directly linked to the main process by a fast gantry automation allowing minimum cycle times without any productivity loss. Learn more here:

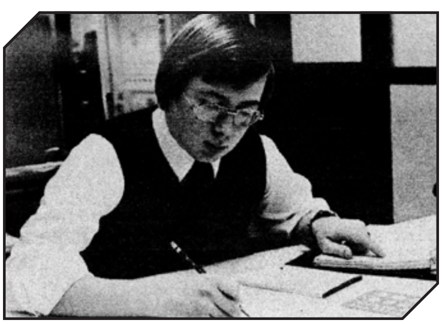
www.geartechnology.com/videos/Gleason-Hobbing-with-Parallel-Chamfering-of-Smaller-Gears-/



DMG MORI Gear Skiving

Animation of the technology integration of gear skiving for mill-turn and turn-mill machining centers. Learn more here:

www.geartechnology.com/videos/DMG-MORI-Gear-Skiving/



Gear Talk:

In the blog entries "Luck of the Draw" and "The Journey Continues," Chuck Shultz looks back at his early years in the gear industry. We'd like to hear how our readers first became involved in gear manufacturing as well. E-mail your story to *publisher@geartechnology.com*.

www.geartechnology.com/blog/luck-of-the-draw/

www.geartechnology.com/blog/the-journey-continues/

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RANDALL PUBLICATIONS LLC
1840 JARVIS AVENUE
ELK GROVE VILLAGE, IL 60007
(847) 437-6604
FAX: (847) 437-6618

EDITORIAL

Publisher & Editor-in-Chief
Michael Goldstein
publisher@geartechnology.com

Associate Publisher & Managing Editor
Randy Stott
wrs@geartechnology.com

Senior Editor
Jack McGuinn
jmcguinn@geartechnology.com

Senior Editor
Matthew Jaster
mjaster@geartechnology.com

Associate Editor
Alex Cannella
alex@geartechnology.com

Editorial Consultant
Paul R. Goldstein

Technical Editors
William (Bill) Bradley, Robert Errichello, Octave Labath, P.E., John Lange, Joseph Mihelick, Charles D. Schultz, P.E., Robert E. Smith, Mike Tennutti, Frank Uherek

DESIGN

Art Director
David Ropinski
dropinski@geartechnology.com

ADVERTISING

Associate Publisher & Advertising Sales Manager
Dave Friedman
dave@geartechnology.com

Materials Coordinator
Dorothy Fiandaca
dee@randallpublications.com

e-Marketing Specialist
Matthew Stott
matthewstott@geartechnology.com

China Sales Agent
Eric Wu, Eastco Industry Co., Ltd.
Tel: (86)(21) 52305107
Fax: (86)(21) 52305106
Cell: (86) 13817160576
eric.wu@eastcotec.com

CIRCULATION

Circulation Manager
Carol Tratar
subscribe@geartechnology.com

Circulation Coordinator
Barbara Novak
bnovak@geartechnology.com

RANDALL STAFF

President
Michael Goldstein

Accounting
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Publisher & Editor-in-Chief
Michael Goldstein

We've just come off a very strong year for gear manufacturing, and most of you are looking forward to another good year in 2019. At least, that's what the results of our annual State-of-the-Gear-Industry survey tell us.

Every year, we survey the gear manufacturing community to find out the current trends in production, sales, employment and the overall mood. Even though we're probably approaching the end of our long period of economic expansion, even though the global trade wars are impacting our material prices, and even though we're struggling—like all manufacturing industries—to find, train and keep skilled labor, the overall mood seems higher than it's been in some time.

For the most part, it's still good to be a gear manufacturer.

According to the survey, roughly 86% of you are optimistic about your company's ability to compete over the next five years. That's a slight increase from the 83.6% who were optimistic last year. More importantly, there's been a significant shift toward extreme optimism. The number who are extremely optimistic more than doubled since last year's survey (going from 18.7% in 2018 to 38.6% in this year's survey). This tells me that for a lot of you, business is really, really good.

And our data says that trend should continue. More than two-thirds of gear manufacturing operations saw production volumes increase in 2018, and more than two-thirds also expect product to increase further in 2019. The same is true of sales. You can see the full results of the survey beginning on page 22.

But don't stop after you've finished reviewing the survey results. In order to give you a more complete picture of the state of the gear industry, we've also tapped a number of industry experts to get their opinions on the most important trends and issues facing gear manufacturers today. In a special edition of "Ask the Expert" (page 34), we've compiled and presented those ideas for you.

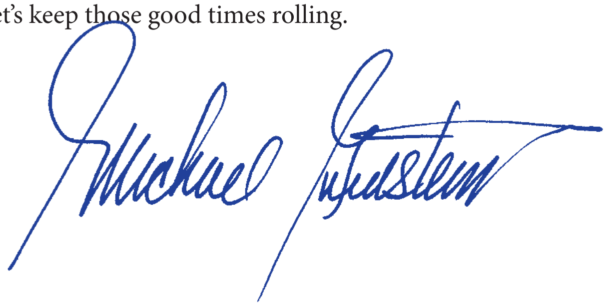
By far, the most important trend identified – both by our survey and by the individual experts who've weighed in – is the skilled labor shortage. It's an enormous problem with no easy solution. We need skilled machinists. We need people at every level trained in the basics of gear theory. We need people who understand gear inspection, gear design and heat treating.

The AGMA also recognizes this as the No. 1 challenge facing our industry, and the association is working hard on solutions. A few months ago, we talked with AGMA President Matthew Croson about some of the association's current projects, including the AGMA Foundation's "Get Into Gears" program that's aimed at helping individual companies attract talent to their organizations. In our interview, Croson also talked about the soon-to-be-unveiled AGMA National Training Center at Daley College in Chicago. If you haven't already done so, I invite you to watch the entire interview on *Gear Technology TV* (*www.geartechnology.com/tv/*). You should also visit *www.agma.org* and click on "Education," because the association offers a wide variety of in-person and online training, both for members and non-members.

Of course, we try to do our part every issue as well, by providing technical information the industry can use. This issue is no exception, with our focus on big gears and our coverage of multifunctional machining. More importantly, we have our *GT LIBRARY* online, where you can go and read archived articles any time to learn about everything from the basics to the state of the art. All the past articles are indexed in a keyword-searchable database, so all you have to do is use the site's internal search engine to find an article on any gear-related subject. In fact, I'd encourage you to guide any new employees to the *GT LIBRARY* and invite them to type in "basics." They'll find plenty of good reading material from our more than 34 years of publishing to get them started.

Times are good in the gear industry. But they won't continue unless we address the skilled labor problem. What looks like a gravy train today can't possibly continue unless we figure out how to attract people to our industry, and then give them the training that allows them to progress from the basics to intermediate skills and even expertise.

Let's keep those good times rolling.



EMAG VLC 200 GT

PROVIDES SINGLE-CHUCK MACHINING OF AUTOMOTIVE GEARS

The EMAG Group's VLC series offers customers multifunctional machines that perform an array of hard machining processes on transmission components in quick succession. The company, which is headquartered in Salach, Germany with its U.S. location in Farmington Hills, MI specializes in turning and grinding, and has now added another important element to this portfolio, the VLC 200 GT. This machine was developed by EMAG engineers especially for the chuck machining of automotive gears. Users benefit from highly efficient turning and grinding processes in a single clamping operation.

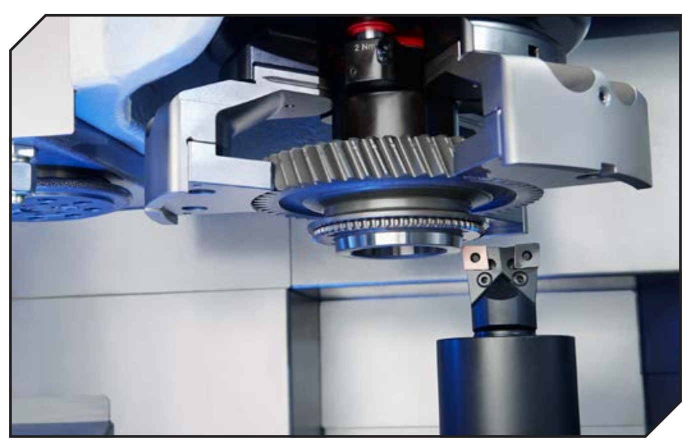
Complete Process, Including Dressing

A simple description of the process gives you some idea of the advances in productivity made possible by the VLC 200 GT. To start with, the machine is loaded at exceptionally high speed by the integrated pick-up spindle. To minimize non-productive times, EMAG has optimized features such as the mechanism of the machining area door. Once the spindle with the part

reaches its machining position, the process starts with hard pre-turning of the shoulder and the bore hole in quick succession. Only a few micrometers of material are then left to be removed from the gear. That means the subsequent grinding process, using either aluminum oxide or CBN grinding wheels, takes significantly less time. Meanwhile, the machining quality also benefits from the combination of turning and grinding: When there is only a small amount of material remaining to be ground away after turning, the specifications for the grinding wheel can be based more precisely on the end quality required — as a result, surfaces with an average peak-to-valley height R_z of less than 1.6 micrometers can be created reliably with the VLC 200 GT. In addition, this multifunctional technology offers users a multitude of possibilities generally: internal and external grinding spindles, scroll-free turning tools, block tool holders, and EMAG's 12-station tool turret can all be installed as required.

Lower Tool Costs

There is an additional advantage in terms of tool costs, because during this process the grinding wheel wears down more slowly and therefore does not need to be dressed as often. When it does need dressing, the VLC 200 GT features a separate diamond-coated dressing roll designed specifically for this. "With its separate rotating dressing system and gap control monitoring, the machine is perfectly equipped to exploit the advantages of CBN grinding," says Peter Loetzner, President & CEO of EMAG LLC. To ensure sustained process reliability and high machining quality, the integrated measuring pin is used to check the diameter and length of the clamped component at the end of the process. Operator comfort and ease of access were important priorities for EMAG's developers, so large doors allow easy access to the machining area. The tools and clamping devices are easily accessible and can be changed quickly and conveniently.



"We are offering producers of gears a custom-fit, flexible, highly productive solution with excellent value for money. That is inevitably going to win out in the marketplace," Loetzner says.

For more information:
EMAG LLC
38800 Grand River Avenue
Farmington Hills, MI 48335
Phone: 1-248-477-7440
www.emag.com

SMT

RELEASES *MASTA 9*

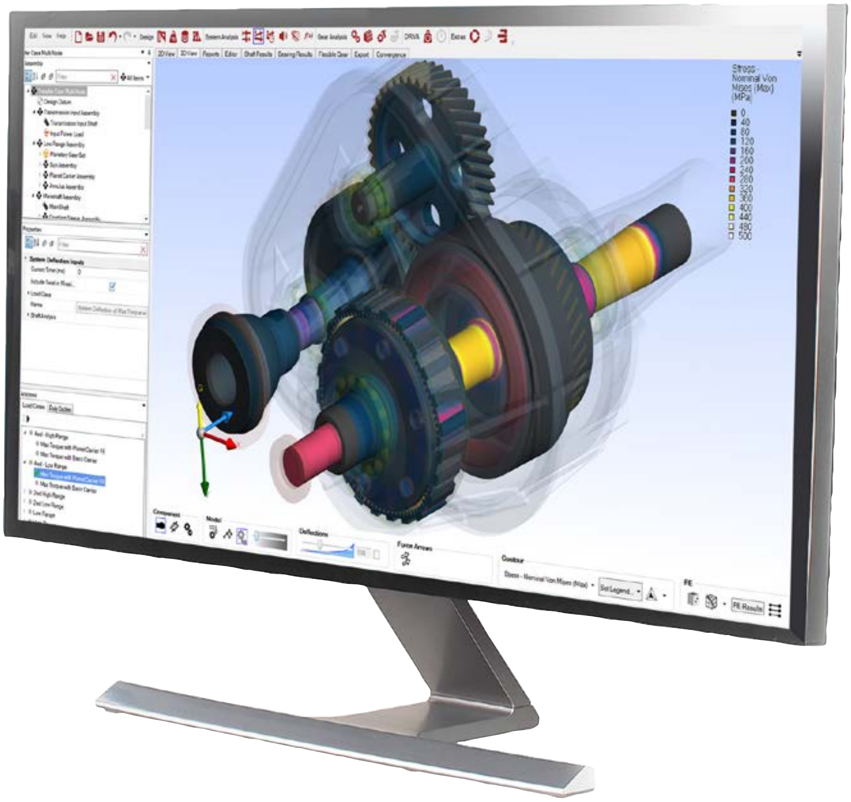
SMT, a globally integrated leader in mechanical transmission engineering services and software development, recently announced the next major software release. Available immediately for all users and evaluators, this latest release builds on previous versions and includes several innovative enhancements. Areas of new or revised functionality include the following:

Gear Whine/Harmonic Excitation Analysis

- New results available including air-borne sound power for a full FE component
- Interface improvements to allow more flexibility in the results shown, including showing the response at multiple locations on one plot
- Export of operating deflection shapes that can directly be used in acoustic analysis packages
- Display of operating deflection shapes in 3D view

Shaft FE Meshing

- Create a detailed FE model using the shaft geometry defined in *MASTA*.
- Includes all cylindrically symmetric features such as fillets



Bearing Clearance at Mounting Points

- Automatically add mounting clearance if it occurs due to fitting and thermal effects

Flexible Spline Coupling

- New spline contact type to model each flank contact
- Simple setup process for FE nodes

CVT Model Improvements

- Define separate fixed and moving sheaves
- Include axial forces on sheaves

In addition to these, many other small functionality and user interface improvements from previously included features are also available.

For more information:
Smart Manufacturing Technology (SMT)
Phone: (248) 687-1191
www.smartmt.com

Kennametal

DEVELOPS VIBRATION-FREE BORING SYSTEM

Kennametal has developed a new boring system that boasts an effective anti-chatter mechanism, and also offers an extensive range of indexable heads and shank sizes.

Someone who knows all about it is Sam Eichelberger, product engineer for lathe systems engineering and part of the team that developed the internal dampening mechanism. "Perhaps the most important thing to know about the new bar is that it's plug-and-play," he says. "There's no need whatsoever for tuning or adjustments—you simply pull it out of the package, mount it in the turret, and get boring."

Eliminating vibration and therefore chatter greatly extends tool life, never mind its positive effect on part surface finish. And when tools last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SkiveLine

longer, they can be pushed harder, with feed rates, cutting speeds, and depths of cut many industry experts once thought unachievable.

Eichelberger is one of them. He lists a number of features that not only make the vibration-free boring system the most easy-to-apply bar you'll ever bore with, but also the most productive. These include a serrated, bolt-on connection at the bar's business end that securely clamps a variety of styles and sizes of indexable heads.

Better yet, the heads themselves have been put on a diet, with a shorter length and lighter weight that provides greater stability, contributing to the bar's improved performance. They're also coolant-fed, to precisely direct a stream of high-pressure coolant where it's needed most. The result is hassle-free chip control together with maximum cooling in the cutting zone.

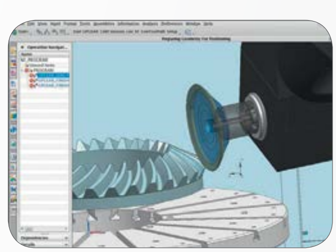
Most important of all is the internal dampener. Said Eichelberger, "The bars are both vibration and maintenance-free. Within the bar there sits a mass that's supported by a pair of elastic supports, inside of which sits a dampening fluid. This mass vibrates at a predetermined frequency during machining, attenuating the natural frequency of the bar around it to suppress vibration."

Considering the higher cost of such a boring system, they'll also appreciate the fact that the heads are replaceable in the event of a crash, avoiding damage to the bar itself. And users of Kennametal's older boring system will find that their new heads fit perfectly with the use of an adaptor.

"The portfolio for our Imperial bars ranges from one-inch in diameter up to four inches, while the metric version starts at 25 mm and goes to 100 mm", Gable said. "There are a variety of interchangeable head styles available as well, everything from screw-on positive rake inserts for fine-finishing needs to negative rake, clamp-style geometries for heavy roughing. The bar's designed to excel in demanding applications, and that's exactly what it does."

For more information:
Kennametal
Phone: (724) 539-5708
www.kennametal.com

Gleason HELLER
CP4000



Buehler

OFFERS *DIAMET* HARDNESS SOFTWARE UPGRADE FOR LEGACY HARDNESS TESTERS

Buehler, an ITW company has announced that the DiaMet hardness software upgrade is now available for legacy Wilson testers. The *DiaMet Hardness Software* is a proven platform in hardness testing. *DiaMet* can integrate and transform legacy testers to improve quality management using software's database; measurement results are automatically saved, and test reports are easily generated. With the use of a digital imaging, testing is simplified and ergonomically improved for the operators, since filar eyepiece measurement is no longer required. More importantly, *Diamet Software* measurement process provides more consistent test results between multiple operators.

A *DiaMet* upgrade package includes a USB3.0 digital camera, camera cable and workstation. By upgrading to *DiaMet Software*, users will now be able improve work efficiency and reduce or eliminate manual data entries. The test program or test job may be categorized in Folders; filtering feature allows easy recalling of test program/test job; all of which, bring to ease to any internal or external auditing process. *Diamet* software will take your organization closer toward Industry 4.0.

The *DiaMet* upgrade is available for the following testers: Wilson Tukon 1102/1202, Wilson 402 MVD/SVD, Wilson 432/452 MVD/SVD, Buehler MicroMet 5100 series and the Buehler MicroMet 6000 series. Please note that the 1102/1202 and MicroMet 6000 series may be upgradable to semi-auto or fully automated systems.

For more information:
Buehler
Phone: (847) 295-6500
www.buehler.com

KISSsoft & SKF

RELEASE NEW INTERFACE TO BETTER DEVELOP GEAR UNITS

SKF and KISSsoft have worked together to create a new interface that makes it much easier to develop gear units: when designing machines, engineers can select suitable bearings based on the very latest bearing technologies in the interface. This enables KISSsoft's customers to use these two calculation approaches: the usual ISO calculation, which includes calculation using the latest bearing data from SKF.

KISSsoft users are provided with the latest SKF bearing data via SKF's cloud services. The user is supplied the appropriate results in an engineering report generated by the *KISSsoft* calculation software. By creating this new interface, SKF and KISSsoft are responding to the request, from many engineers, for a single tool that includes many different types of design data, and design guidelines and restrictions, automatically updates them, and is documented in a user-friendly format from end to end. If you would like more information about the new interface, you will find it here.

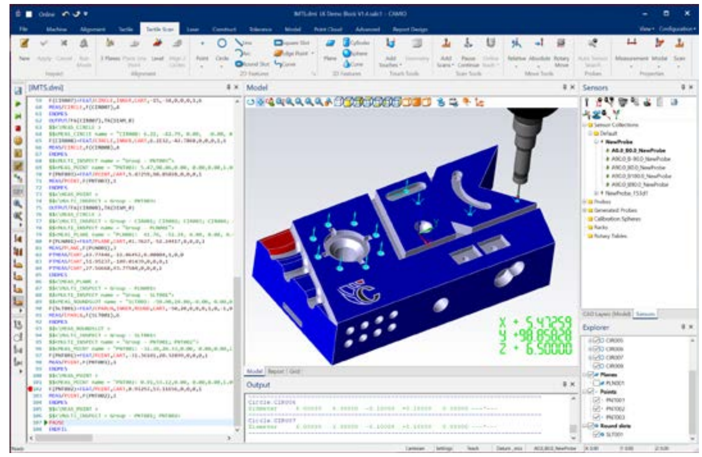
Victoria van Camp, member of SKF AB's management board and head of technology development, "This partnership between SKF and KISSsoft shows our ability to combine our different digital platforms, to enable us to produce new developments even more rapidly than before, right in the earliest phase of development. We are contributing to making agility a reality in mechanical engineering, as well as in other sectors. This is an exciting step for both our companies. We are convinced that users will welcome it, and that it will provide a strong basis for other joint optimization projects!"

Dr. Stefan Beermann, KISSsoft AG's CEO, added: "Our collaboration with SKF gives our customers a unique way of linking a desktop application with cloud-based calculation services, combining the powerful, all-embracing features of a local installation with the flexibility and constant updates of an Internet-based service."

For more information:
KISSsoft AG (A Gleason Company)
Phone: +41 55 254 20 50
www.kisssoft.ag

LK Metrology

LAUNCHES LATEST VERSION OF CAMIO SOFTWARE



Metrology software has challenges in most application environments—and LK Metrology's new 8.5 version of their *CAMIO CMM* software has a range of new features to help meet those challenges.

The *CAMIO* software has become the "software of choice" for many of the world's largest manufacturers because it allows the user to focus on accelerating lead times and improving product quality. Regardless of whether inspecting stamped, molded or machined parts, *CAMIO* drives accurate and efficient inspection programs for geometric features along with full surface analysis with Part-to-CAD comparisons. *CAMIO*'s interoperability across CMM platforms, sensor technology and manufacturing sites becomes its unique advantage.

Dennis Freimark, LK Metrology's North American chief software applications engineer explains, "Common practice is to provide a couple of new releases of metrology software like *CAMIO* every year, but in 2018 LK Metrology acquired the Nikon *CAMIO CMM* software business and needed to re-brand it, refresh the interface and implement a new licensing mechanism. While the re-branding took a significant amount of work and delayed the possibility for a 2nd major *CAMIO* release in 2018, we were still able to add many new features and enhancements for our customers, some of which are listed above."

Freimark adds, "The shift from Nikon *CAMIO* to Lk Metrology *CAMIO* has been a smooth transition for our customers, and the new 8.5 version incorporates many of the needed enhancements that provides CMM users with greater measurement flexibility for better product conformance."

For more information:
LK Metrology
Phone: (810) 263-6100
www.lkmetrology.com

Marposs

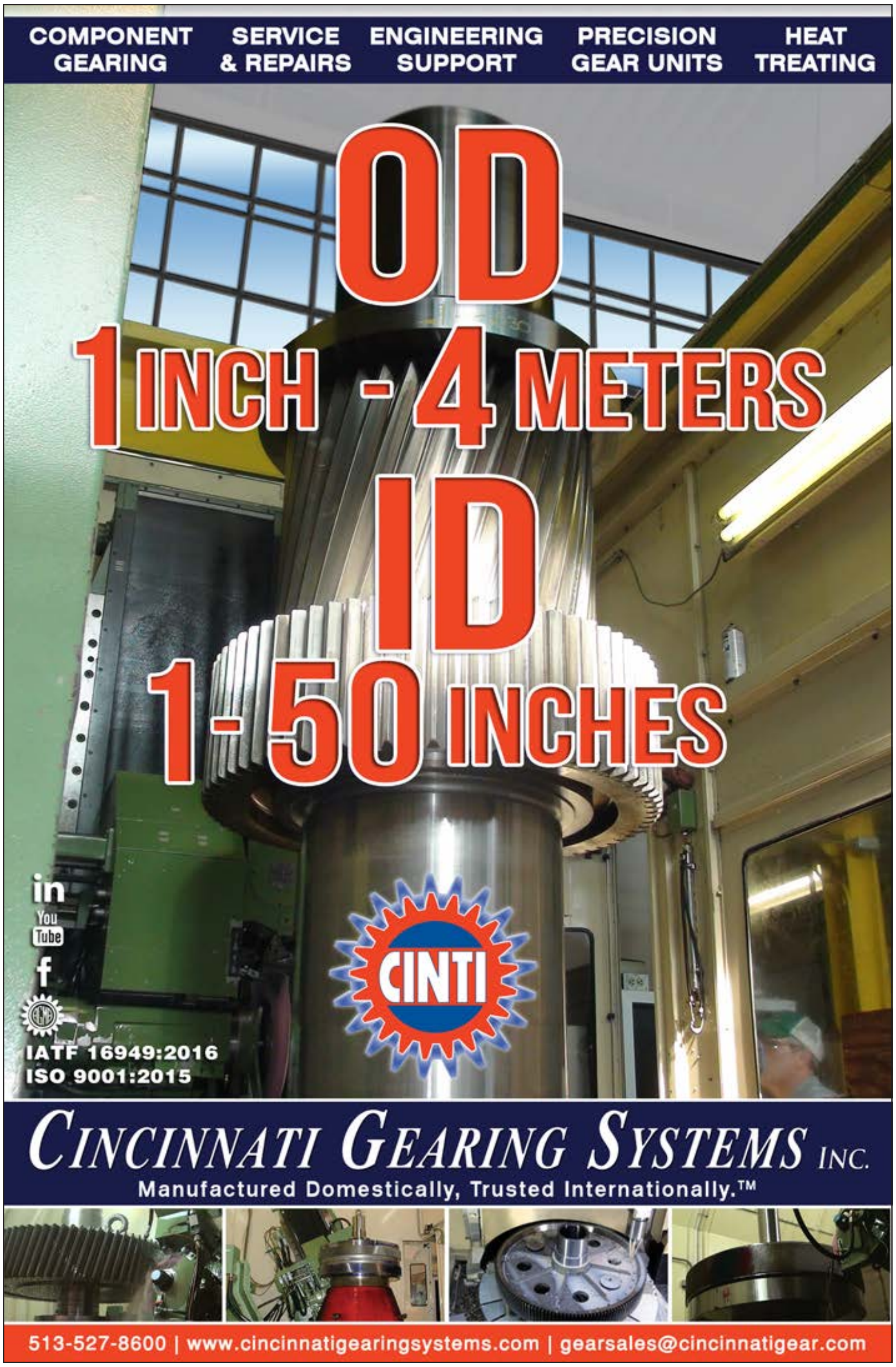
OFFERS GRINDING GAUGE FOR IMMEDIATE MACHINE COMPENSATION

Marposs Corp. has announced the availability of its new P3dME electronic gauge amplifier for post-process monitoring of smooth and grooved parts. This device, in conjunction with Marposs measuring heads, is a flexible, practical, and reliable solution for checking parts immediately after they have been machined. The P3dME will measure the workpiece and provide immediate compensation information to the machine tool. This ensures that parts are within tolerance limits and helps to optimize cycle-times.

The P3dME is a compact gauge that can be installed on the machine tool as a standalone device or integrated into the machine front end PC using a dedicated HMI. It features a 7-inch touchscreen with an intuitive, easy-to-use operator interface. Its robust housing is designed to withstand harsh shop-floor environments and resist abrasive grit, metallic particles, and cutting fluids.

The unit is available with either two or four channels for connecting to Marposs LVDT or HBT type measuring heads. Depending upon the chosen measuring head, the P3dME has a measuring range of ±250 to 2,000 µm.

For more information:
Marposs Corporation
Phone: (888) 627-7677
www.marposs.com



Mitutoyo

ADDS LASER SCAN MICROMETER TO SENSOR SYSTEMS PRODUCT LINE

Mitutoyo America Corporation is pleased to announce the release of the LSM-6902H Laser Scan Micrometer to its sensor systems product line. The LSM-6902H Laser Scan Micrometer non-contact, high-accuracy measurement system is an excellent option for measuring pin gages or plug gages.

The ultra-precise scanning motor in the LSM-6902H enables the highest measurement accuracy down to 0.3 µm with excellent Gage R&R performance since measurements are non-contact. The standard output is RS-232C with analog I/O with an optional 2 channel Digimatic code output unit available.

Features include an accuracy of ±0.5 µm over the entire measuring range and a higher accuracy of $\pm(0.3 + 0.1\Delta D)$ µm over a narrow range, suitable repeatability available in the 25 mm/1" class, a resolution of 0.01 to 10 µm (selectable) (0.000001 — 0.0005 in), a scanning rate of 1,600 scans/s and a laser scanning speed of 112 m/s.

For more information:
Mitutoyo America Corporation
Phone: (630) 820-9666
www.mitutoyo.com

2019 State of the Gear Industry

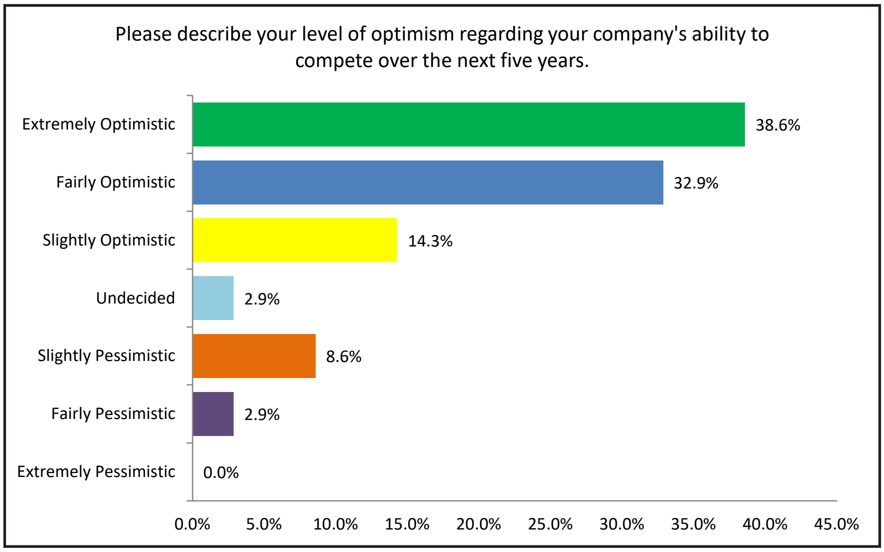
Reader Survey Results

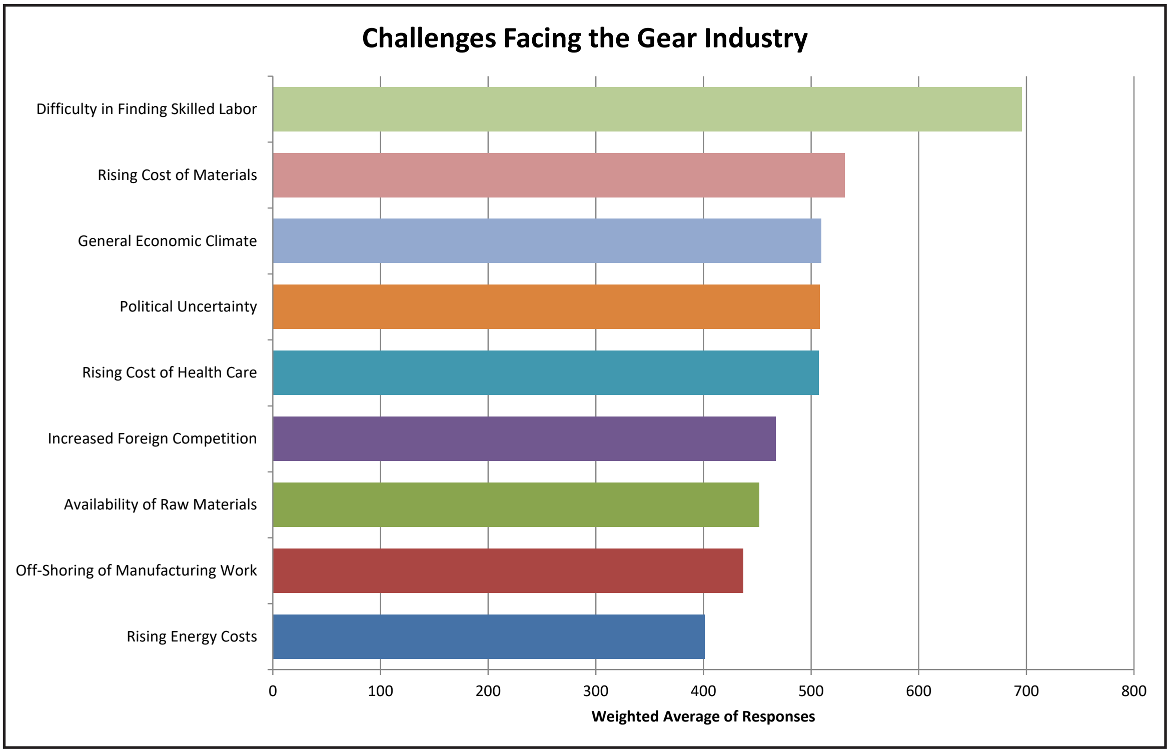
Gear Technology's annual State-of-the-Gear-Industry survey polls gear manufacturers about the latest trends and opinions relating to the overall health of the gear industry. As in years past, the survey was conducted anonymously, with invitations sent by e-mail to gear manufacturing companies – primarily in North America, but also including some gear manufacturers around the world.

All of the responses included in these results come from individuals who work at locations where gears, splines, sprockets, worms and similar components are manufactured. They work at gear manufacturing job shops as well as captive shops at OEMs. A full breakdown of the respondent demographics can be found at the end of this article.

Summary

Overall, the gear industry enjoyed a very strong 2018, and the optimism expressed by survey respondents is the highest in recent years. When asked about their optimism regarding their companies' ability to compete over the next five years, 85.8% of respondents indicated some level of optimism. This number was around 83% the past two years. More importantly, the optimistic have gotten more optimistic, with more than twice as many in the "Extremely Optimistic" category compared with last year's results.





Significant Business Challenges

Here's a sampling of what some of our respondents had to say about the challenges they're facing today:

"Re-shoring."

"Pending recession."

"Lead time, raw material costs."

"Grinding from solid."

"Electric vehicles as well as weight savings which force several material types… aluminum, plastic…"

"3D printing, 5-axis milling. Lack of machine operators and tradespeople. Lack of engineers."

"The gas powered cars and trucks going away by 2022. Electric car and trucks will not need transmissions or transfer cases."

"New highly-advanced lubricant technology for a major step-change in performance and efficiency of gears and rolling element bearings."

"Gear cutting is not just about gear machines any longer. Many lathes have the capability to incorporate gear cutting and deburring into the machining process with a high level of accuracy."

"Dealing with demand > capacity and material issues. Aging equipment and upgrading to modern technology in effort to aid lean manufacturing processes."

"Threaded-wheel hard gear finishing, spiral gash helical broaching, multi-thread cobalt steel PVD coated hobbing (wet), gear set transmission error vs NVH designs."

"Market demand."

"Advances in heat treating, hard finishing, and deburring. Increasing domestic capacity of large helical broaches."

"Increasing material prices, lack of available labor, lack of capacity."

"Conversion to electric drives reducing gear quantity requirements, adoption of improved surface finishing on gears, metal additive manufacturing."

"Lack of capacity."

"Condition monitoring is being pushed to be smarter."

"Competitiveness."

"Price."

"IOT sensors and communications."

"Sanitary demands for the food and beverage industry."

"Automation: Due to the lack of qualified employees we need to turn to better, cheaper, and more user friendly automation."

"Material selection and heat treatment."

"Newly created aerospace designs."

"Electrification instead of mechanical systems. Finding qualified operators. Economic instability. Energy production trends."

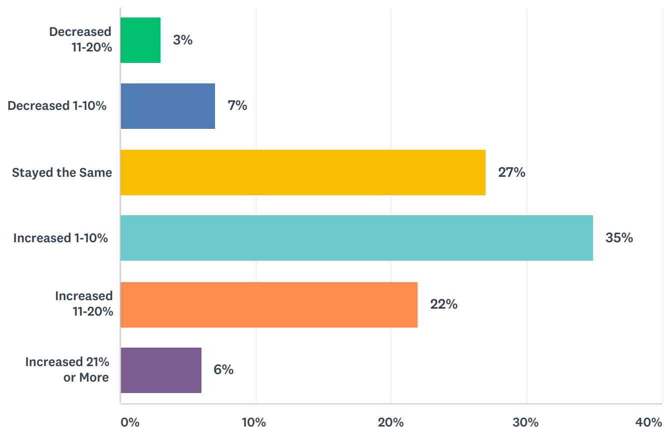
"Faster delivery times requested."

"New electrification designs and impact on industry."

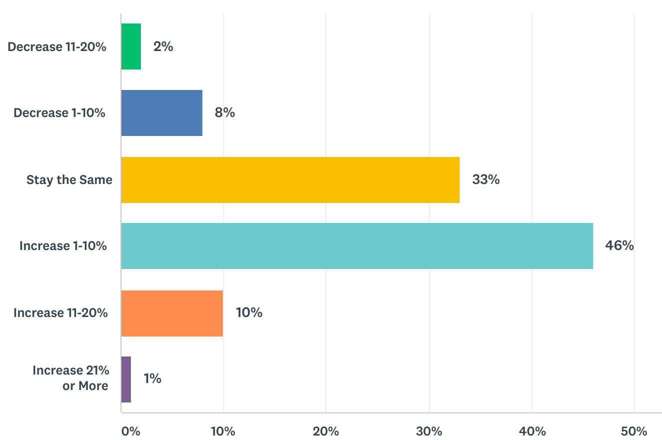
"Tariff costs and misconceptions surrounding Buy America(n) acts."

Employment

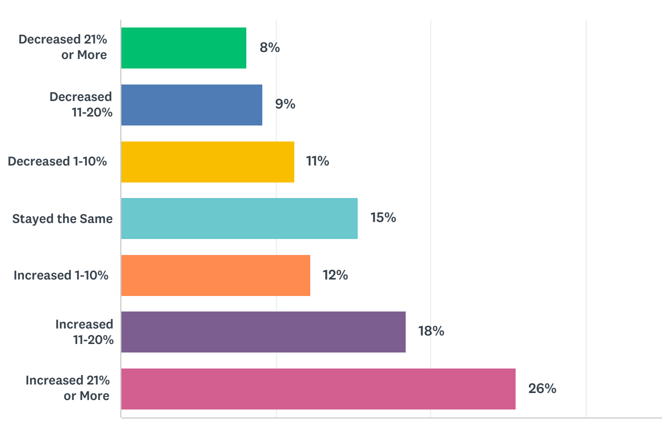
How has your location's LEVEL OF EMPLOYMENT changed over THE PAST 12 MONTHS?



How do you anticipate your location's level of employment will change in the NEXT 12 MONTHS?



How does your location's employment level compare with its employment level 10 years ago?



"The ability to find experienced employees to run machines."

"Low cost at low volume."

"CNC machining and measurement, AI, cash flow."

"The need to continually invest in best practices equipment."

"I think the relaxing of the regulations allowed our customers to be more competitive and thus giving us more work."

"Offshore threats."

"Materials."

"Precision machining."

"Lead time on equipment and tooling."

"Increase of imported product."

"Tariffs."

"Advancements in CNC gear making technology and hopefully price reductions in equipment. Also, CNC retrofit technology improvements."

"Lack of manufacturing talent will remain a challenge. On the gear development side, electric vehicles driving significant change. On the market side, large gear market will remain slow for some time."

"Tariff impacts and potential changes to procurement of components and finished products."

"The economy is due for a slow-down, though not necessarily a recession."

"Trade War."

"Cost cutting only costs the end user."

"Light materials."

"Lack of skilled workers."

"Raw material pricing will have a direct effect on the gear purchasing posture."

"Longer lead times – materials and services."

"Higher tolerances and quality needs."

"Lack of capital funding on automation that is necessary to counteract the shortage and growing costs of labor."

"Gears with improved efficiency, new transmission solutions for electric vehicles, more hard finishing, increased manufacturing by power skiving, more additive manufacturing of steel gears."

"Aerospace market is strong."

"Labor force is reduced, driving up the labor rates."

"Global commodity pricing and performance of global economies."

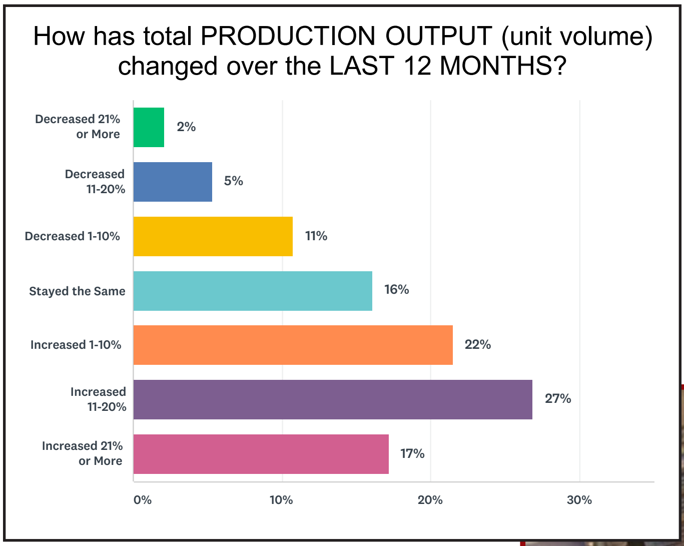
"Workers and new equipment."

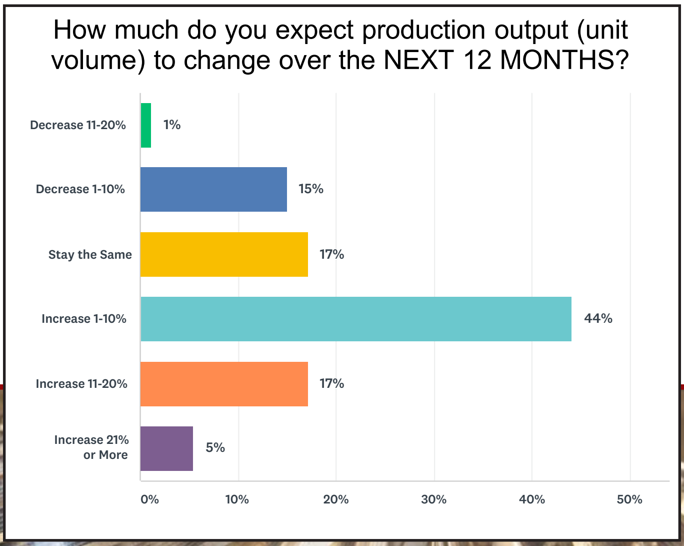
"Personnel."

"Vehicle electrification."

"The current slowdown in North American manufacturing, as well as potential tightening of credit."

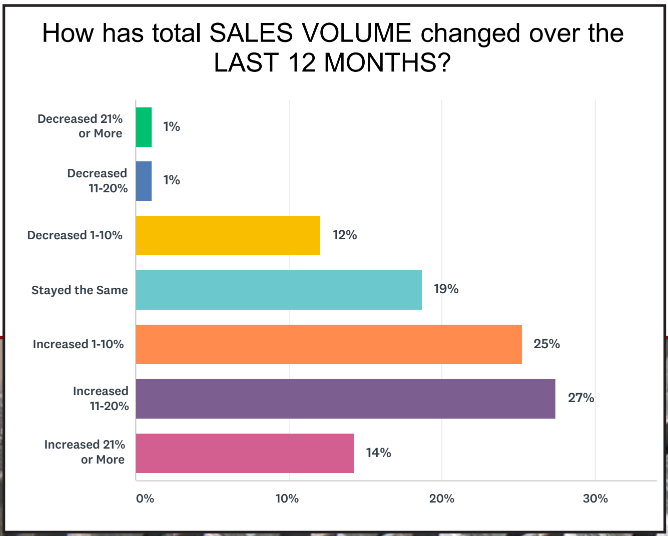
Production

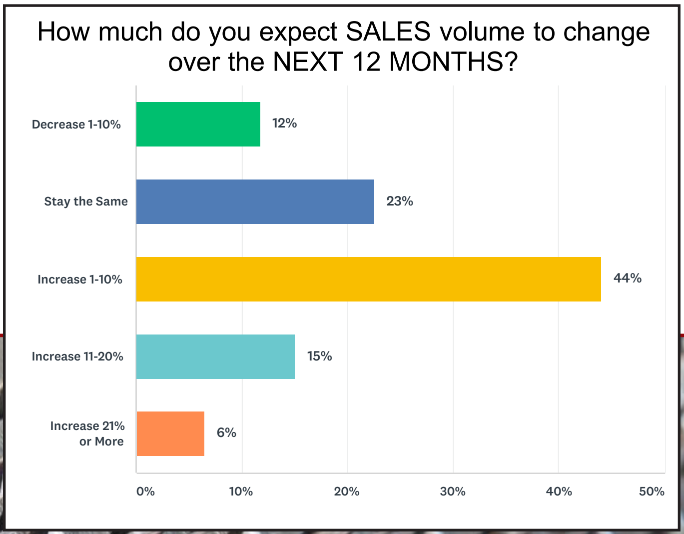




> *There are many major transformations occurring in the design and manufacturing of gearing; to reach the next level of performance requires intelligent systems.*
>
> John J. Perrotti, CEO/President, Gleason Corp.

Sales





> *We all must focus on the concept of Industry 4.0 and utilizing big data to drive inefficiencies and waste from our gear manufacturing. Developing a strategy to gather and analyze data for continued incremental improvement is critical to remaining competitive.*
>
> John Winzeler, Winzeler Gear

Capital Spending

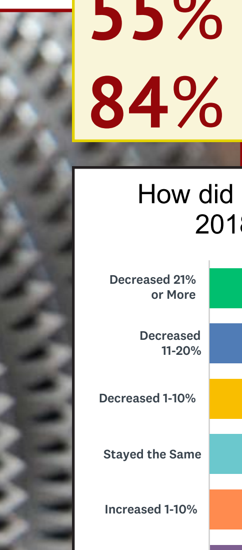
83% of respondents work at locations that spent more than $100,000 on capital equipment in 2018.

52% work at locations that spent more than $1,000,000.

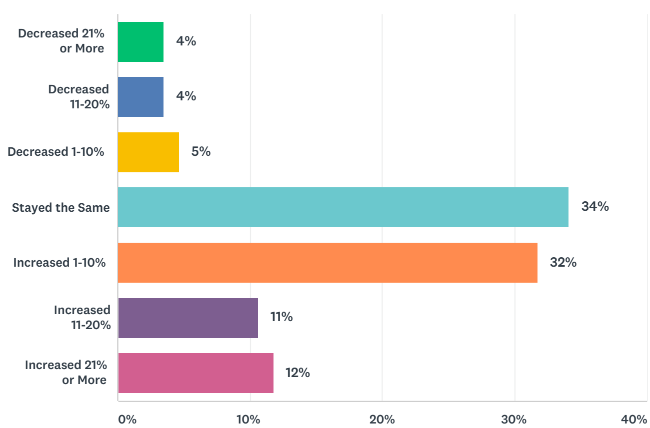
13% of respondents' companies spent less than last year.

55% of respondents' companies spent more

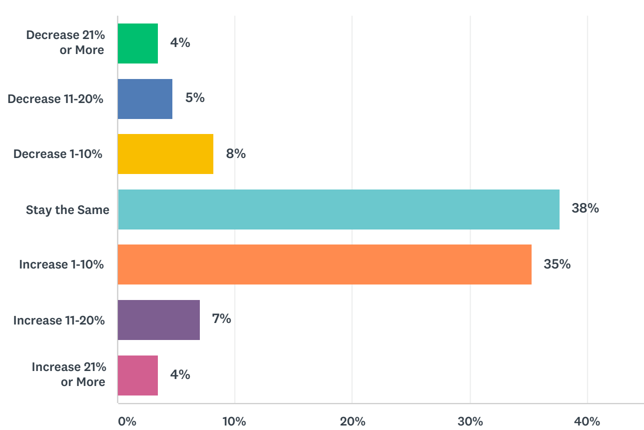
84% of respondents expect to spend the same as 2018 or more in 2019.



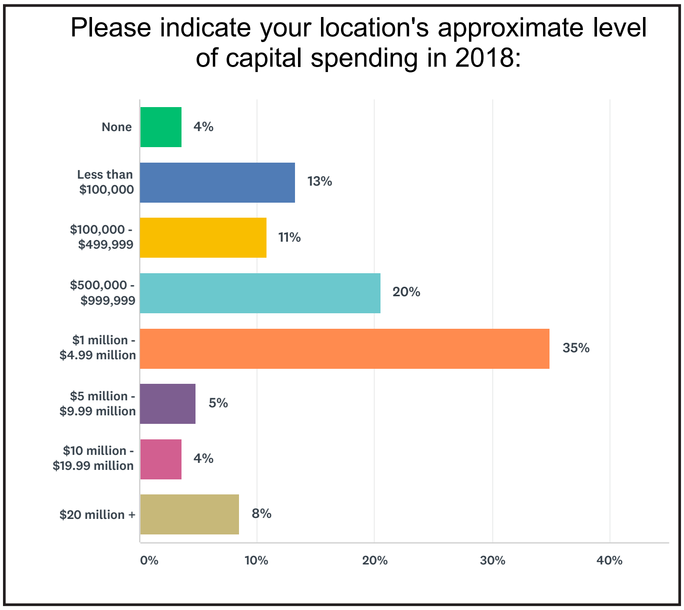
How did your location's CAPITAL SPENDING in 2018 compare with the previous year?

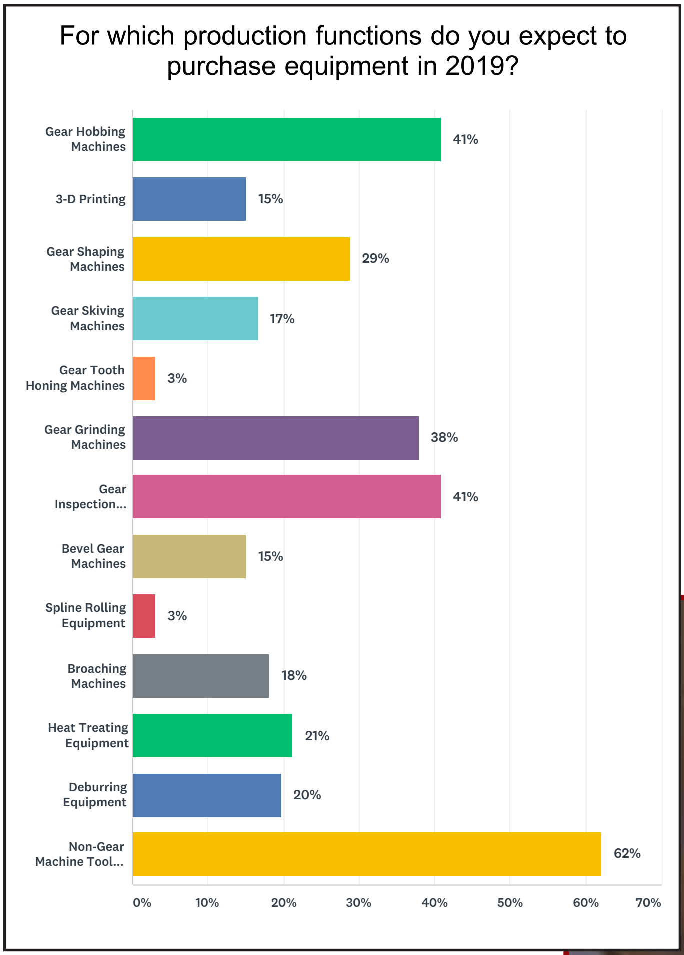


How do you expect your location's 2019 capital spending to compare with 2018?

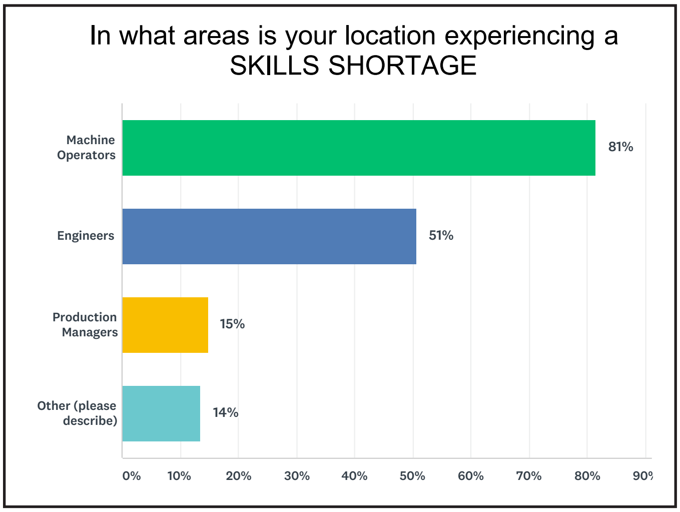


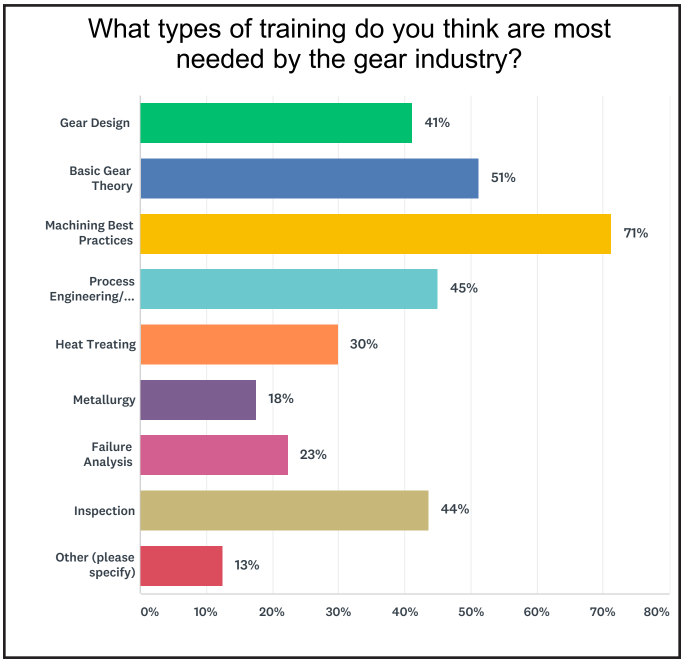
Capital Spending





Skilled Labor



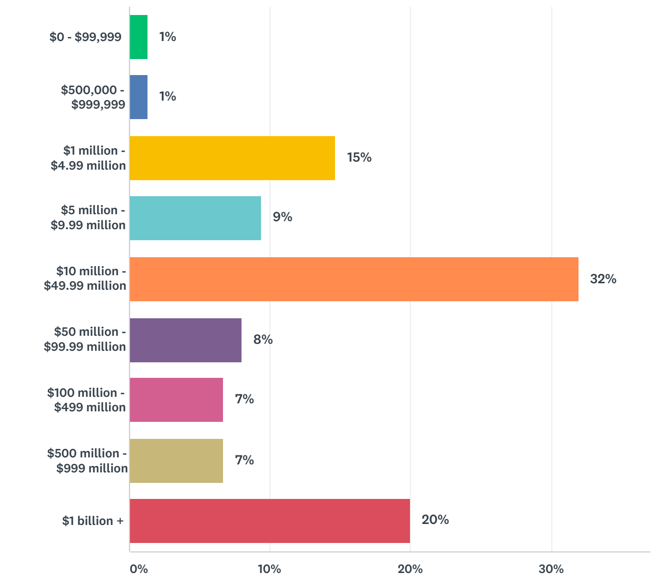


"The single largest issue facing AGMA members — and the industry at large — is finding and retaining talent."

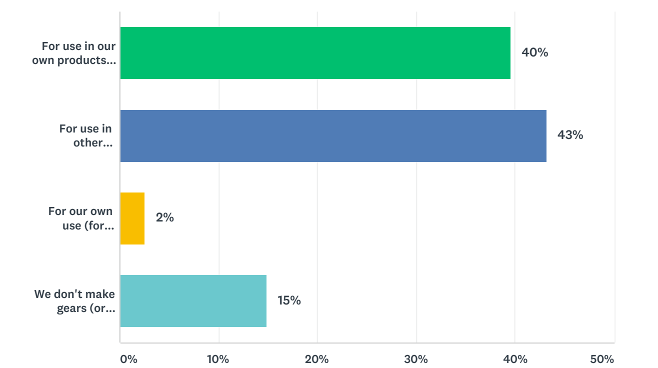
Matthew Croson, President, AGMA

Demographics

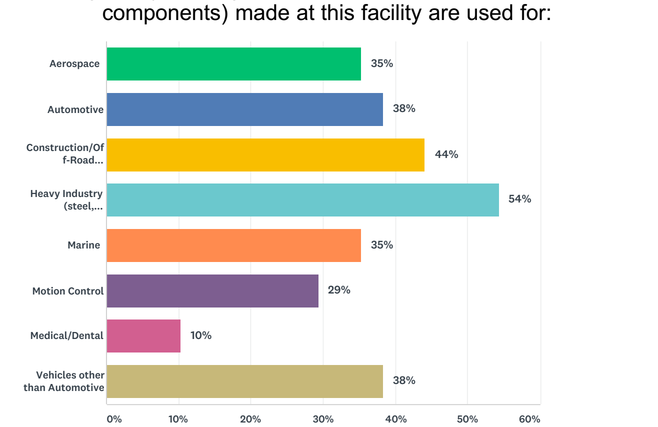
What is the approximate annual revenue for your company? (If this location is owned by another company, please use figures from the corporate parent)



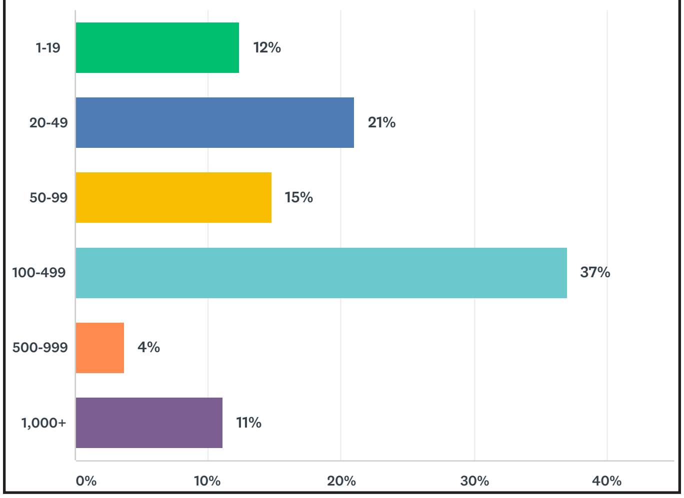
Gears (including splines, sprockets, worms and similar components) are manufactured at this location:



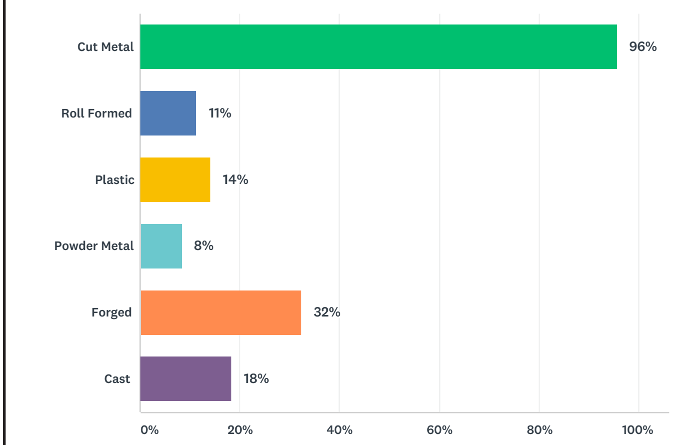
The gears (including sprockets, splines, worms and similar components) made at this facility are used for:



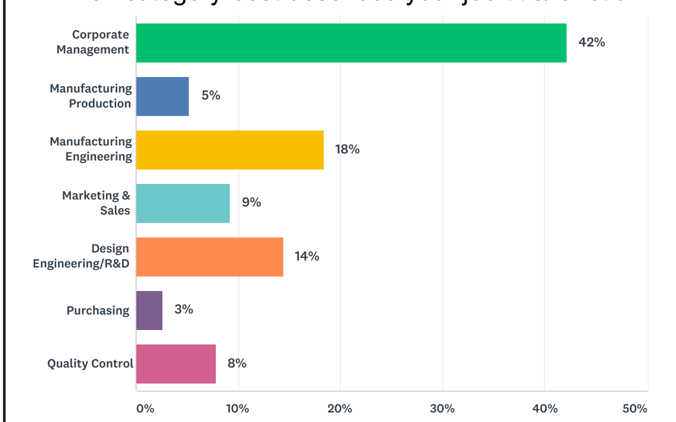
How many employees work at your location?



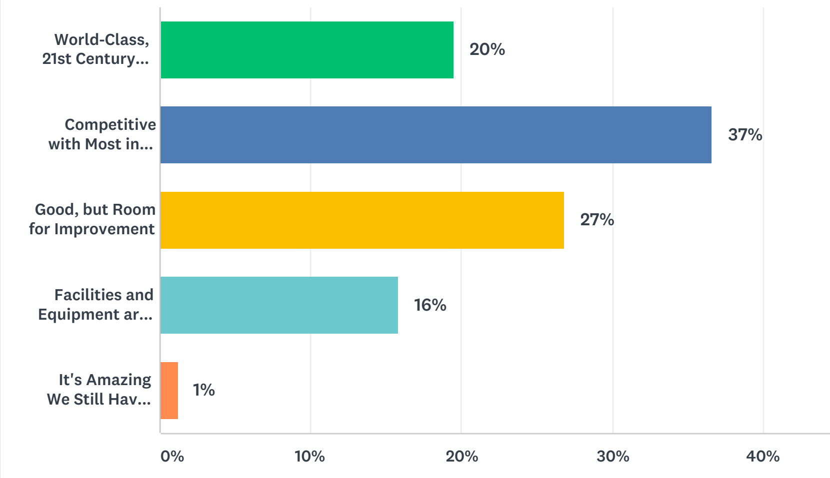
The gears manufactured at this location are:



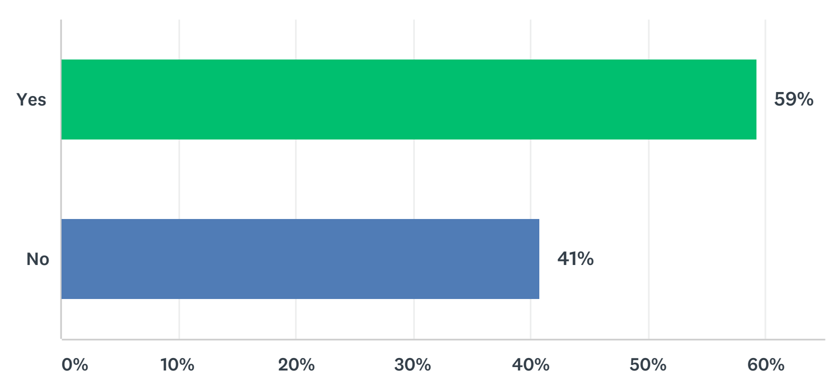
Which category best describes your job title/function?



Classify your company's manufacturing operations and technology.



Is your company currently a member of the American Gear Manufacturers Association (AGMA)?



> ***The gear industry is facing its greatest challenge since the recession in 2008-2009. We've enjoyed ten years of overall market expansion—especially in the automotive industry—where we had programs every year for 6-, 8-, 9- and 10-speed transmission projects. There is also a significant process change from hob shave to hob grind. With these automotive projects maturing, we are now faced with a customer demand of increased quality requirements and ways to decrease the cost-per-piece of production—especially as it relates to tool cost-per-piece.***
>
> David Goodfellow,
> President, Star SU

Thank you to all of our 2019 survey participants!

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Keep reading! There's more on the state of the gear industry in our special edition of "Ask the Expert" beginning on page 32.

State of the Gear Industry Special Edition

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

For this issue's Ask the Expert installment, we contacted nine individuals and their respective companies or organizations, here and abroad, with the simple question, i.e.—simple to ask, not to answer —

What are the most important trends affecting the gear industry today?

Matthew Croson, *President, AGMA*

The single largest issue facing AGMA members—and the industry at large—is finding and retaining talent.

AGMA conducted an industry survey to guide our long range planning process and we received more than 460 responses from members, non-members, suppliers, customers—really, the entire supply chain provided input. And it didn't matter whether you were part of a large, small or medium-sized company; whether you were part of management, engineering or R&D; whether you were a customer, machine tool supplier or gear cutter; finding people was the primary challenge facing industry. Whether you talked about it as "grayhairs ready to retire," as one respondent put it, or "it's harder to attract millennials to manufacturing," as another put it—people was the challenge.

The AGMA Foundation responded by launching its "Get in to Gears" program. We have developed a full suite of marketing materials to promote the industry to potential employees. We want every company that produces gears, or is part of the gear manufacturing process, to leverage the free tools we have made available to industry. The beauty of the program is that the AGMA Foundation leveraged its assets to develop these free tools, essentially saving thousands of dollars in design work alone. The materials can also be tailored to each company; e.g., you can place your own logo, website and information about your company on the brochure, Power Point, posters or handouts that we put together. The details are at *https://agmafoundation.org/getintogears.*

AGMA and the AGMA Foundation listen to its members, and respond to current trends impacting the industry today—just as our members must do for their ever-changing customer needs. In this case, we are responding in a new way to essentially innovating how the Foundation delivers value to the industry it serves, and helping ensure that our industry gets its fair share of the most valuable resource a company can have—its people.

John J. Perrotti, *CEO/President, Gleason Corp*

The expectations for gears continue to become more stringent in terms of efficiency, duty-cycle and, importantly, noise characteristics. Particularly with the future growth of electric drives, including in automotive, the quality requirements for gearing continue to increase. To meet these challenges requires a systems-based approach from design through manufacturing.

There are many major transformations occurring in the design and manufacturing of gearing; to reach the next level of performance requires intelligent systems. These systems begin with creating a digital twin so that complex processes can be modeled and become highly predictable. At Gleason, we focus on gear driveline systems design and building manufacturing intelligence into our design and analysis software so you just don't have a theoretical solution, but one that can be realized in practice with defined production processes and known data—including costs and quality. This capability—complemented by advanced simulation tools—provides the ability to modify variables and consider a range of possible solutions.

Once a gear enters the manufacturing stage, the development and optimization process continues as information is captured about the production process and the part quality which can be used either in a real-time mode—to quickly send corrective settings back to the machines—or to send information to a cloud-based environment where it can be stored and analyzed over longer periods of time. For example, Gleason has developed in-process inspection capabilities with its GRSL laser-based inspection that can measure most gear features in a matter of seconds and present this information for closed loop corrections. In addition, the experiential learning captured from the data can also be used to further refine design parameters.

These knowledge-based solutions are becoming part of broader manufacturing systems, including advanced automation where multiple tasks are combined and connected as part of the information loop. It is no longer separate islands for design, machines, tooling and inspection, but highly integrated solutions with data applied to customized algorithms which over time can support machine (systems) in learning to continually optimize your results.

Finally, watching how quickly gear producers and consumers are able to adapt to the digital transformation needed for long-term success against the near-term backdrop of an uncertain global marketplace with trade issues and other geo-political challenges, will make 2019 an interesting time for all involved.

Prof. Dr. Karsten Stahl, *Chair, Institute of Machine Elements, Gear Research Center (FZG), Technical University Munich*

Within an estimated global production of about 10^8 gear transmissions per year, automotive powertrains certainly play a decisive role. During the next years we will see a significant increase of vehicles with electrified powertrain. In such New Energy Vehicles — like BEV — the total number of required gears will be drastically reduced compared to conventional vehicles. Additionally, the transmission in an electric powertrain is more compact and seems less complex. These changes present the question about the future of gears in automotive applications.

But despite of the assumed simplicity of the powertrain of New Energy Vehicles, their requirements are becoming more demanding compared to conventional cars with internal combustion engines. Since the combination of a high-speed electric motor with a gearbox shows significant advantages in terms of costs and weight in contrast to direct drive topologies, an elimination of the transmission is not expected in the future. Although the total number of necessary gears in electrified transmissions is reduced, the requirements in terms of power density, efficiency and NVH are becoming much more ambitious. To meet the increased requirements many research projects are being carried out worldwide, focusing on both component-level and overall system-level optimization. For continuous adaption of the powertrain to the increasing demands of electrified vehicles, ongoing research activities on transmission and gears will be necessary.

Against this background, research, development and the production of high-end gears for the automotive industry will have a promising future.

Dwight Smith, *Vice President, Mitsubishi Heavy Industries America, Inc., Machine Tool Division*

It is useful to look at three large segments of the overall gear industry, i.e. — automotive, industrial and aerospace. The Machine Tool Division of Mitsubishi Heavy Industries America, Inc. is fortunate to have deep involvement in all three sectors.

It appears that the automotive sector will begin a cooling trend. With the evolution away from conventional sedans to crossovers, SUVs and pickup trucks, car transmission production is turning down, and in some cases (e.g., GM's Warren Transmission Operation and Baltimore plant) — ceasing production. Although 2018 production topped 17 million vehicles overall, this may represent the peak, and softer sales volumes in the next several years are expected. In addition, the increase in electric and hybrid vehicles, as well as future autonomous vehicles, will require gear grinding and, in some cases, improved surface finish via gear tooth polishing, as available on the newly introduced ZE16C/ZE26C machines from Mitsubishi.

From a process perspective, hard gear finishing — primarily gear grinding — will continue to grow. In particular, grinding of internal gears with the Mitsubishi ZI20A will be of great interest, as it is the best technology to reduce noise and improve final accuracy after heat treatment. Helical internal planetary ring gear production will continue to shift to the skiving process due to flexibility and cost.

The industrial sector — especially robotics and automation — is expected to increasingly incorporate gear grinding for both internal and external gears. For gear cutting, the greatly increased throughput and accuracy of modern CNC hobbers, such as Mitsubishi's GE series and electronic guide shapers (ST series), will make it imperative for job shops and other gear producers to replace older mechanical machines. The need for companies to get machines on the floor quickly and into profitable production will make our quick delivery and stock machine program very useful.

In the aerospace sector, civil aircraft orders remain strong for at least the next several years. The need to improve productivity should drive machine purchases in both the green cutting side as well as for gear grinding. There is a large fleet of old and obsolete gear machines that should be replaced as suppliers work to improve productivity and reduce labor cost.

Dr.-Ing. Oliver Winkel, *Head of Technology Application, Liebherr-Verzahntechnik GmbH, Kempten/ Germany*

1. We see several trends that are coming up more and more nowadays:
2. Handling and use of data (IoT, Industry 4.0, exchange formats, …)
3. High flexibility of the gear cutting machines (job shops, sub-suppliers, TIER1, …)
4. Reduction of setup and change-over time (maximizing uptime of the machine)
5. Precision grinding and noise reduction (quieter gears, E-Motive)
6. Chamfering and deburring (higher quality and lower costs)
7. Gear skiving (relatively new technology)
8. Hiring of qualified skilled workers

Some comments on the above points and how Liebherr is addressing them:

1. ***Handling and use of data.*** It is common that a worker programs the machine by having a printed part and hob drawing, and uses a hand calculator to calculate missing values. The future is that all of these values are transferred electronically into the machine by using standard exchange formats like GDE, DIN 4000, REXS or others. Missing values are calculated by the machine control.With the new Liebherr LH Geartec HMI, we are already making a big step in this direction.Some call it IoT or Industry 4.0, but in general it is all about handling, collecting and using data. It is important to not only collect terabytes of data — which is very easy with the dozens of sensors in the machine — but to use the data reasonably.

One example would be the process monitoring (e.g., in gear hobbing) to detect tool wear and especially unexpected tool failure. Another is the so-called Liebherr kilometer-0-cycle, where we can compare with a standard cycle the actual status of the machine or all axes with the originally delivered condition. This enables the customer to find worn components or to initiate preventive maintenance.

2. ***High flexibility of the gear cutting machines.*** Many of our customers request more and more flexible machines that are not optimized to a specific part but rather are able to machine a huge variety of parts as productively as possible. This means that regardless of shaft or disc-type gear, small or bigger module, small or large diameter, etc. — the machine should be able to cut the part.
   The reason is that the job shop and sub-supplier business increases, and more and more parts are outsourced, so you never know what kind of parts are requested from your customers over the lifetime of a machine, which can be easily be 10-20 years.
3. ***Reduction of setup and change-over time.*** The higher the variety of parts, the more often you have to change-over or make a new setup. Even in typical mass production — as in the car or truck industry — the variants increase. A typical speed gear can have maybe 7 variants, a differential gear maybe 15. To maintain high uptime of the machine, the setup and change-over times have to be reduced to a minimum. On Liebherr machines, quick-change grippers, fixtures and pallets are steps in this direction; a guided setup via the CNC control is another.
4. ***Precision grinding and noise reduction.*** The trend to higher power density and less noise is ongoing; both lead to the clear trend of hard-finishing gears worldwide — especially gear grinding and generating grinding. This usually offers the highest productivity and leads to excellent gear quality — even on medium batch sizes. But sometimes just grinding is not enough. For cars — and especially electrical cars due to the missing masking noise of the combustion engine — the need for very silent gearboxes is increasing. Besides high-precision machine and drive technology in gear grinders, Liebherr approaches this topic with additional features like silent shift grinding (SSG), deviation-free topological grinding (DFT) or noise excitation optimization grinding (NEO) to offer new potentials to improve the NVH performance of gears.
5. ***Chamfering and deburring.*** The higher power density also leads to a more effective use of the tooth width, so the contact pattern comes closer to the faces. Therefore, the chamfering of the teeth becomes more and more important. At the same time, the quality regarding shape and consistency should improve. On the other hand, the chamfering cost should be very small and setup should be very easy and fast (see above). In recent years the ChamferCut-technology (invented by LMT-FETTE) was successfully introduced and established by Liebherr in the gear industry. And the cooperation continues as we just recently introduced the new opportunity of using ChamferCut, despite interference contours.
6. ***Gear skiving.*** An old process is suddenly brand new. Being an option to gear shaping or, in some cases, even broaching or hobbing, the gear skiving process offers new perspectives to increase productivity or reduce cost-per-piece. While many different machine suppliers (gear cutting machines as well as machining centers) offer this feature, every gear producing company should make themselves familiar with the skiving process and find out whether it is applicable or feasible for them or not. While having introduced its skiving³ (cubic skiving) technology in combination with the new LK 300/500 gear skiving machine in 2017, Liebherr will be pleased to consult with customers on their way to evaluating or maybe establishing this new process in their process.
7. ***Hiring or qualifying skilled workers.*** Finally, gear making is not easy. It is not part of any standard education — whether it is mechanical engineering or manufacturing or anything else. Therefore, it was, is and will always be difficult to find experienced or skilled workers or gear specialists all over the world. The only way seems to be to train them on our own. A first step might be to support schools or universities to get kids and young engineers in contact with gears and to start their fascination on their abilities and challenges. In the end, this will never be enough, so we all have to add on our own company knowledge. In this way, Liebherr supports its customers with regular basic gear technology seminars plus customer-specific, advanced seminars and — most importantly — technology application support when necessary.

John Winzeler, *President, Winzeler Gear*

We continue to be challenged to design and produce gears that meet higher standards for sound quality. From automobiles to appliances, sound is a reflection of quality. Hence we must continue to work towards producing higher-accuracy gears with reduced variability throughout production.

Reducing gear product development time continues to be a challenge. Metal-to-plastic gear conversions to improve sound quality, and reduce weight and cost require extensive material technical data that may not be available for appropriate gear design calculations. Future solutions require expanding the dynamic testing of plastic gears — especially at elevated temperatures.

There is a continued focus on collaboration with clients and suppliers to develop innovative gear products. Engineering is a “team sport,” yet few companies approach it in a real-time, collaborative manner. Gear manufacturing capabilities must be considered from the concept phase of a new product design.

We all must focus on the concept of Industry 4.0 and utilizing big data to drive inefficiencies and waste from our gear manufacturing. Developing a strategy to gather and analyze data for continued incremental improvement is critical to remaining competitive.

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Aaron Isaacson, *Managing Director, Gear Research Institute*

In my opinion the AGMA Emerging Technologies Committee (ETC) has done a great job selecting topics likely to affect the gear industry in the next few years. If you haven't heard about the ETC, I highly encourage you to take a look at the information compiled on their website (*www.agma.org/emerging-technology*). I've been personally involved with several R&D programs in two of the identified areas, specifically 3-D Printing / Additive Manufacturing (AM) and New Materials. Progress is being made faster than you probably realize.

Most people imagine crude plastic trinkets with rough surfaces and poor dimensional accuracy when they hear that something was 3-D printed. However, dramatic progress has been made in the world of AM in recent years. Metal parts (yes even gears!) can be produced with very little porosity and reasonable accuracy. There have been two projects in the past year come through the Gear Research Institute's (GRI) test lab to characterize the bending fatigue performance of metal gear teeth fabricated using additive processes. Sure there is still work to do before you can print a replacement transmission gear for your old John Deere tractor, but in both instances the fatigue performance greatly exceeded my expectations.

This semester at Penn State, I am advising a multi-disciplinary team of senior undergraduate engineering students to produce 3-D-printed plastic gears for use as replacement parts in their senior capstone design project. This is an exciting opportunity to investigate a wide variety of materials and fabrication techniques for gear applications and, hopefully, teach a few students a thing of two about gears along the way.

New materials and the advancement of existing materials and processing technologies are areas where there is likely to be continued improvement in 2019.Cleaner gear steels, lightweight hybrid gears and the expanded use of polymers for gear applications are examples of current research efforts that could transition to commercial applications in the coming year or two.

The GRI Aerospace Bloc research consortium has been investigating triple vacuum melt steel for gear applications. During the steel making process, each vacuum melting operation removes a significant number of impurities (non-metallic inclusions) in the steel. The inclusions create stress risers in the material and lead to premature crack formation. The ultimate goal is to dramatically improve the fatigue life of the gears. Early results are promising — stay tuned!

Hybrid gears use a lightweight material like titanium or carbon fiber for the hub and body of the gear, but have hardened-steel teeth. The gears have similar load carrying capacity to gears made completely from steel, but are significantly lighter; therefore they have lower inertia and reduced losses in high-speed applications. They offer tremendous potential for weight savings in a rotorcraft gearbox.

Lastly, several polymer manufacturers have introduced high-strength plastics with much higher glass transition temperatures compared to what was previously available for gear applications. These materials can be reinforced with various filler materials to get higher strength than typical plastic gears, opening up a range of new application possibilities. These materials have led to a dramatic increase in R&D ideas applicable to polymer gears. In fact, we are exploring the formation of a polymer gear research consortium. If your company is interested, please don't hesitate to contact me for further information.

David Goodfellow, *President, Star SU*

The gear industry is facing its greatest challenge since the recession in 2008-2009. We've enjoyed ten years of overall market expansion — especially in the automotive industry — where we had programs every year for 6-, 8-, 9- and 10-speed transmission projects. There is also a significant process change from hob shave to hob grind. With these automotive projects maturing, we are now faced with a customer demand of increased quality requirements and ways to decrease the cost-per-piece of production — especially as it relates to tool cost-per-piece. This has manifested itself in improvements of substrate material such as carbide and MC90, and wear resistant coatings such as ALTENSA.

So the biggest challenge today, especially in automotive, is to find ways to increase tool performance for the cutting tools throughout their entire usable life. At Star SU, we are investing not only in new tool production, but in the total life cycle management of the tool — from the new tool through the last regrind and coating.

The main activities are focused around increasing tool performance while decreasing tool cost-per-piece with proper applications of substrate material, high performance wear-resistant coatings, enhanced tool surface conditioning, and edge prepping. These activities require a lot of research and development, as well as investment in new capital equipment to improve the process of re-sharpening and coating.

While we are working on the cost reduction measures, we are also faced with significant challenges of tariffs, as well as significant material price increases. We've also seen a substantial increase in the utilization of power skiving and Scudding globally, and a challenge in keeping up with the high demand for these cutters, both new and refurbished.

We will now be faced with even greater challenges with the impact of the development of the electric vehicle, where there are indications that by 2025 35-38% of global automobile production will be electric vehicles (or roughly 6 million vehicles). This could have a significant impact on the number of gears being produced in the automotive industry and industry as a whole.

Dr.-Ing. Dipl.-Wirt.-Ing. Christoph Löpenhaus, *Laboratory of Machine Tools (WZL) of RWTH Aachen*

New materials and treatments. Developments in E-Mobility and jet engine design show a clear trend to high-speed transmissions with speeds >15.000 rpm. In these applications a high number of load cycles are transferred via a single gear set. The expected lifetime-per-gear-set is much higher than in conventional applications today. Consequently, new methods in lifetime prediction (ultra-high cycle fatigue range), as well as countermeasures for late fatigue failures, have to be developed. In our expectation the meaning of clean steels will rise, as late failures often originate in inclusions or comparable weakest links in the material matrix. In high-cost applications, steel grades with higher amounts of alloys are currently being developed and tested in WZL's aerospace-approved lab. Furthermore, alternative material structure compositions obtained in alternative heat treatment procedures show a high potential for strength increase. Besides the potential in fatigue life, the influence on machinability/grindability needs to be analyzed.

Noise reduction. Especially in E-Mobility, the masking noise of the combustion engine is missing; this leads to a more pronounced perception of gear noise.

Additionally, the large speed range in these applications shows the importance of control on all three scales: gear (runout, pitch), tooth flank (modifications), and surface (waviness). A strong trend in consideration of all three aspects in gear design is visible making use of powerful tooth contact analysis, e.g. — developed at WZL. Especially runout and pitch need to be addressed, as the shaft rotational frequency is in the range of human hearing at high gearbox speed. Therefore, WZL works on tolerances for pitch and runout in high-speed applications. Furthermore, results at WZL show that a controlled disturbance of regularity of the gear mesh, e.g. — by changing flank corrections from tooth to tooth — shows impressive results in the decrease of tonality and could build up a new era of gear design regarding noise excitation.

Internal gears. Power density optimization puts planetary gear stages on the table. The high noise and strength demands require heat treatments and hard finishing of the surfaces. This poses multiple challenges to gear manufacturing of internal gears, i.e. — what is a suitable finishing technology with high productivity compared to discontinuous profile grinding. Multiple technologies show potential, including: honing of internal gears, internal generating gear grinding, or hard skiving. Furthermore, the ring thickness of internal gears decreases more and more. On one hand, multiple manufacturing steps in a single clamping setup via process integration help optimizing the quality; on the other, intelligent ways for clamping of gears in the machine are necessary to allow for process integration.

Additionally — and especially for internal gears — flank deviations due to deformation in the clamping device must be avoided; otherwise, a polygonal geometric error over the circumference results.

Editors' Note: Have questions or comments regarding the above? We'd love to hear from you. Simply contact Managing Editor & Publisher Randy Stott (*wrs@geartechnology.com*) or Senior Editor Jack McGuinn (*jmcguinn@geartechnology.com*).

Manufacturing **Strong**

Thoughts on Big Gear Production in 2019

Matthew Jaster, Senior Editor

For this year's exercise in large gears, we're not going to dwell on size range or length, merely look at the fundamental challenges and latest technologies required to manufacture large parts in the gear industry. This could be a gearbox assembly for the construction, mining or oil and gas industries or simply a large standalone gear pinion set for a custom application. Whatever the industry or application, large gears require more preparation, planning and precision than other areas of gear manufacturing.

HMC FOCUSES ON HIGH-QUALITY GEARING

HMC Gears (Princeton, Indiana), focuses on advanced technology in gear cutting, gear grinding and custom machining with an emphasis on large gear manufacturing. Some of the biggest challenges in manufacturing large gears include the size/weight of the part versus the accuracy and tolerances required to make an exceptional quality product.

According to Robert J. Smith III, president at HMC Gears, the precision planning and preparation required to manufacture these products always involves correct rigging, materials, fixturing, and tooling, technologically advanced machines, specialized processes and highly trained personnel.

A perfect example of this was a most recent project HMC completed for the Arkansas Dam Project. This low-speed gear and pinion set was large, heavy and required exact high precision tolerances and finishes.

"The low speed gear in this project was 173.2" diameter with a 49.5" facewidth. HMC assembled a 61.75" diameter × 142.25" long low speed shaft into this gear and performed all of the necessary pre and post assembly machining including grinding of the teeth to AGMA Class 12. With the size, exact high precision tolerances, finishes and 126,000 lb. weight of this assembly, HMC's planning and preparation had to be spot on. The gear set was installed and is running with no issues to date," Smith said.

Smith said that the primary change in large gear manufacturing has been an increased demand for higher quality gearing.

"A few years ago AGMA 8 was considered high quality. Many users today recognize that high quality on their gears and even higher on their pinions equates to longer life due to increased contact between the gear and pinion. Example: AGMA specifications require approximately 60 percent contact for Q8. Q12 is required to have 85 percent or better. The method for achieving higher quality gearing was very difficult and expensive due to the previous technology. However, today with the updated tooling and machine tool technology higher AGMA qualities can be accomplished on gears of six and seven meters," Smith said. (See sidebar)

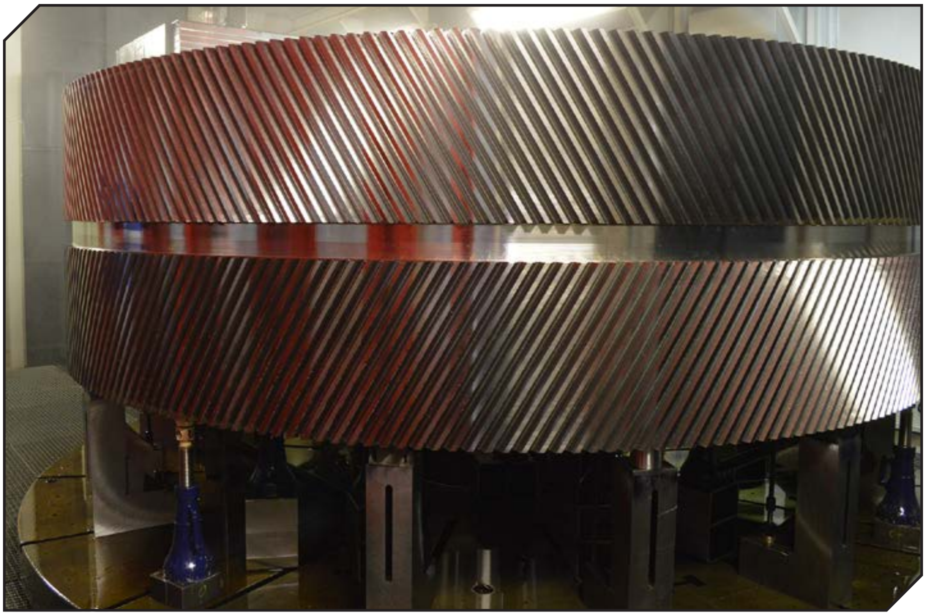
In order to run the latest machine tool technology and keep the tooling current, it's vital to have a qualified staff that is capable of growing with the company. Replacing these skilled workers, however, is still a challenge.

"The search for qualified skilled help in large gear manufacturing isn't a new problem. It's something manufacturers have had to deal with for decades. Gear making requires people with knowledge and skill. These people have been and continue to be hard to find. Therefore, it is important to nurture your program with the training of new hires and interns," Smith added.

According to Smith, another important area is the training and skill needed to handle and lift these very large components.

"Lifting and handling are not a

Recent upgrades in tooling and machine tool technology have made it easier to manufacture higher quality gears in 2019 (photo courtesy of HMC).



Advanced gear manufacturing capabilities and engineering knowhow are keys to meeting the unique challenges of large gear assemblies today (photo courtesy of HMC).

problem for a gear maker that has prepared their infrastructure for the handling and facilitating of eight meter and larger gears weighing as much as 75 to 80 tons. The key element is the training that must go into those that handle and lift these very large components with cranes capable of such size and weight. With respect to shipping there are several trucking companies with trailers capable of hauling very large heavy gearing," Smith said.

The following is an example of some of the unique manufacturing challenges and engineering expertise needed when HMC worked with a customer on a large mill gear. HMC Gears was contracted by a lime producer to provide dimensional verification of a spare mill gear that was being slated for installation during the year.

"Upon completion of our visit, it was determined that many of the necessary dimensions were incorrect and the gear would not physically fit their mill," Smith said. "There was no documentation available for the mill, the gear or pinion. Using our WEKO tracking arm and Faro laser, our field engineers compiled enough data to design and manufacture a new gear and pinion set, but would have to verify bolt circle dimensions once the old gear had been removed. The HMC forged gear dimensions were 5.5 meters in diameter and weighed in just under 30,000 lbs.

The uniqueness of this project was the many unknown design variables of the process and the limited timeline both in manufacturing time and outage schedule. The gear was manufactured (without the flange bolt holes) just prior to the customer's outage. Upon approval of the final outage plan and mobilization of HMC's crew, the new gear was setup on a vertical lathe awaiting final dimensions.

"With the first half of the gear off of the mill, our engineers verified the needed dimensions and relayed that information to the shop. The bolt circle was then machined on the second day of the outage and by the third day was prepped and ready for shipment. The gear was then loaded and shipped, arriving on site at noon on the fourth day of outage. Our crew had the first half of the gear bolted on by that night, and finished the install and alignments ahead of schedule. Our cutting-edge gear manufacturing capabilities coupled with our knowledgeable staff made this project a success," Smith said.

So what exactly does the future hold for large gearing applications?

Advances in technology never cease to amaze Smith.

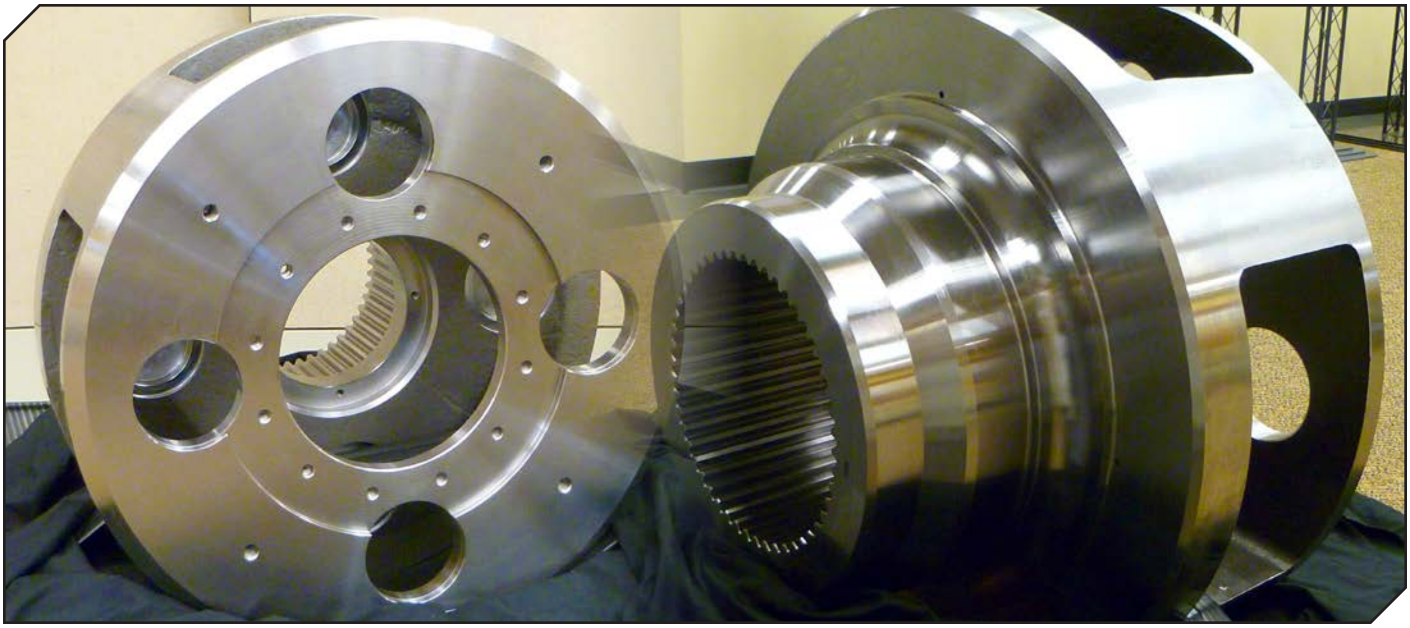
"We machine very large gears today in less than half the time we were making them 10 years ago. But it is doubtful that those same increases in efficiently can be appreciated again in 10 years if we are still using the conventional manufacturing tools and machine currently used. However, if some type of laser or other exotic technology comes along then the game might change dramatically," he added.

For more information:
HMC Gears
Phone: (866) 990-9462
www.hmcgears.com

FAIRFIELD TOUTS ENGINEERING EXPERTISE AND PRODUCTION CAPABILITY

The large gear market appears to be making a bit of a comeback in 2019 after several years in a down cycle, according to Lou Gilbert, director of sales at Fairfield Manufacturing. Markets like oil and gas, mining and locomotive are ramping up in areas where the gearing is large and requires specialized equipment and heat treatment to produce. Gears produced in markets like military, commercial vehicle and construction are also stronger though these are typically higher in volume and have smaller requirements.

"The challenges in large gear manufacturing today include operational routings, planning/sequence, material availability



A recent collaboration between Oerlikon Fairfield and Scot Forge involved developing a process for large forged carrier assemblies (photo courtesy of Oerlikon Fairfield).

and machine capacity. Since Fairfield has been in business for nearly 100 years, we have some advantages. Fairfield can often handle these large fluctuations in business due to having the floor space (over 600,000 sq.ft) to handle large amounts of material and inventory, as well as already having the production equipment in place and heat treatment on site. We control our own destiny in this way. The rest comes from internal teamwork between planning, manufacturing engineering, operations, purchasing and sales… not to mention daily customer communication," Gilbert said.

A recent collaboration between Oerlikon Fairfield and Scot Forge involved developing a process for large forged carrier assemblies. In the past, many customers have complained about a series of similar problems when it comes to cast planetary carriers including excessive scrap, redundant inspections, expedited freight costs, overtime labor costs, wasted floor space, lead time increases, on-site travel costs, opportunity costs and more.

The forged solution—compared to castings—offers a complete planetary carrier solution that meets the individual requirements of each customer. Oerlikon Fairfield and Scot Forge offer design for the forging process, the machining concept, complete FEA analysis and forge simulation, material selection, material testing and NDT testing criteria as well as future design improvements.

These two partners have been validating the process for a few months and are in the early stages of offering it to the general public. (*Editor's Note: Stay tuned for updates on this collaboration in future issues of* ***Gear Technology****).*

In regards to technology advances in gear manufacturing, Gilbert said there are two key trends the organization is keeping an eye on that are driving long-range future gear demand. The first is electrification. As this technology continues to develop, in all industries, and capability increases, power transmission will evolve.

"For example, typical "T-drive" (engine, transmission, drive shaft, axle, wheel) applications, that are dominant today in transportation, could develop into axle drive's, or, as e-drive power density increases, individual wheel drives may be common place. This could completely change transmissions as we know them today," Gilbert said.

The second is an increase in horsepower and torque requirements.

"Many industry trends continue to show a demand for more horsepower and torque to be transmitted through the same sized gear/transmission system/envelope. This is always a challenge as OEM's must ensure durability in a more severe duty cycle. To remain competitive, OEM's and gear manufacturers will need to explore special coatings, material types and processing steps. This could help to minimize investment for manufacturers and well as minimize change management for OEM's downstream," Gilbert added.

All in all, the company is optimistic about 2019. "Our commitment is proven by continued capital investment, hiring and production optimization," Gilbert said.

For more information:

Oerlikon Fairfield
Phone: (765) 772-4000
www.oerlikon.com

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Phone: (800) 813-8395
www.scotforge.com

CONDITION MONITORING WITH DB SANTASALO

DB Santasalo in the U.K. boasts a 3.5 m gear diameter Klingelnberg machine, which uses state of the art technology to check the profile, lead and pitch of some of the largest high quality gears in the world, following machining. It can also be used as a coordinate measuring machine, performing basic NDT checks for fabrications, gear cases and gears all on the same machine. These checks are completed to ensure that the gear teeth have been machined correctly and that the gearbox meets strict design criteria. This, alongside the company's stringent test processes ensures that David Brown Santasalo gearboxes are robust and reliable.

These checks are vital as the gears are being produced, but what happens when the gears have left the production line and are in their natural habitat? According to a recent news release from DB Santasalo, the company has recently developed a new system to monitor the health of the gearbox during operation. Utilizing this method, the company can spot issues before they become a problem helping you to avoid minor repairs and prevent gearbox failure.

Developed by a team of specialists with a deep understanding of drive system technology and rich heritage of designing and manufacturing gear units, this condition monitoring method examines oil particle counting. Particle counting gives a warning of the failure at a much earlier stage than gearbox vibration can, especially on low speed applications. By adding oil particle counting into the mix, along with 24/7 remote monitoring and cloud based technology, it adds a new dimension that will support customers' process reliability. This can essentially provide proactive maintenance that detects defects at such an early stage using sensor technology.

Having the ability to monitor the health of the oil in the gearbox, means potential gear unit failures can be detected months, or even a year in advance. This enables the user to plan maintenance activities around operational requirements. This is an interesting concept considering the time and cost involved in building a new gearbox. Additionally, if a shutdown does occur, the effect on a company's production capabilities can lead to a huge impact on revenue.

The operation and longevity of a gearbox requires the lubrication and related monitoring and maintenance operations to be carried out correctly. The main function of lubrication is to provide a metal contact preventive oil film on the rolling surfaces of bearings and gear wheels. In addition, it transfers the heat generated by the bearings and the gears to the environment and removes impurities and wear particles. In addition, the oil film between the tooth flanks is essential for the operation of the gear unit.

Small metal particles in the lubrication oil are the first indicators of initial damage. Online monitoring and trending of the metal particle's quantity and size, enables the early detection of damage in gear teeth or roller bearings.

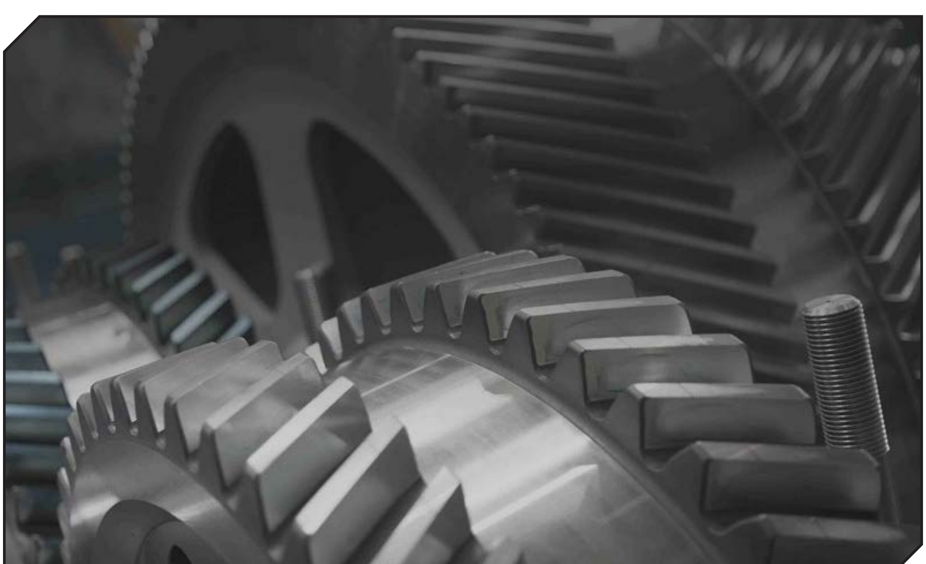
Typically, hundreds of liters of oil circulate through a gearbox. The GearWatch oil particle counter is placed on the pump-filter-unit of the gear, whilst an inductive sensor detects oil circulation from both ferromagnetic and non-ferromagnetic particles. The particle counter is also immune to air bubbles and other dust present in the oil, ensuring it provides an accurate reading.

The next step in lubrication condition monitoring is through an oil quality sensor, which enables online monitoring of the gear unit's lubrication oil condition. The user is kept informed of changes in fluid condition, as it occurs and can react to unpermitted operating conditions. Analysis can then be made about the condition of the oil, for example ageing or mixing with other fluids.

On a general level, the infrastructure for digitalization has been significantly improved, while today it's considered "normal" to be able to handle large amounts of data and use it remotely. As DB Santasalo begins to understand the capabilities and opportunities of these developments; suppliers, manufacturers and customers can all benefit.

GearWatch delivers a "one-shop-service" meaning they monitor, analyze the findings, and propose a course of action to rectify the issues. If necessary, the company then provides the repair or maintenance to get the machine up and running. This is available in three packages: DBS GearWatch Standard, DBS GearWatch Oil Monitoring and DBS GearWatch Pro, giving customers several options to adapt to their specific requirements.

The latest phase of this condition monitoring technology was launched in the fall of 2018. The company will continue to offer customized solutions for gear units and drivetrains in the future.



The operation and longevity of a gearbox requires the lubrication and related monitoring and maintenance operations to be carried out correctly (photo courtesy of DB Santasalo).

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The Growth of Australian Regenerative Load Testing

Michael Sutherland, CNC Design

Historically, gearbox original equipment manufacturers (OEMs) and repair organizations have tended to offer their customers 'no-load, full speed' ('spin') tests as a standard performance test. If a 'load test' was specified, the supplier would probably offer a locked torque 'back-to-back' simulated load test, which requires a large investment in tooling to connect shafts of the test and slave gearboxes.

Advances in cost-effective power electronics, however, have enabled businesses to consider the installation of an efficient regeneration system that enables the possibility of load testing industrial gearboxes in the medium power ranges (a power level that typically would have been price-prohibitive to install in many facilities).

Regenerative load testing recycles the energy that conventional load testing methods needed to dissipate. A typical system will utilize two similar-sized motors (one to drive the equipment, the other to generate power) and a speed-matching gearbox (similar in ratio to that of the 'test' gearbox). Systems are designed to suit a customer specification; a low-voltage (480/690 Volt) system can handle electrical power up to about 3.2MW, while larger power requirements need to switch to medium voltage, due to limitations on current at low voltages (Fig. 1).

Motor drives and electrical cabinets are modular, enabling companies to build capability on a budget — starting at 100/200 kW — with the knowledge that it is possible to increase power capacity at a later date by adding drives. When planning an expansion of the test facility, it is important to consider the holistic workshop layout. Consideration must be given to operator and visitor safety, piping and cable management, lube system tanks and pumps, cooling systems, and any increased loadings on the floor plate design, to name but a few.

Energy losses on a typical regenerative test are about 20% of the nominal rated power; these losses are due to the drive efficiency in both motor and generator, plus the gearbox losses from bearings and gear tooth mesh heat. Therefore, a nominal 1 MW test (Fig. 2) would only require approximately 200 kW through the main supply, enabling smaller workshops with a limited power supply to offer significantly higher load capability.

Figure 3 demonstrates power consumption of a typical load test; the plot identifies the test motor (blue), the regenerated power (green) and the consumed power (orange), while stepping up load in 25% increments.

Speed 'matching' is important for efficient generation, as the generator ideally rotates at the same speed as the driving motor to avoid frequency

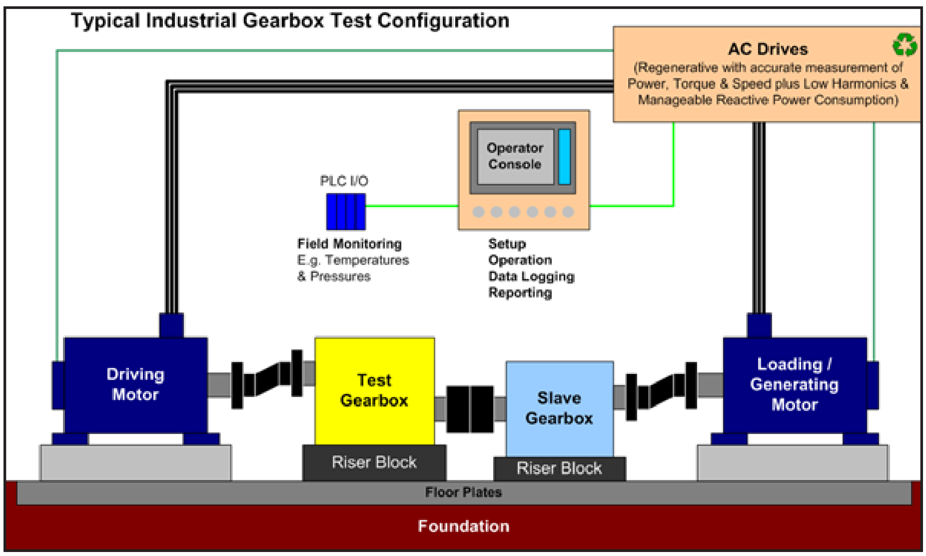

Figure 1 Schematic of a regeneration GearTEST set-up.

Figure 2 1MW-load GEARTest installation at Hoffman Engineering, Perth, Australia.

conversion losses. However, there is a tolerance band of approximately +/- 10% where the efficiency of conversion is reasonable.

It is nevertheless worth noting that for service providers wanting to offer a wide range of test powers and speeds, there will be a requirement to hold a range of step-up/step-down test gearboxes to maximize regeneration benefits.

The regenerative energy saving potential especially pays dividends when testing gearboxes with rated powers over 300 kW. Tables 1 and 2 highlight potential cost savings on annual electricity consumption alone, based on testing two gearboxes a week across a range of powers. It is worth noting that, as electricity costs vary substantially around the world, prices from the U.S., Australia and Germany are used for comparison. All prices are converted to U.S. dollars utilizing purchase power parity figures in U.S. dollars from OVO Energy *(https://www.ovoenergy.com/guides/energy-guides/average-electricity-prices-kwh.html)* as a baseline.

As test powers increase, calculations highlight the significant savings to be made by adopting regenerative technology, and those benefits are magnified significantly in geographical areas where electricity costs are high. However, cost savings alone do not seem to be driving investment strategy.

Over the past ten years in Australia, the 'load' testing of industrial gearboxes has become somewhat of a standard requirement in many repair specifications. It is Australian end-users that have perceived significant value in load testing both repaired and new gearboxes, citing increased reliability and the associated reductions in unscheduled down-time as major factors that save cost over the long term.

What is interesting to observe in the Australian market is that the demand for 'load' testing has driven a number of industrial gearbox service providers to make an investment in load test capabilities — some even duplicating capacity to compete at a local state level, rather than rely on a national strategy.

Table 3 identifies the competitive landscape in Australia and the recent growth of the regenerative test capacity. A high proportion of new investments have tended towards regenerative technology for the cost and performance benefits described above.

While it is the Australian mining sector that has pioneered the drive in demand for industrial gearbox load testing for reliability, other industries may benefit from more comprehensive testing, especially in applications where the gearboxes and associated plant have very high installation and maintenance costs; e.g. — marine drives, gear-driven hydro turbines and sub-sea marine turbines.

Future developments in (trademarked) *GearTEST* solutions are focused around Industry 4.0 concepts, with improved sensors for better data acquisition and reporting. Traditional *GearTEST* report parameters such as power, speed, temperatures, pressures and flows are all recorded and processed through the control system, while additional features such as test lube oil condition analysis, shaft alignment features and auto-adjustable mount plates to enable simulation of inclined installations are all possible.

As yet, the cultural shift of end-users specifying load tests does not seem to have gained much momentum outside of the Australian mining sector, but as gearbox repair companies continue to seek new areas of competitive advantage, regenerative load testing capability is a potential area of differentiation that could improve a company's value-added proposition.

Of course as regenerative load testing

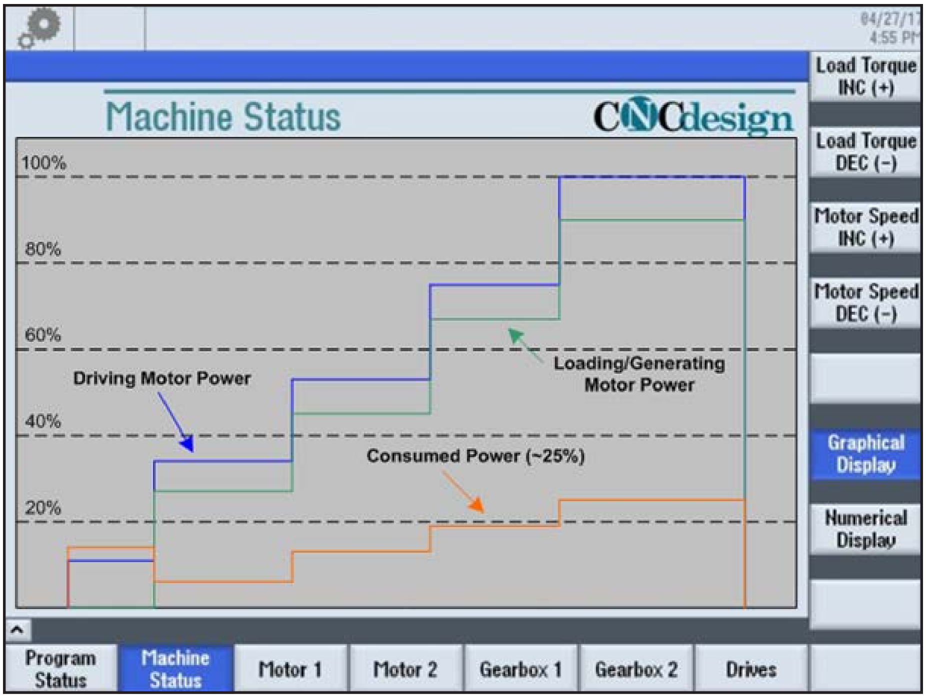

Figure 3 Power consumption.

Table 1 Cost saving potential: Australia in USD

Gearbox Rated Power (kW)	Test Time (hours)	Average $/kWh cost (Australia)	Electricity Cost per TEST (With out Regen)	2 Test Per Week - Test Cost Per Year (USD)	Electric Cost with Regeneration (Per Year)	POTENTIAL ENERGY SAVINGS PER YEAR (USD)
100	4	$0.21	$84,00	$7,644.00	$1,490.58	$6,153.42
500	4	$0.21	$420.00	$38,220,00	$7,452.90	$30,767.10
1,000	4	$0.21	$840.00	$76440,00	$14,905.80	$61,534.20
2,000	4	$0.21	$1,680.00	$152,880.00	$29,811.60	$123,068.40
3,200	4	$0.21	$2,688.00	$244,608.00	$47,698.56	$196,909.44
4,000	4	$0.21	$3,360.00	$305,760.00	$59,623.20	$246,136.80
4,500	4	$0.21	$3,780.00	$343,980.00	$67,076.10	$276,903.90

becomes more accessible, it is likely that an increasing number of end-users will specify it in the industrial markets, as well as part load testing rather than the 'spin' test; this may well become the global industry standard, as currently seen in the local Australian market.

For more information:

CNC Design Pty. Ltd.
A.B.N. 66 006 029 296
Unit 2 / 137-145 Rooks Rd, Nunawading
Victoria, Australia, 3131
Office: +61 (0) 3 9411 1522
Mobile: +61 (0) 425 811 522
michael_sutherland@cncdesign.com.au
www.cncdesign.com

Michael Sutherland is national sales manager for CNC Design Pty. Ltd. He previously worked for the company (1987-1993) as senior project engineer, and (1993-2000) in the same position for CNC Design's Korea location. From 2000-2012 he was senior project engineer for Siemens Inc. USA, and then (2012-2016) as senior application engineer, business and development national sales manager for Siemens KK in Japan. Sutherland returned to CNC Design in 2017.

Table 2 U.S. and Germany savings

Gearbox Rated Power (kW)	USA average rate $/kWh	USA Regeneration Savings (USD)	German average rate $/kWh	German Regeneration Savings (USD)
100	$0.12	$3,516.24	$0.32	$9,376.64
500	$0.12	$17,581.20	$0.32	$46,883.20
1,000	$0.12	$35,162.40	$0.32	$93,766.40
2,000	$0.12	$70,324.80	$0.32	$187,532.80
3,200	$0.12	$112,519.68	$0.32	$300,052.48
4,000	$0.12	$140,649.60	$0.32	$375,065.60
4,500	$0.12	$158,230.80	$0.32	$421,948.80

Table 3 Advertised gearbox load test capacity in Australia 2018

Australian Gear Repair Service Providers	Workshop Location	Estimated Year Installed	Rated Power Capacity (KW)	Load Source
Gear Drive Services	Perth, WA	2008	800	ReGen
David Brown Santasalo	Perth, WA	2010	450	ReGen
Hoffmann Engineering	Perth, WA	2010	1,000	ReGen
Wittenbacker (WES)	Perth, WA	2012	600	Dyno
SEW Eurodrive	Mackay, QLD	2015	500	ReGen
Sumitomo	Mackay, QLD	2018	500	ReGen
Siemens	Rockhampton, QLD	2015	3,000	ReGen
Eickoff Australia	Sydney, NSW	2018	1,000	ReGen
David Brown Santasalo	Sydney, NSW	2000	500	Dyno
DCL Engineering	Sydney, NSW	2006	50	Hydraulic
Sumitomo	Sydney, NSW	2014	150	Regen
State Wide Bearings	Newcastle, NSW	2010	90	Dyno
Hoffmann Engineering	Newcastle, NSW	2015	90	Regen
Geared Engineering	Sydney, NSW	2013	50	Dyno

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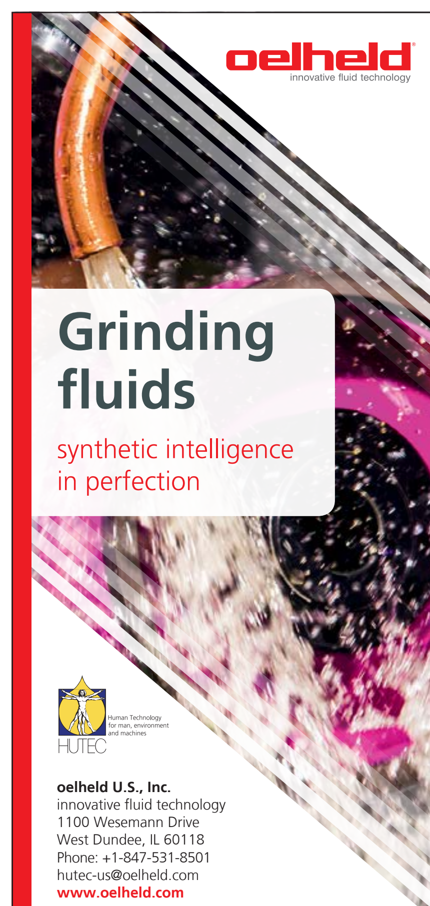
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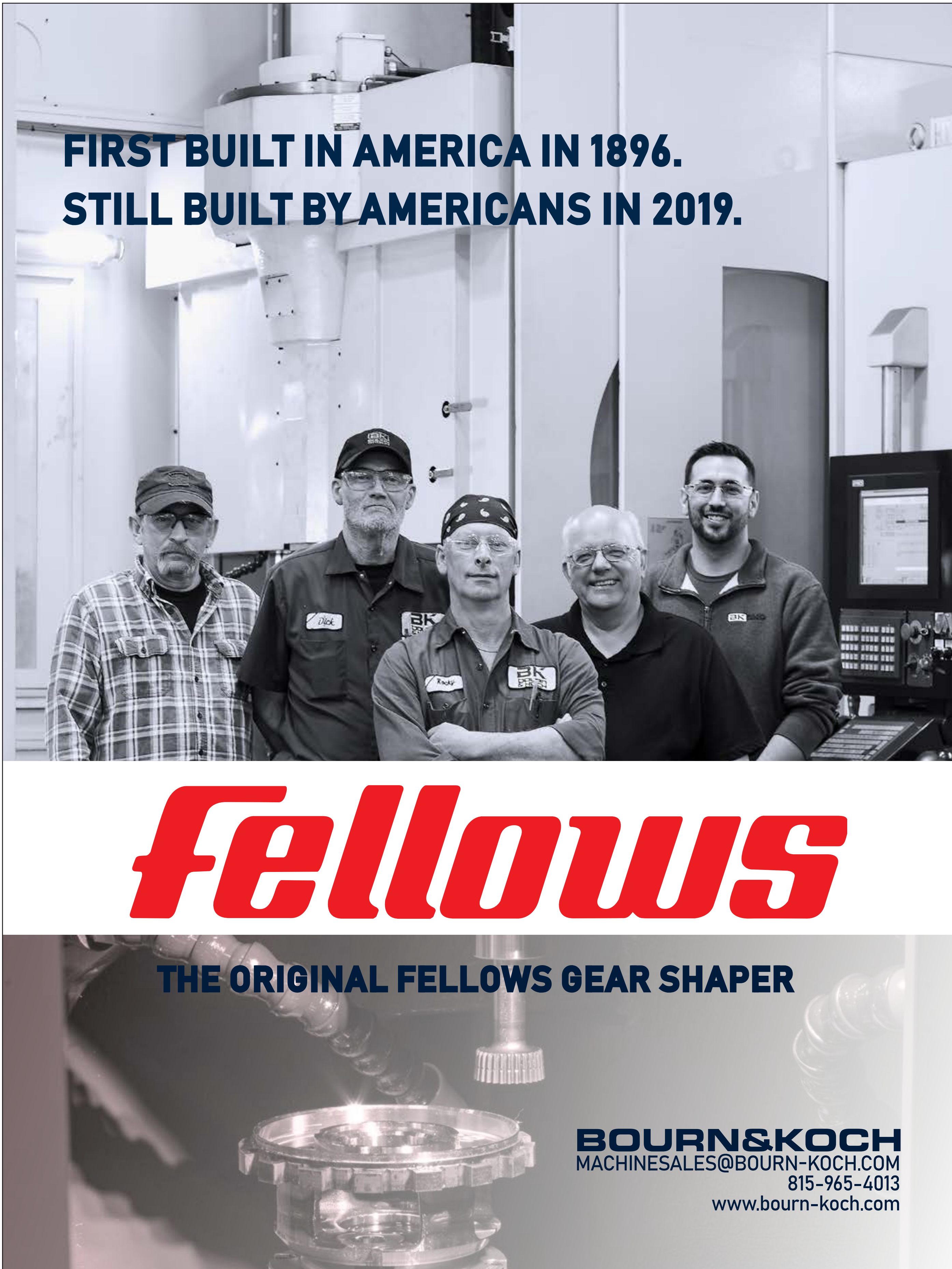
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Getting In Sync

Power skiving is here to stay, and as a result of this industry shift, it's become paramount to improve how well machining spindles synchronize with each other.

Alex Cannella, Associate Editor

Advanced cutting techniques like gear skiving are forcing multitasking machine manufacturers to improve their machine spindles' synchronization.

Gear skiving is making big waves in the gear industry. Though the process has existed for over a century, recent advances in machine construction have finally brought it into the spotlight as a competitive manufacturing process. For certain types of parts, especially internal gears, a high-end, dedicated gear skiving machine — like those produced by Gleason, Klingelnberg, Pittler, Profilator, Toyoda and others — is the most productive option.

Unfortunately, not every gear manufacturer has such a machine. However, many *do* have a mill-turn machine or multitasking machine, and although they'll never have the same productivity as a dedicated gear skiving machine, it *is* possible to do gear skiving on those. For this article, we talked with two machine tool manufacturers — Mazak and Okuma — to see how far they've come.

Gear skiving, in its current iteration, has come far and done much for the industry, specifically for the manufacturing of internal gears. As a high speed cutting process, it greatly reduces the time it takes to cut a workpiece. But as Arthur Bloch once said, "every solution breeds new problems." For multitasking machines, the problem of the day manufacturers face is getting a machine's milling and lathe spindles to synchronize at high rotational speeds. Dedicated gear manufacturing machines tackled this issue long ago, but for multitasking Millturns, high-speed spindle synchronization hasn't previously been a priority, and so they have some catching up to do. Making sure a machine's spindles are accurately synchronized to each other is vital for ensuring no errors occur during the gear skiving process.

"It's all rotational accuracy," Chris Peluso, lathe applications engineer at Okuma, said. "If the drives can't tell you where the spindle is at any given time, it can't match the two. The lathe spindle and the milling spindle need to be synchronized at a ratio based on the number of teeth on the part and the number of either cutting teeth or threads on the cutting tool. So if you can't maintain that perfect ratio at speed between the tools and the workpiece, you can come out with a bad part or have a catastrophic failure."

It's not hard to imagine how having the spindles out of sync would lead to catastrophic failure or bad parts. During these high-speed processes, both the workpiece and the cutting tool are in motion. Getting a specific point on a cutting tool to line up with the centerline of the workpiece it's meant to cut while both of them are spinning at high speed is like getting celestial bodies to align. It needs very exact timing to happen. And as with any cutting process, it needs to happen repeatedly in rapid succession. And because it's gear production, it needs to be done with accuracy requirements of within a few microns. *And* each spindle needs to move at an entirely different speed. For example, a workpiece's spindle could be moving at 500 rpm, while the cutting tool's spindle needs to move double that. And when you break down all the different variables at play in a particular gear — the dimensions and number of teeth, the speeds each spindle needs to move at for the tool to meet the workpiece in the intended manner, the cutting tool being used, and the angle it strikes the workpiece at — it becomes obvious how being just a hair off with any of these variables can result in a drastically different cut than desired, and that includes the timing of the spindles.

(Editor's note: high-end, dedicated gear skiving machines typically offer synchronized spindle speeds of 3,000 rpm or higher.)

Accuracy requirements are always high in gearing applications, but with all these different moving parts, gear skiving makes those demands tighter than ever, which is why the issue has suddenly come into focus. Multitasking machines traditionally haven't needed to synchronize their spindles as tightly as dedicated gear manufacturing machines, as they've generally been within necessary tolerances for other cutting techniques, and if it ain't broke, there's no reason to fix it when there are a dozen other ways to reduce manufacturing time. But now that gear skiving is growing in popularity, multi-tasking machine manufacturers are looking to their spindles with higher scrutiny.

"If an endmill in a milling operation would fluctuate plus or minus, say, 5%, that's not really going to cause any issue in terms of chip load," Joe Wilker, advanced product manager, hybrid machines at Mazak, said. "The chip load will vary, but a very, very small amount. But we can't have that type of variance in a gear skiving application. So we have to have much finer control of both the milling spindle's rpm and the part spindle's rpm."

That shift to electrics versus gear-driven machinery is the primary way companies such as Okuma and Mazak have been solving the synchronization issue. A big part of the equation is moving away from spindles with mechanical drives and instead opting for ones driven by electric motors. But there are other steps involved, as well, such as Okuma's "High accuracy C-axis," which features a higher resolution than competing encoders and have an accuracy of ±2.5". Okuma also tries to ensure high accuracy by producing everything in-house, which can help reduce the amount of confusion involved in maintaining and tweaking machinery.

"Because it is all in-house, we can tune the servo-drives," Peluso said. "So how much gain is needed for positioning versus how much is needed for locational accuracy, that can all be modified by the people here in the U.S.…Say they have a one manufacturer's control and somebody else's drive, who's responsible for tuning the drive to work with the control? With us, there's only one source. There's only one person to talk to. If it's the control or the mechanical side, we have all the resources at our disposal here."

Mazak, meanwhile, recently developed a pair of new multi-spindle multitasking machines that were unveiled at the last IMTS. One is the Integrex e-1250V/8 AG (Auto Gear), a vertical multitasking machine. The other, the Integrex i-200ST AG, a horizontal multitasking machine with a tilting B-axis. Both machines are capable of manufacturing gears, as well as other gear components such as shafts, rings, complex workpieces and gearbox parts.

"These AG machines are for shops that normally would turn away gear work or send gear work out and/or do not have the capital to purchase a high production gear machine," Wilker said. "With one machine platform, one work holding the overall part accuracy is improved within relation to part datums and gear features."

The machines also run Mazak's *Smooth Gear Cutting* software packages for skiving, hobbing, and milling, in addition to their gearskiving abilities.

Both companies have upped their programming game, simplifying the complicated process of gear manufacturing and its numerous variables to just a few required data points. Mazak has their Smooth series, and Okuma has their own built-in gear programming function along with a servo-navi designed for tuning spindles. All the user needs to know are a few gear factors such as the module or number of gear teeth, and by answering these few questions, the CNC software builds the fully editable programs that are required for cutting the feature, including the emergency retract routine, which keeps the spindles in sync while the cutter moves to safety.

"We basically developed some user-friendly CNC technology programming, making it easier for operators at all skill levels to program gears," Wilker said. "There's always been this black voodoo of 'Oh, gear cutting. That's over here in the black box and nobody knows anything about it.' And we see it as: 'It's basically part geometry.'"

"You don't have to sit there and calculate what rpm does the main spindle need to run, and then what speed does the work spindle need to go, and if I want to do this number and depth of cuts, how do I do all of this?" Peluso said. "So we really simplified the programming standpoint."

Through software and mechanical improvements, the issue of synchronizing spindles has actually become pretty well-tackled, at least in the minds of the experts at Mazak and Okuma. Manufacturers have gotten spindle synchronization to where standard modules are produced with relative ease. But like anything else in manufacturing, there's always room for improvement, and dedicated gear machines still have the edge in their max speeds that spindles can synchronize at. And going back to Arthur Bloch, every solution still breeds new problems. We'll see what new problems arise to be tackled next.

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Mazak USA
Phone: (859) 342-1700
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The Quest for the All-in-One Machine

Multitasking machines have a pretty clear sales pitch: They can do what you need them to and make a gear, but if you're a job shop with fingers in a lot of pies, you can also use them for anything else you might need to make. Hobbing, cutting, milling, now even gear skiving. If it's a cutting process, a multitasking machine can probably do it. Therefore, when you can do everything you need to with one machine, the time and space savings are immense. No more taking the part off and resetting it as it travels from machine to machine, reducing lead time and the potential for user error. No more needing an entire warehouse of machines just to get one gear out the door. That's the multitasking machine's core selling point: in goes the blank, out comes a finished gear.

Every company, including Mazak and Okuma, will make this their first and primary bullet point when listing the virtues of multitasking machining, but WFL Millturn focuses on taking that philosophy as far as it can possibly go. For many years, they have integrated in-process metrology to the list of steps you can all do on one machine as part of the company's long-term strategy to make their machines literal one-stop shops capable of doing every single step of the entire manufacturing process. This means that a customer using a WFL Millturn can easily program the part (including the gear featres), simulate, machine all operations and then measure before taking the perfect part out of the machine. According to Kenneth Sundberg, managing director of aftermarket sales at WFL, this is the work WFL does every day and how the company differentiates itself from the competition.

"This is what we do at WFL: complete machining," Sundberg said. "This is simply our DNA. To be number one in complete machining; this is our ambition. This is our focus every day."

So what benefits does the latest step in that process yield for you, the manufacturer? The main benefit, according to Sundberg, is reduced floor-to-floor time. Having advanced programming and simulation software like Crashguard Studio, as well as metrology equipment in the machine itself, means that manufacturers can double check their work without having to take a workpiece out of the machine. They will not have to drag it to dedicated metrology equipment, bring it back and put it back on, or alternatively have to wait to start the next piece until the previous one has been checked. Like with everything else in multitasking machining, its primary benefits are reducing setup time and minimizing the number of points during the manufacturing process for potential human error to occur.

It's important to note however, that as with almost all in-process metrology systems on offer today, WFL's onboard measuring equipment is *not* a replacement for a full metrology lab. In the future, the sky may well be the limit, but for now, WFL's in-process metrology doesn't track every criteria required for measuring gears according to AGMA's practices. Instead, in-process metrology's main job is to quickly and accurately check the main features to secure the quality of a machined gear. It aids in ensuring workpiece consistency for repeated jobs and makes sure that nothing's gone awry mid-process, but completed components should still go through proper lab testing to provide the required gear quality data according to the gear standards required.

"If you have one component and it has to be right, this is extremely important to be able to measure in the machine," Sundberg said. "Otherwise you have a lot of hassle with setting up the part again and you lose time and so on."

WFL is on a mission to create truly all-in-one multitasking machines.

WFL is running into increased demands for automation and a push for machines that can run 24/7.

"We see that the demand for automation is growing all the time, and the main topic is that customers want the machine up and running for the majority of the available hours," Sundberg said. "And there's not enough skilled workforce for that, so that's a big limitation. And if you invest in an expensive machine like a WFL Millturn, then you should make sure that you get the hours out of it that you can. Here we see that automation is a very big topic for smaller to midsize batch manufacturing."

Which all leads to WFL's recent acquisition of Frai, an automation solutions company. The acquisition is too recent to publicly announce any advances, but Sundberg noted that this acquisition would help WFL improve its automation and help push the company along in its quest for the ultimate, permanently operating all-in-one machine.

While many multi-tasking machine manufacturers are now offering gear skiving, it's not as much of a focus for WFL as a majority of the customer requests are solutions for larger gears where the traditional methods like hobbing, InvoMilling, and profile milling are beneficial. WFL's wheelhouse is machines primarily designed for small batches of large parts, where other traits such as high torque and high machine rigidity are of higher importance. In this case, Sundberg noted that the mechanical drives WFL traditionally uses are of higher importance. That said, Sundberg stated that WFL is working on new developments suitable for batch manufacturing of gears where certainly gear skiving will be one feature covered.

"We are still committed for the future to offer this technology for precision machining," Sundberg said. "It is definitely something that has come to stay and will expand in a lot in the next [few] years."

In the meantime, WFL's quest to be the best at single-setup manufacturing remains the company's primary focus.

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Beautiful on the Inside

Higher Quality Internal Gears

Dwight Smith, Mitsubishi Heavy Industries, Inc.

Automotive gear manufacturers have implemented significant improvements in external planetary gear manufacturing yielding quieter gears. In addition, process stability has increased due to the post-heat treatment finishing processes employed.

Beyond planetary pinions and sun gears, external transfer and final drive gears are commonly ground or honed, or in some cases, ground and honed. Add to this the widespread use of low pressure or "vacuum carburizing", the current bill of process for automotive gears bears little resemblance to the hob and shave pre-heat treat processes of 20 years ago.

As hybrid and electric vehicles are developed and brought to market, the demand for quieter gears continues to rise. In planetary gear systems, the internal ring gear is the final frontier for improvement to meet the requirement for quieter transmissions.

This article explains various complete solutions for cutting and finishing internal ring gears.

MSS 300 Super Skiving Machine.

Three Ways of Creating the Teeth in Internal Gears

The three commonly used methods of cutting internal gear teeth each have benefits and a place in the gear manufacturing world: shaping, broaching and gear skiving/Super Skiving.

There have been few revolutions in the slow evolution of the internal gear. Shaping has long been used for the production of ring gears. When helical internal broaching was developed, transmission designs changed to take advantage of this process and the huge increase in productivity. Up to 20 or more shapers were replaced by one helical broaching machine with two stations.

Broaching Machine.

Shaping Machine.

After over 100 years of development, internal gear skiving and Super Skiving have advanced to augment, or in some cases, replace broaching. However, all three methods of internal gear production — shaping, broaching and Super Skiving — are green processes with the steel in a soft state prior to heat treatment.

	Gear Shaping	Broaching	Gear Skiving
Tool Type	Shaper Cutter	Helical Broach	Super Skiving Cutter
Accuracy	ISO 6-7	ISO 6-7	ISO 4-5
Cycle Time (C/T)	240 sec.	40 sec.	60 sec.
Productivity (16H/day)	210pcs/day	1,680pcs/day	840pcs/day
Modify Geometry	Lead adjustable (ST Series)	No modification	Both pressure angle and lead
Ratio of typical per piece tool cost	2.05	1.2	1
Internal gear with steps	Possible	Not Possible	Possible if between gap is over 40mm
Merit	All gear types (External, internal, with steps, special profile, etc.) can be cut	Mass production of single part type	Multiple part types. High/medium production. Lowest tool cost. Flexible part capability.
Demerit	Long CIT. Tool life short. Tool cost high. Internal gears under	High capital investment and space required. Tool cost high. Internal gear < M2.	Cutter manufacturing, interfering geometry limits. Internal gear under M3.
Application/Production per machine	M3. Production max 5,000/mo.	Production max 30,000/mo.	Production max 20,000/mo. For mixed production of around 5,000/mo.

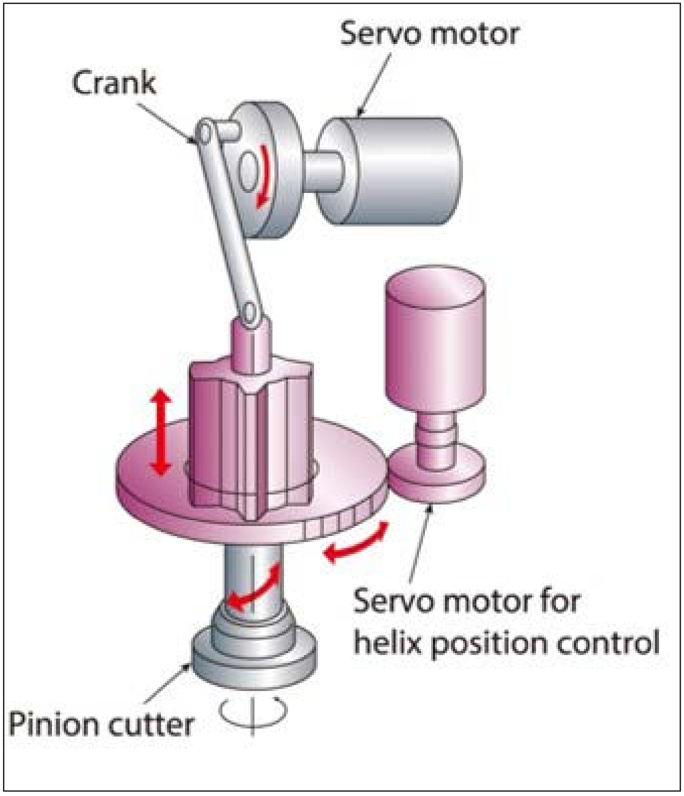

Figure 1 Shaping process.

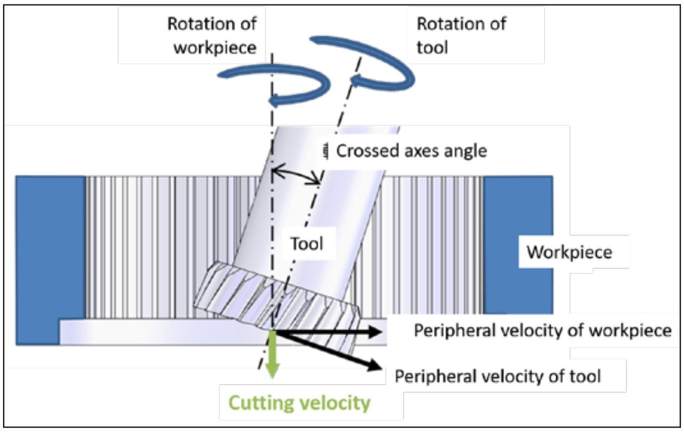

Figure 2 Skiving tool and workpiece.

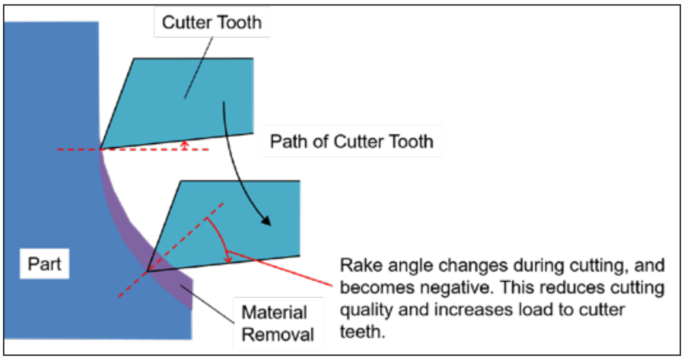

Figure 3 Skiving rake angle.

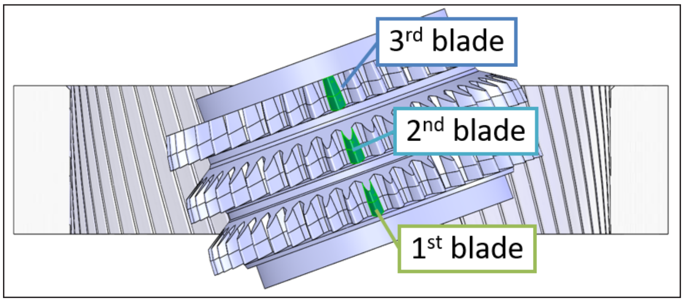

Figure 4 Super skiving tool.

Shaping is the slowest process, with some portion of the total cycle time used in retracting the cutter to the starting position of the cutting stroke. Most modern shapers, including Mitsubishi Heavy Industries' (MHI) ST models, use a quick return stroke to minimize this lost time.

Gear skiving is faster than shaping, but slower than broaching. An advantage with this process is quick change overs for flexibility in production mix. Medium volumes are well suited for this process.

The pinion type skiving cutter operates at crossed axes with the workpiece, while rotating synchronously. This generates a sliding motion at the contact point thus creating the cutting action. However, as the cut progresses the cutting resistance increases because the angle between the rake face of the tool and the face of the workpiece becomes significantly negative (obtuse).

Intensive development at MHI has created simulation software that completely describes the cutting process for Super

Skiving. This information creates optimal specifications for the cutting tool and cutting conditions. Multiple blade cutting tools were developed to dramatically improve tool life and reduce cycle times.

The actual cutting action of the Super Skiving cutter is similar to the conventional pinion type tool. The advantage comes from the multiple blades for cutting the tooth space rather than just one cutting blade. By using a tapered roughing portion of the tool, all three blades are involved in cutting. For example, if a pinion cutter requires three cutting passes to create the gear, the super skive tool can remove the same amount of material with one pass because it has three times the number of cutting blades.

The sophisticated simulation software developed by MHI allows cutting tool engineers to understand the full effect of every tooth involved in the cut and to optimize the tool and process.

Internal helical broaching is an economical choice for the highest volume mass production with minimal product mix. The process is well developed and reliable. A technological advancement in machine technology for helical broaching is the electromechanical drive system.

Current, state-of-the-art broaching machines utilize electromechanical drive systems. This allows the elimination of large and inefficient hydraulic systems. In traditional hydraulic systems for helical broaching, the broach machine required a specific helical guide (lead bar) to rotate the tool during the machining stroke.

The advent of electromechanical broach machines allows helical broaching without the need for the specific mechanical guides. A CNC axis controls the rotation of the tools during the broaching stroke, creating the exact helix needed. Minute adjustments are also possible, and changing from one helix to another is accomplished via the CNC program and does not require any mechanical changes.

Electromechanical systems use energy only when needed to produce the part. In contrast, a hydraulic system generally needs to run a large pump continuously, using prodigious amounts of electricity and creating noise and thermal pollution as well. In addition, the constant torque of the electromechanical drives produces a smoother cutting action. This can produce more consistent part quality, better surface finish on the parts, and improves tool life.

Newly developed Nanodynamic coating improves broaching efficiency. The per-piece cost of consumable tooling may be cut by half, and perhaps even two thirds. Utilizing constant force tool design improves tool life and can result in a shorter tool, which in turn can reduce tool cost. Combing the advancements in broach tools with fast and rigid electromechanical machines, broaching is often the process of choice for mass production of internal helical gears.

Helical broach.

Internal Gear Finishing After Heat Treatment

As with all steel parts, heat treatment distortion of ring gears is a fact of physics. In most typical automotive production, ring gears are cut in the green state and then heat treated without any hard finishing. Since the typical process does not finish gears after heat treatment, it is desirable to minimize distortion. To reduce distortion, many internal gears are made of semi-hardened steel and cut in this condition before heat treatment. The steel for some applications is in the range of 20-30Rc. The use of this pre-hardened steel has a negative effect on tool life for any of the cutting processes used: broaching, shaping or gear skiving. Heat treatment is often gas nitriding or ferritic nitrocarburizing, which is utilized due to the reduced distortion these processes create.

From the product perspective, the resulting post nitride hardness may be acceptable, but some applications could benefit from the carburizing and hardening heat treatment process that yields 58-60Rc and increased case depth. The use of softer green steel has a beneficial effect on tool life as well. Requirements for quieter transmissions for EV and hybrid vehicles drives, the need for a post-heat treatment finishing process.

Tooth Flank Finishing After Heat Treatment

Carburized and hardened parts will likely emerge from heat treat with distortion. The best solution is to grind the teeth to achieve the necessary quality and process stability. Profile grinding of one gap at a time is too slow and expensive for high volume production. The development of MHI's threaded wheel grinding system provides threaded wheel (generating) grinding as an economical process for finishing of internal gears after heat treatment. The ability to utilize generative worm wheel grinding for internal gears represents a dramatic breakthrough in technology and is in production in the US and Asia.

Patented grinding wheel design.

This unique grinding process has proven to be fast, stable and capable. Dressable, vitrified, threaded grinding wheels, of either vitrified cBN or conventional abrasive, are formed to generate the internal teeth with continuous motion. The crossed axis angle creates the needed high tool speed at the tooth surface.

Using grinding spindle speeds up to 15,000 rpm creates high metal removal rates, with tool speeds up to 40 meters/second. This results in productive internal gear grinding process that is economical for mass production.

By comparison, the typical honing process for internal gears has a tool speed of approximately 5 meters/seconds. The reported consumable tool cost for honing internal gears using diamond coated tools is three to six times higher than generating internal gear grinding.

In the prototype gear manufacturing environment, the ability to make profile angle adjustments (fH_α) during production is valuable. Complete multi-axis control of the internal generating process permits symmetrical and asymmetrical pressure angle adjustment, as well as barreling (involute crowning) and tip relief via dresser micro-geometry. Helix taper and fH_β are also adjustable via on-screen operator controls.

Details of the grinding worm

The unique and patented multi-threaded grinding wheel has a barrel shape for clearance during operation. This wheel operates at a crossed axis angle to achieve higher sliding velocity, which in turn produces a higher metal removal rate for better performance.

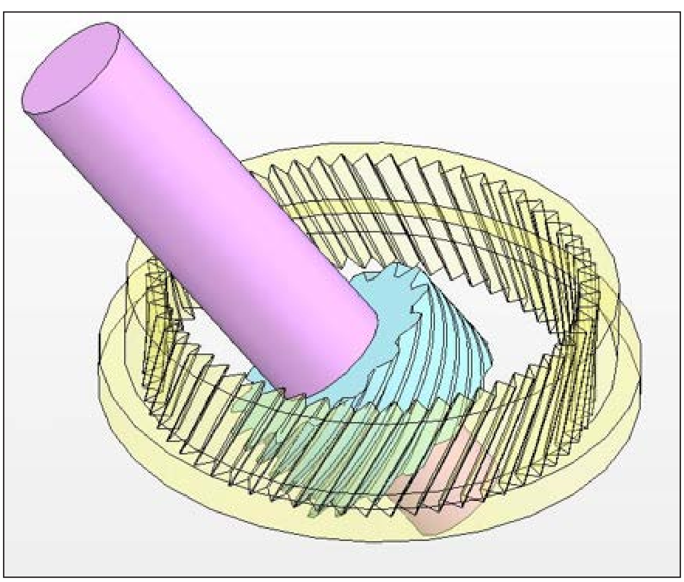

Figure 5 **Workpiece and grinding wheel.**

For a mass production system of a minimal part types, the process line can be designed as follows:

Figure 6 **Broach grind process flow.**

For production with a number of different part types, internal gear skiving can be utilized rather than broaching.

Figure 7 **Skive grind process flow.**

For the broadest part mix and lowest production volume, gear shaping can be used for the green cutting operation.

Runout, or F_r, is a common quality concern for manufacturers of internal ring gears as this is a typical result of heat treatment. Huge improvement is possible with generating internal gear grinding. A recent test showed pre-grind F_r values in the 0.092 mm range reduced to 0.009 mm. This represents an approximate quality improvement for this characteristic from ISO 10 to ISO 4.

With the aforementioned green processes, higher quality gears after heat treat are achievable with internal generative gear grinding. MHI is uniquely qualified to supply and support broaching, gear skiving and shaping on the green end as well as generative internal gear grinding after heat treatment.

For more information:

Mitsubishi Heavy Industries America
Phone: (248) 669-6136
www.mitsubishigearcenter.com

Dwight Smith, vice president, Mitsubishi Heavy Industries America, Inc. Machine Tool Division has nearly 30 years in the gear manufacturing industry, including metrology, analysis, and project management. Smith also serves as a committee chairman for AGMA, and is an instructor for the AGMA Basic Gear School.

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CNC Face Milling of Straight and Spiral Bevel Gears

Claude Gosselin, Joachim Thomas and Nicolai Meixel

Introduction

Contrary to what appears to be popular belief, 5-axis CNC gear manufacturing is not limited to milling with end mill, ball mill or *CoSIMT* (*Conical Side Milling Tool — it is the generic form of the Sandvik InvoMill and Gleason UpGear tools*.) tools, where throughput is too low to prevent production at any significant level.

Straight and spiral bevel gear manufacturing on 5-axis CNC machines using face mill cutters provides essentially the same throughput as conventional gear cutting machines — with these added benefits:

- Machine setup time is near zero, as opposed to mechanical machines
- Different gear types can be cut on the same CNC machine
- Blank turning can be done on the same CNC machine prior to gear cutting
- Deburring and chamfering can be performed on the same machine after tooth flank generation

The end result can be a part with only one chucking operation, which pretty much eliminates material handling, intermediate storage and repetitive runout adjustments at chucking.

The part programs for each step, i.e. — blank turning, tooth cutting (generation or plunge cut), and deburring/chamfering — can be combined so that only one program need be fed to the CNC controller to completely produce a part. This significantly reduces the risk of errors and enables storing the complete manufacturing definition of any part in a single file.

Currently, CNC face milling is dominated by Gleason's Phoenix and Klingelnberg's C-series machines — both 6-axis-capable. (*In the following, the Gleason Phoenix and Klingelnberg C-series machines will be referred to as "Phoenix-type" machines*.) While both offer superior machining quality and reliability, they cannot be used for any other purpose — blank turning, for example — because the proprietary interface between user and controller does not allow it.

It is also an expensive proposal to cut small-size, straight and spiral-bevel gears — say in the 1 to 3.5 mm module range — on machines targeted for more noble tasks.

The CNC machines found on the market vary in size and capability, and can handle blank diameters anywhere from less than 10 and up to 2,500 mm.

In face milling, one major limit is related to the capacity of the spindle to deliver the torque required by the face mill cutter and provide sufficient stiffness to guarantee vibration-free cutting and, accordingly, a good tooth surface.

Standard Coniflex (*Coniflex is a registered trade mark of the Gleason Works, Rochester NY*.) dish-type cutters for straight-bevel gears come in diameters of 4.25", 9" and 15". Therefore, modules above 5 to 6 mm, where cutter diameter is likely to exceed 9", cannot be accommodated on most 5-axis CNC machines, given the large cutter diameter and associated mass.

Standard face mill cutters for spiral bevel gears range from 1" to well above 15", in variable steps. A practical upper limit for a 5-axis CNC machine appears around 6" because of cutter mass and required spindle torque, which allows the face milling of spiral bevel gears up to around 6 mm module. For larger modules, CNC machines become as large and expensive as comparable Phoenix-type machines.

Both Coniflex cutters for straight bevel gears and face mill cutters for spiral bevel gears can be purchased from different vendors, either in solid form or with adjustable blades that can be reground separately, if tool procurement is not an issue.

However, the generation of the part programs that replicate exactly face milling cutting processes such as fixed setting, spread blade and duplex helical (*all registered trade mark of the Gleason Works, Rochester NY*) is a significant issue faced by manufacturers willing to cut Coniflex or spiral bevel gears on 5-axis CNC machines.

If end mill or ball mill tools are used, commercial software such as *SolidCAM*, *MasterCAM*, *GibbsCAM*, etc. can drive the tool if a point-cloud surface — a *STEP* file for example — is provided.

Gleason's *UpGear* process (Ref. 1) is intended only for *CoSIMT*-type tools on Gleason-Heller 5-axis CNC machines. While it replicates exactly a spiral bevel gear from its machine settings, it does not allow face milling. Dontyne's *CLGM* (Ref. 2), GWJ's *Gear Engineer* (Ref. 3), *KISSsoft's* CNC module (Ref. 4), and DMG-Mori's *gearMILL* (Ref. 5) all offer spiral bevel gear modules cutting with end mill and ball mill tools, and currently do not replicate the Fixed Setting, Spread Blade and Duplex Helical (all *registered trade mark of the Gleason Works, Rochester NY*.) cutting cycles from the basic machine settings.

On the other hand, aside from Gleason's *CAGE* and Klingelnberg's *KIMoS*, *HyGEARS* (*HyGEARS is a registered trade mark of Involute Simulation Softwares, Quebec, Canada*) (Ref. 6) is the only software capable of generating the same exact Coniflex straight bevel gear and face milled spiral bevel gear tooth surfaces when using the same machine settings — for any cutting process. *HyGEARS* has been in use on conventional and Phoenix-type machines since 1994 and on 5-axis CNC machines since 2012, with results consistently identical to those of *CAGE* and *KIMoS*.

The next paragraphs introduce some *HyGEARS* basics, such as the *Tooth Flank Generator* (*TGF*) and the closed loop. Examples illustrate actual use in industry.

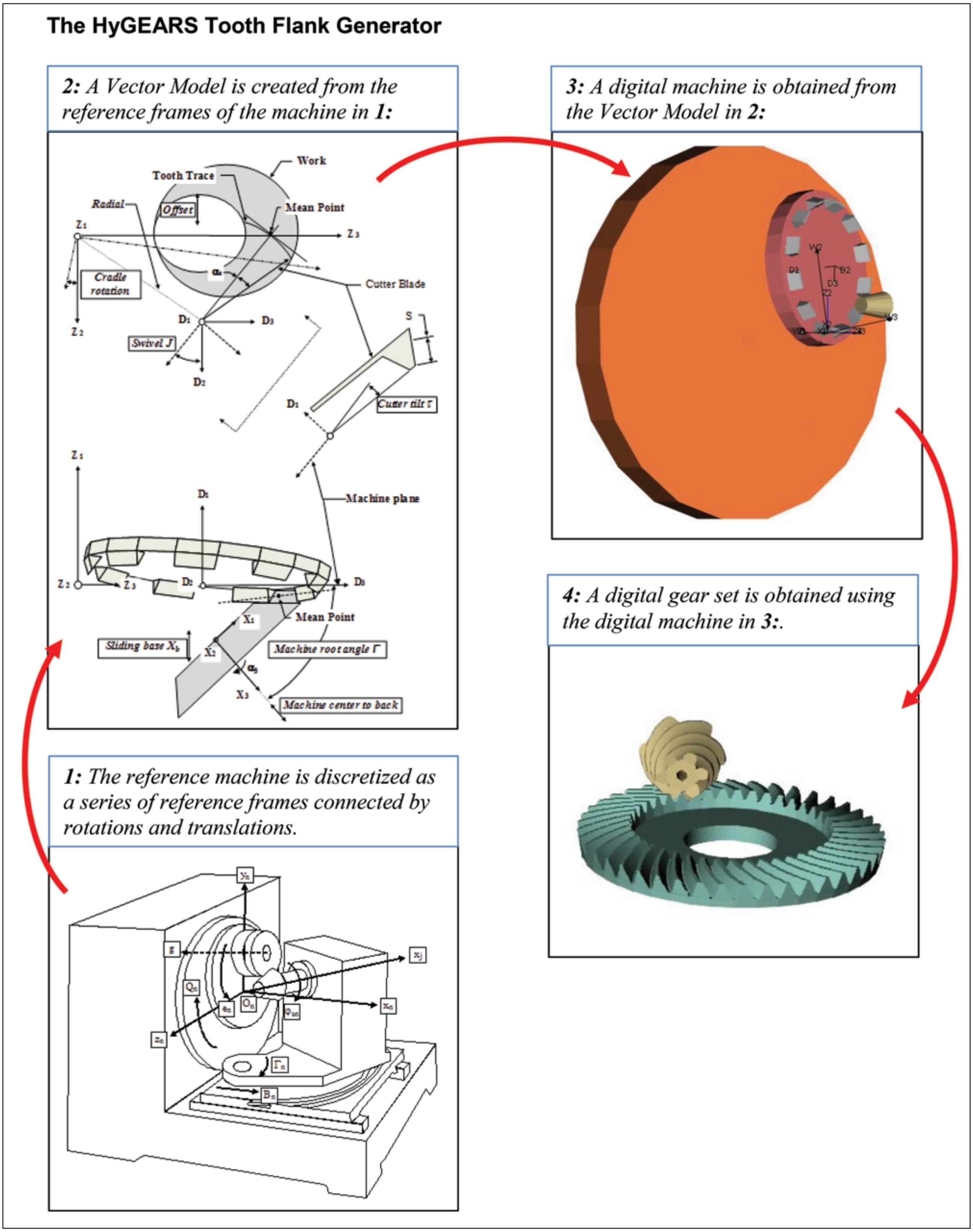

Figure 1 Logic of *HyGEARS* Tooth Flank Generator.

The *HyGEARS* Tooth Flank Generator

HyGEARS is built around an advanced *Tooth Flank Generator* (*TFG*) (Ref. 7) that can be described as a group of software functions defining the shape of a tool and its movements relative to a workpiece, i.e. — the functions replicate the generating process.

The generating process describes one cutter blade, representing one tooth of a theoretical generating gear that meshes with the workpiece. The fundamental relation is:

$$\overline{N} \cdot \overline{V}_r = 0 \qquad (1)$$

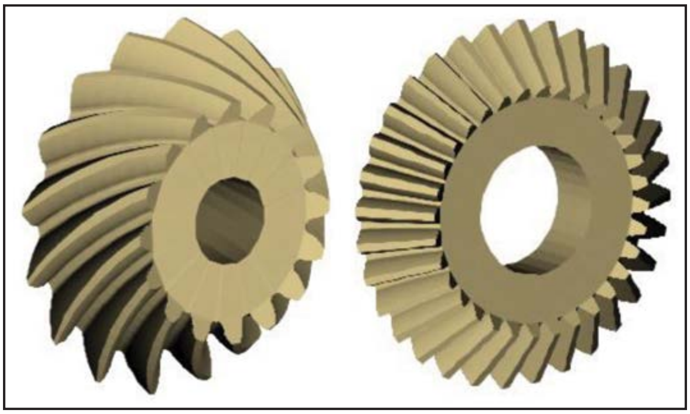

Figure 2 Spiral bevel and Coniflex pinions.

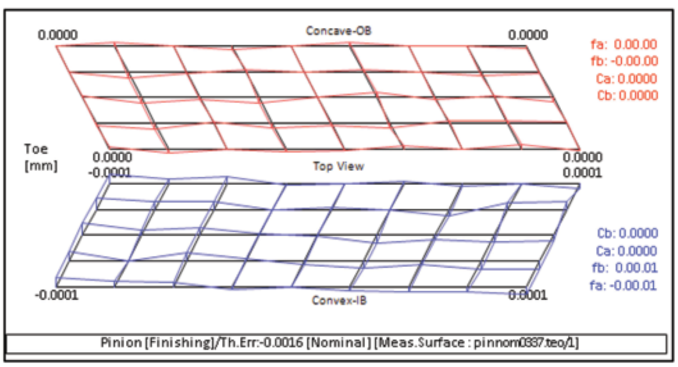

Figure 3 Software comparison: Gleason's *CAGE* vs *HyGEARS* Simulation.

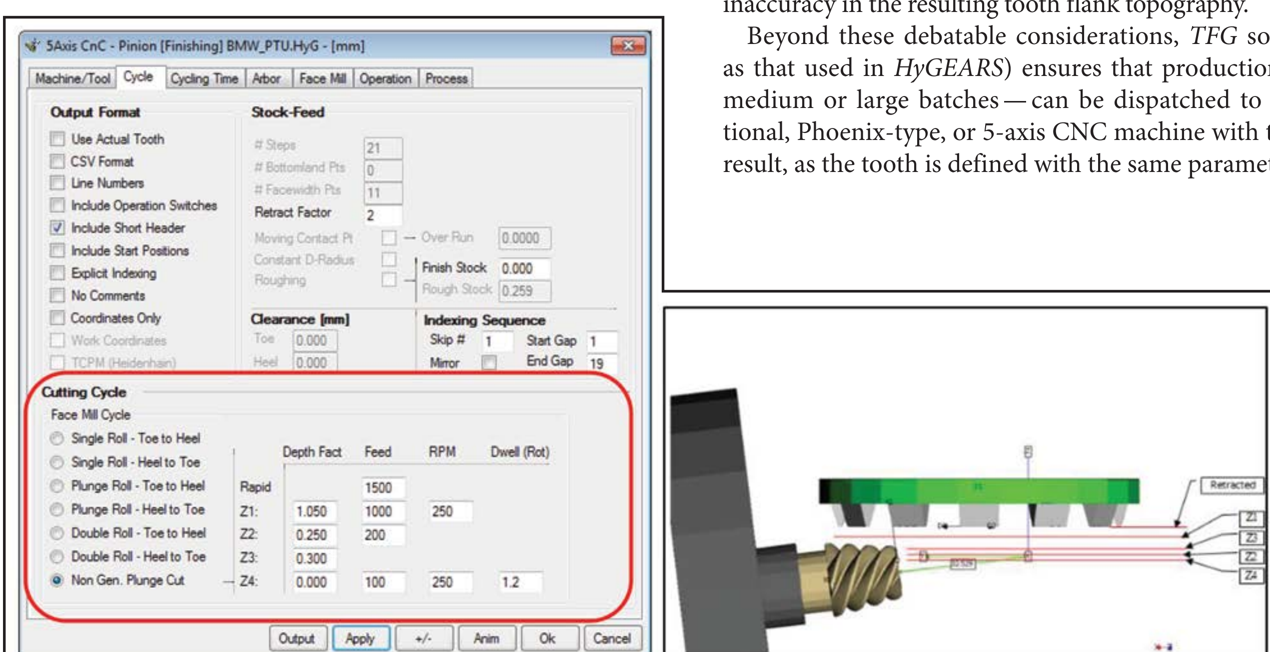

Figure 4 *HyGEARS* face milling cycles.

Where — the relative speed vector between tool and work surfaces is in a plane perpendicular to the common normal vector.

When applied to the reference frames (Fig. 1, upper-left), Equation 1 yields an unbounded surface in a reference frame attached to the workpiece. The surface is a function of the machine settings and three variables, respectively — cutter position α_c (angular or linear), workpiece roll angle α_3 and S, the position of a point along the edge of the cutter blade:

$$S = f(\alpha_c, \alpha_3) \qquad (2)$$

The solution (Eq. 2) is a series of contact points between cutter blade and workpiece describing a line along the path of the cutter blade. The envelope of a series of such lines is the generated tooth. Figure 2 shows a spiral bevel and a Coniflex straight bevel pinion obtained by replicating one generated tooth around the axis of rotation.

The *TFG* includes work and tool adjustments and movements found in conventional and Phoenix-type cutting machines. In all CNC machines, machine settings can be continuously altered during cutting to allow improvements in gear kinematics; these alterations include modified roll and helical motion — both supported by the *HyGEARS TFG*.

Figure 3 compares the pinion IB and OB tooth surfaces simulated by Gleason's *CAGE* (red and blue lines) and *HyGEARS* (black lines) for the same machine settings. Clearly, the *HyGEARS* tooth surfaces match those of Gleason's *CAGE* within 0.1 µm. This is true for all face mill cutting processes when the same machine settings are used.

It can be debated whether the parametric definition of a gear tooth from machine settings and cutter tool geometry is better or worse than a point-cloud, such as a *STEP* file. The machine settings-based definition allows creating a point-cloud that can be fed to commercial CAM software, capable of generating part programs; the opposite of course is not possible. In addition, point-cloud-based surfaces are subject to mathematical waviness caused by interpolation. Surface waviness affects surface coordinates and normal and tangent vectors, which often leads to some level of inaccuracy in the resulting tooth flank topography.

Beyond these debatable considerations, *TFG* software (such as that used in *HyGEARS*) ensures that production — in small, medium or large batches — can be dispatched to any conventional, Phoenix-type, or 5-axis CNC machine with the same end result, as the tooth is defined with the same parameters.

Cutting Cycles

In order to completely cover the tooth, conventional and Phoenix machines may plunge the face mill tool slightly before generation begins and retract the tool slightly after generation ends; or plunge at center roll and then roll in each direction before retracting and indexing. Tool plunge is critical since too fast a movement may damage the cutting blades when hitting the blank. Plunge is also critical in cycle time since it creates a bottleneck because of the usually slow plunge feed rate. Up-roll and down-roll in single and double roll cycles are also required to cover LH and RH cutters.

HyGEARS offers a comprehensive set of face mill cutting cycles (Fig. 4).

Toe-to-heel and heel-to-toe cycles for single roll, plunge roll, double roll and non-generated plunge cut can be selected for generated gears, and non-generated plunge cut for non-generated gears. By selecting an appropriate toe or heel clearance the tool can be plunged outside the part and thus allow fast plunge, thereby reducing cycle time. Return from end to beginning of cycle is done at high feed rate, again to reduce cycle time. Finally, the non-generated plunge cut cycle offers a comprehensive set of possibilities to guarantee excellent results (Fig. 4).

For Coniflex gears, only one cutting cycle is offered in which the flanks on one side are generated, after which the tool changes sides and cuts the opposite tooth flanks (Ref. 9). Thus only one Coniflex tool is used — as opposed to the cutter pairs found on Gleason mechanical machines. Using a CNC machine allows setting up each flank differently in order to obtain specific kinematics, if desired. As shown by Stadtfeld (Ref. 9), cycle times of CNC versus mechanical machines can be slightly longer; but since the same machine can be used to cut other gear types, the time disadvantage is out-weighed by the flexibility advantage.

The Closed Loop

The *Closed Loop* (Ref. 10), i.e. — *Corrective Machine Settings* — calculates the required changes in machine settings to remove manufacturing errors and match the manufactured tooth surface to the design. This implies that the theoretical tooth flank surface is known from the cutter definition and the machine settings, and therefore excludes a point-could approach.

Given machines vary from one to another, and are not always exactly identical to their definition, and given actual tools can be slightly different from their design values; *Closed Loop* is usually required to eliminate manufacturing errors when face milling gears. *Closed Loop* requires a coordinate measuring machine; *HyGEARS* supports all major CMMs on the market.

Surface errors can be classified in two broad categories (Fig. 5):

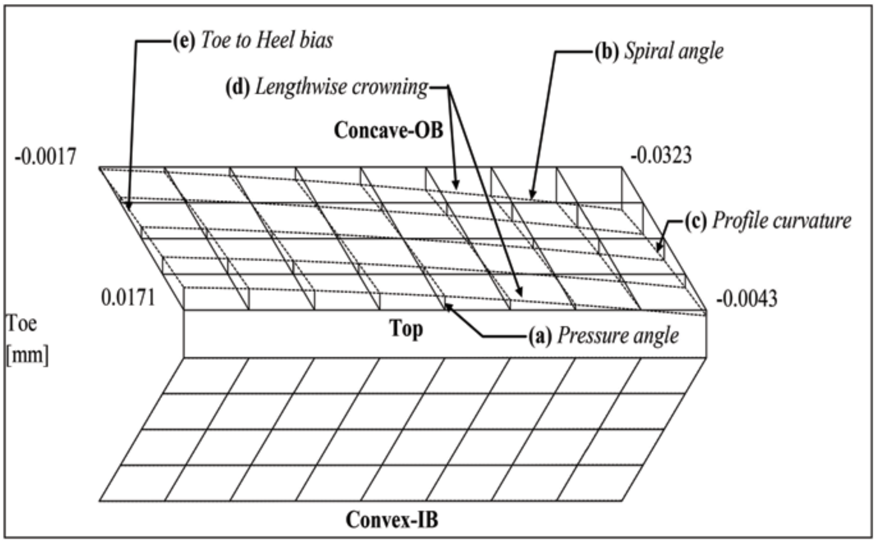

Figure 5 **Typical surface errors.**

- First order : pressure angle (a) and spiral angle (b)
- Second order: profile curvature (c), lengthwise crowning (d), toe-to-heel bias (e)

The *HyGEARS Closed Loop* algorithm finds a set of machine settings that minimizes surface errors. The modified machine settings are then used to generate a new part program based on the selections made for the first cut.

Closed Loop is integral to *HyGEARS* for all the supported cutting processes — for both Coniflex and spiral bevel gears.

Global View of *HyGEARS*

Figure 6 shows graphically how *HyGEARS* is integrated: 1) different gear types can be designed (or imported from existing summaries) and analyzed; 2) part programs are created for any tool and saved as parametric operations; 3) the part is cut on any CNC machine; 4) the part is measured on any CMM; 5) *Closed Loop* is calculated from CMM output; 6) the part program is re-generated using the modified machine settings of the *Closed Loop*; and 7) the part is re-cut — if needed.

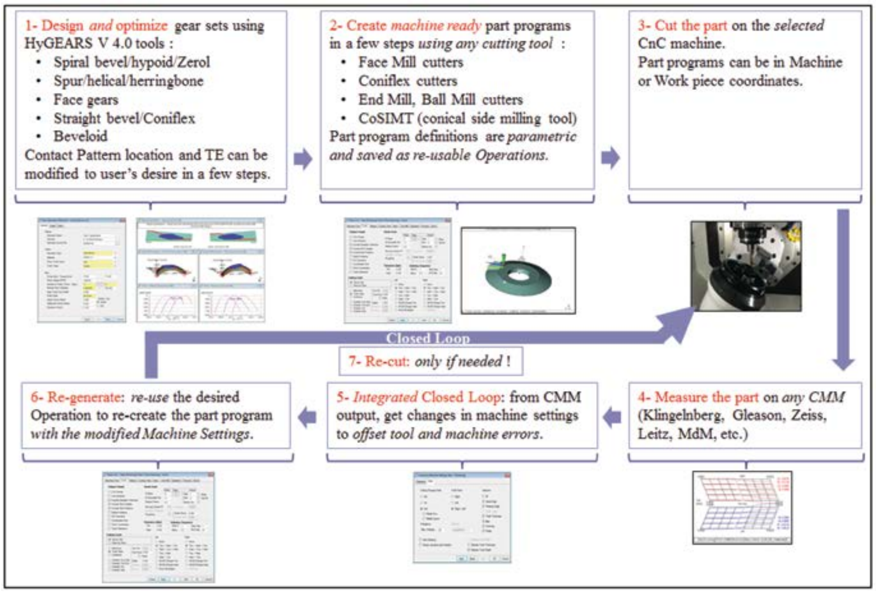

Figure 6 ***HyGEARS*: global view.**

Applications

The two following application examples show results obtained using *HyGEARS* to face mill different geometries on 5-axis CNC machines; such results are typical of actual production.

***Application 1.* 32-tooth, 1.25 mm module, Coniflex pinion; 4.25" dish-type cutter.** The pinion was cut on a tilting turntable-type 5-axis CNC machine with a Coniflex dish-type cutter. The first cut yielded the results seen in Figure 7; helix (*fb*) and pressure (*fa*) angle errors are visible on both tooth flanks.

Table 1 Averaged surface errors after first cut

AVERAGE ERRORS		(Right)	(Left)
Tooth Thickness	:	0.0087	
Pressure Angle	:	1.57.35	-1.27.45
Helix Angle	:	0.12.59	-0.12.53
Crowning	:	-0.0029	-0.0050
Profile Curvature	:	-0.0024	-0.0032

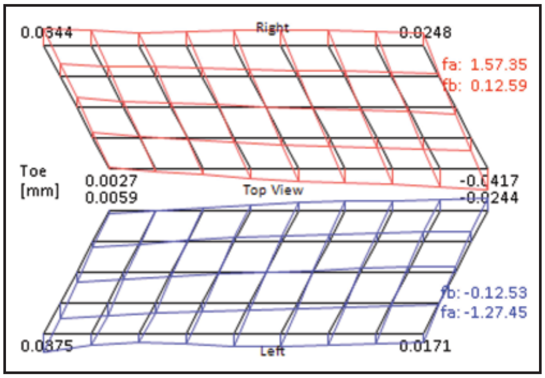

Figure 7 Error surface after first cut.

Figure 8 shows the same part after the first *Closed Loop* iteration; pressure and helix angle errors have all but disappeared.

Table 2 Averaged surface errors after correction

AVERAGE ERRORS		(Right)	(Left)
Tooth Thickness	:	0.0087	
Pressure Angle	:	0.15.49	-0.01.09
Helix Angle	:	0.04.45	-0.02.19
Crowning	:	-0.0024	-0.0049
Profile Curvature	:	0.0017	0.0019

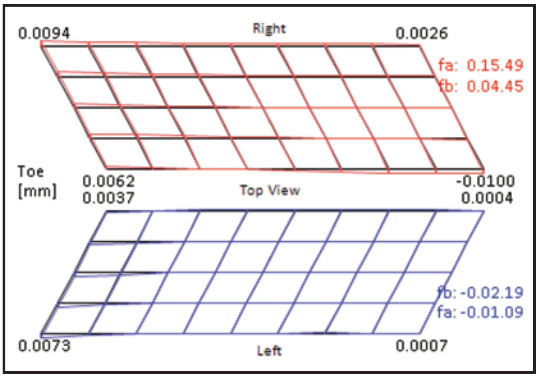

Figure 8 Error surface after correction.

***Application 2.* 26-tooth, 1.5 mm module, duplex helical spiral bevel pinion.** The pinion was cut on a tilting turntable-type 5-axis CNC machine using a 2" face mill cutter. The first cut yielded the results seen in Figure 9; pressure (*fa*), spiral (*fb*) angle and bias errors are visible.

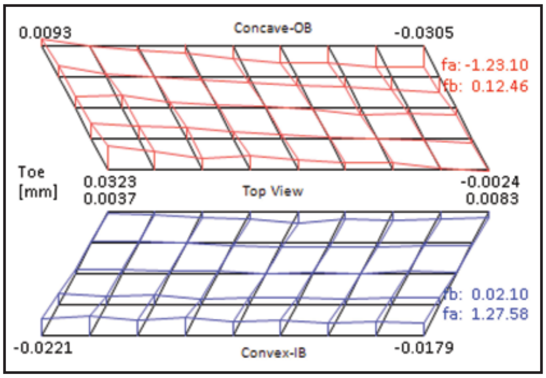

Figure 9 Error surface after first cut.

Figure 10 shows the error surface after the first *Closed Loop* iteration; clearly, pressure, spiral and bias errors have been corrected.

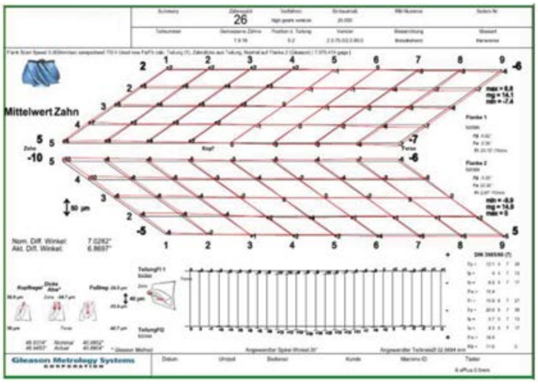

Figure 10 Error surface after correction.

Cycle Times and Quality

The idea of cutting face milled spiral bevel gears on a 5-axis CNC machine rather than a dedicated gear machine is valid as long as cycle times and gear quality are up to standards. Table 3 shows the cycle times required to cut a 9×59 spiral bevel gear set on a small 5-axis CNC machine; the module is 2.5 mm and cutter diameter is 6". The pinion is generated duplex helical, while the gear is plunge-cut (Formate); Figure 11 shows the gear after soft cut.

Table 3 Sample cycle times and DIN quality

	Pinion Z=9	Gear Z=59
Grinding only	3m 52s	16m 29s
Quality achieved	DIN 4	DIN 4
Cutting & chamfering	7m	15m 30s
Quality achieved	DIN 6	DIN 6

Figure 11 Z=59 gear after soft cut.

Conclusions

Face milling of spiral bevel and straight bevel gears on 5-axis CNC machines is a practical and economically advantageous solution for the manufacturing of small module bevel gears in any kind of batch size, because it allows cutting different gear types on the same machine. Gear blank turning before — and chamfering after — tooth generation can also be performed on the same machine to yield a net part with only one chucking operation.

The *HyGEARS* software uses a *Tooth Flank Generator* tested in the gear industry for more than 2 decades. The *TFG* produces exactly the same micro-topography as Gleason's *CAGE* and Klingelnberg's *KIMoS,* when given the same machine settings. This ensures total compatibility between production on 5-axis CNC machines and other machines, conventional or Gleason Phoenix /Klingelnberg C-series.

CMM nominal target files are produced from the *HyGEARS TFG* for any CMM on the market and are thus perfectly compatible with those of Gleason's *CAGE* and Klingelberg's *KIMoS*.

Gears can be designed and optimized from scratch in *HyGEARS*, or the machine settings of existing gearsets can be entered/imported to produce the same tooth surface as that obtained on a conventional or Phoenix-type machine.

HyGEARS generates machine-ready face milling part programs for any 5-axis CNC machine available on the market, and is thus manufacturer-independent. The integrated closed loop allows correction based on CMM output.

HyGEARS, being manufacturer-independent, allows the use of CNC machines already available, or the flexibility to shop around for the CNC machine best-suited size-wise, cost-wise and flexibility-wise for the intended applications — a clear advantage for the manufacturer.

For more information. Questions or comments regarding this technical paper? Please contact **Claude Gosselin**; *hygears@gmail.com*.

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Dr. Claude Gosselin is president (1994–present) of Involute Simulation Software, a developer and distributor of *HyGEARS* software. Previous experience includes work as a designer for Pratt & Whitney Canada Ltd (1978-1980) in gearbox design; computer software; and R&D. He also held a longtime professorship in mechanical engineering (1988–2007) at his alma mater, Laval University, Quebec, and elsewhere did post-doctoral studies in the department of precision engineering at Kyoto University (1987) Japan, hosted by Professor Aizoh Kubo. Gosselin has also served (1996–1998) as an associate editor for the ASME Journal of Mechanical Design.

Dr.-Ing. Joachim Thomas is managing director (2015–present) of ZG Hypoid GmbH in Dietersheim, Germany. His work experience includes stops at MAN Truck Company (1998–2000) — team manager; Klingelnberg (2000–2008) — manager, application engineering; and Voith Turbo (2009–2014) — various manufacturing-related managerial roles. He has also served (2006–2015) as convener of the FVA bevel gear committee and has been (2009–present) a visiting lecturer at Technical University of Munich. Since 1995 Thomas has served as a member of the ISO committee for the rating of bevel gears and tolerances.

B. Ing. Nicolai Meixel was named this year (2018) production manager for custom gearboxes at Neugart GmbH, Germany. Previously (2012–2018), at Neugart's Gearing Competence Center, he was responsible for setting-up and managing a new department for bevel gear design and manufacturing using *HyGEARS* V4 simulation software; calculation of macro- and micro-geometry of straight, spiral bevel and hypoid gears; management of production control on 5-axis CnC machines, including Closed Loop; and development of grinding and fast deburring solutions on 5-axis CnC machines.

Flank Profile Modification Optimization for Spur Asymmetric Gears

A.L. Kapelevich and Y.V. Shekhtman

Introduction

In many gear transmissions, tooth load on one flank is significantly higher and is applied for longer periods of time than on the opposite one; an asymmetric tooth shape should reflect this functional difference. The advantages of these gears allow us to improve the performance of the primary drive tooth flanks at the expense of the opposite coast flanks, which are unloaded or lightly loaded during a relatively short work period by drive flank contact and bending stress reduction. However, despite these potential benefits, the practical implementation of asymmetric gears is very limited. This could be explained by the fact that asymmetric gears are more expensive in production, as they require custom, non-standard tooling. These additional expenses must be justified by significantly better gear drive performance when compared to the best symmetric gears.

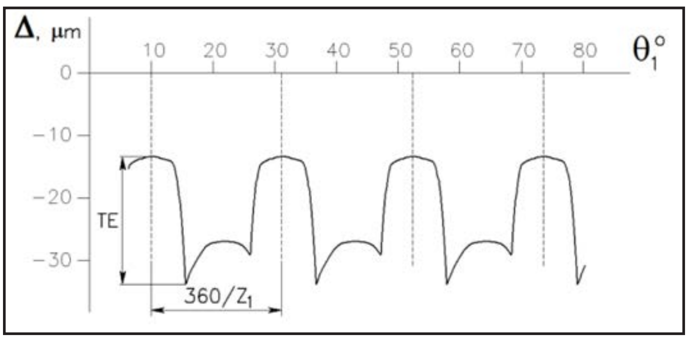


Figure 1 **Transmission error chart. Δ – distance in microns between actual tooth contact point and ideal contact point.**

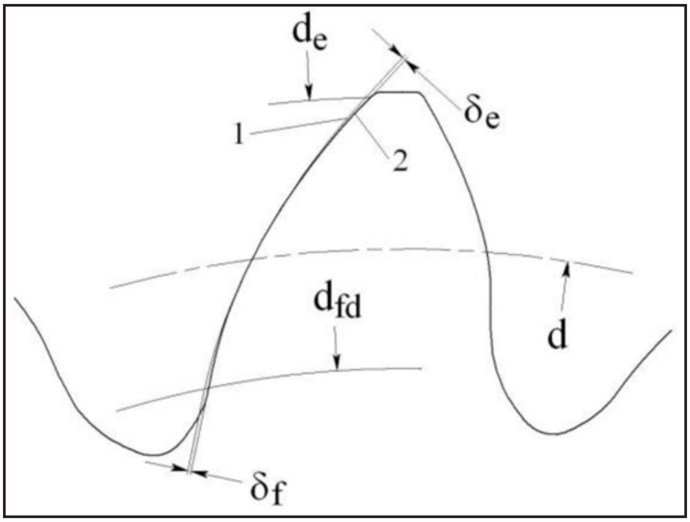


Figure 2 **Tooth flank modification. 1 – ideal involute profile, 2 – modified flank profile; d_f – flank modification depth at the form diameter d_f (near the tooth root), d_e – flank modification depth at the effective tip diameter d_e (at the highest involute profile point near the tooth tip).**

This means they must be completely optimized for a particular gear drive application. Our earlier publications were mainly dedicated to the optimization of macrogeometry of asymmetric gears — specifically, the tooth root fillet and tooth flank parameters, including an asymmetry factor and a contact ratio.

The microgeometry of asymmetric gears is a critical element of gear design. It defines the deviation from the nominal involute flank surface to achieve the optimal tooth contact localization for higher load capacity and lower transmission error (for noise and vibration reduction). Decreasing the spur asymmetric tooth gear transmission error by altering the generating rack profiles was previously studied — in article (Ref. 1), a straight-line rack cutter edge is replaced by a parabola; article (Ref. 2) utilizes a similar approach using rack cutter pressure angle modification.

This article is about the microgeometry optimization of the spur asymmetric gears' tooth flank profile based on the tooth bending and contact deflections. This optimization approach is utilized in *Direct Gear Design* (Publ.: CRC Press) (Ref. 3), along with the previously published asymmetric tooth gear macrogeometry optimization procedures.

Transmission Error Minimization

Transmission error is the angular difference between the actual position of the driven gear and its ideal position if the gear pair were perfectly conjugate, projected on the line of contact and defined as (Ref. 4):

$$TE = r_{b2}(\theta_2 - u\theta_1) \tag{1}$$

Where:
θ_1 and θ_2 — driving pinion and driven gear rotation angles;
r_{b2} — driven gear base radius.

A typical transmission error chart is shown in Figure 1.

The goal of the tooth flank microgeometry optimization is to modify the tooth flank profile to partially compensate for the influence of manufacturing tolerances, assembly misalignments, and operating conditions (including deflections of the gears and other gearbox components under operating load, dynamic loads and inertia, temperature, etc.). All these factors distort a theoretically correct involute mesh by deviating the actual contact points from the ideal straight line of contact, which amplifies transmission error and leads to increased noise and vibrations. Modification of the tooth flank profile alters the drive tooth flank from its theoretical involute profile to bring the actual contact points closer to the ideal straight line of contact, thus reducing transmission error.

In this article the modification of the tooth flank profile (Fig. 2) utilizes the same approach that was used in the effective

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

contact ratio and transmission error definition approach (Ref. 5), which considers only the bending and contact tooth deflections. According to this approach, each angular position of the driven gear relative to the driving gear is iteratively defined by equalizing the sum of the tooth contact load moments of each gear and its applied torque. The corresponding tooth contact loads are also iteratively defined to conform to tooth bending and contact deflections, where the tooth bending deflection in each contact point is determined based on FEA-calculated flexibility and the tooth contact deflection is calculated using the Hertzian equation. This technique is employed in combination with another iteration cycle that defines tooth flank modification depth to achieve minimal transmission error for the selected flank modification type.

There are three most common tooth flank modification types: a tip and root relief, an arc modification, and a parabolic crowning. Figure 3 shows the tooth flank modification types as charts of the roll angle vs. the flank modification depth in microns. The roll angle is defined as:

$$\phi = \frac{180°}{\pi}\tan\alpha \tag{2}$$

Where:

α — involute profile angle.

The tip and root relief and arc modification types are applied to low- and medium-contact ratio gears, since they alter only the double tooth pair contact zones where load sharing between two pairs of teeth occurs. The parabolic crowning modifies a complete involute flank and can be applied to low- and medium-contact ratio gears as well as high contact ratio (HCR) gears with $\varepsilon_\alpha \geq 2.0$.

In a unidirectional, asymmetric gear pair, the drive flank of the pinion is the subject for microgeometry optimization. The coast flank of the pinion and both flanks of the driven gear remain unmodified. However, when optimizing, a part of or the entire modification depth can be transferred from the drive flank of the pinion to the drive flank of the mating gear. Most typical is the transfer of the pinion root relief depth to the tip relief depth of the gear (Fig. 3). If the optimized pinion drive flank contact point X_1 is at the roll angle α_{xd} and its modification depth is δ_x, the mating gear drive flank contact point X_2 roll angle can be defined by the equation:

$$\tan\alpha_{xd1} \pm u\tan\alpha_{xd2} \mp (1 \pm u)\tan\alpha_{wd} = 0. \tag{3}$$

Here and in Equations 4 and 5 the signs ± and ∓ are: top sign is for external gearing and the bottom sign is for internal gearing.

Then the drive involute profile angles α_{xd1}, α_{xd2}, and α_{wd} should be replaced on the related roll angles (Eq. 2):

$$\phi_{xd1} \pm u\phi_{xd2} \mp (1 \pm u)\,\phi_{wd} = 0 \tag{4}$$

and finally, the mating gear drive flank contact point X_2 roll angle is:

$$\phi_{xd2} = \frac{u+1}{u}\phi_{wd} - \frac{1}{u}\phi_{xd1}. \tag{5}$$

The modification depth transfer from the pinion drive flank dedendum to the drive addendum of the mating gear is illustrated (Fig. 4). In this figure both gear pairs with drive flank modifications 1 and 2 should have identical transmission error. This kind of modification depth transfer can make sense for a technological reason, i.e. — when the tooth dedendum modification is impractical, because, for example, it might affect a conjunction of the tooth flank with an optimized root fillet.

In some cases — as with an idler gear or a planet gear of an epicyclic gear stage, which have both drive flanks engaged with two different mating gears — these flanks' modifications should be optimized separately, considering the differences in engagements and loading of opposite flanks. Besides, an asymmetric tooth of the idler gear or planet gear has different stiffness when loads are applied at the high- and low-pressure angle flanks.

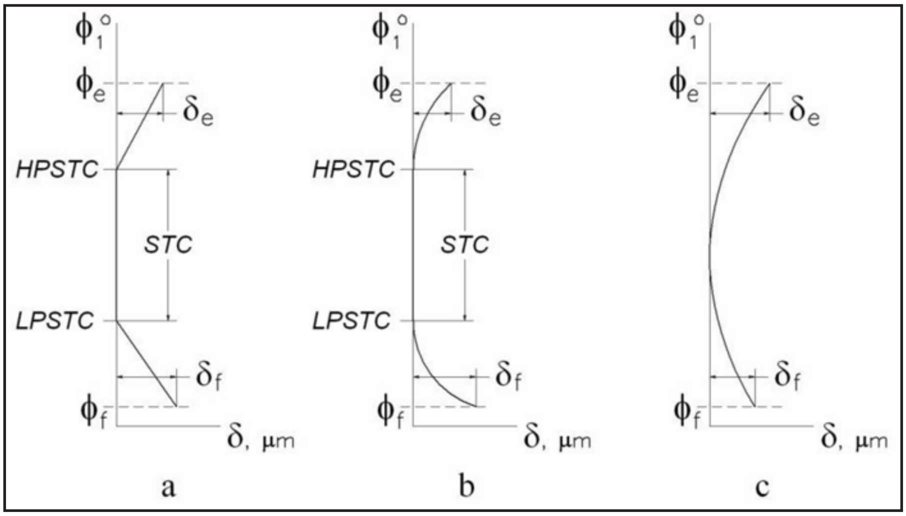


Figure 3 Tooth flank modification types. a – tip and root relief, b – arc modification, c – parabolic crowning; δ – flank modification depth in microns; ϕ – roll angle in degrees, ϕ_e - at the form diameter, ϕ_e – at the effective tip diameter; LPSTC (lowest point of single tooth contact) and HPSTC (highest point of single tooth contact) for gears with a low- medium contact ratio $1.0 < \varepsilon_\alpha < 2.0$.

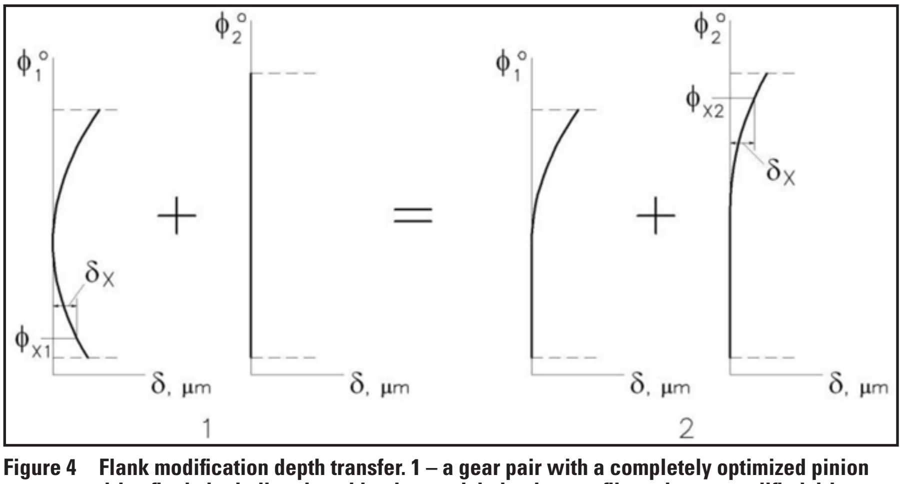


Figure 4 Flank modification depth transfer. 1 – a gear pair with a completely optimized pinion drive flank, including the addendum and dedendum profile and an unmodified drive flank of the gear; 2 – a gear pair with an optimized drive flank addendum of both the pinion and the gear.

Nominal and Effective Contact Ratio

Direct Gear Design defines the nominal contact ratio for external gears as

$$\varepsilon_\alpha = \frac{z_1}{2\pi}(\tan\alpha_{e1} + u\tan\alpha_{e2} - (1+u))\tan\alpha_w \quad (6)$$

Where:

α_w — operating pressure angle;

α_{a1} and α_{a2} — outer diameter profile angles;

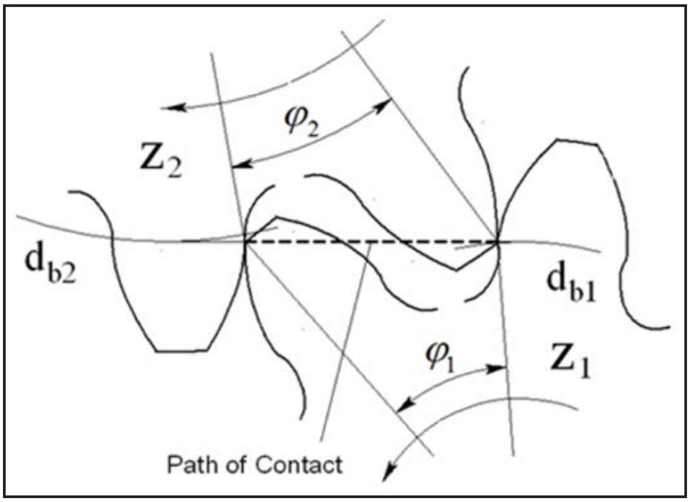


Figure 5 Engagement and disengagement of the mating tooth pair.

$u = z_2/z_1$ — gear ratio, z_1 and z_2 — numbers of teeth of mating pinion and gear.

The effective contact ratio is also affected by tooth deflections under load and defined as the ratio of the tooth engagement angle to the angular pitch (Ref. 5). The tooth engagement angle is the gear rotation angle from the start of the tooth engagement with the mating gear tooth to the end of the engagement (Fig. 5).

Then the effective contact ratio is:

$$\varepsilon_{\alpha e} = \frac{\phi_1}{360/z_1} = \frac{\phi_2}{360/z_2}, \quad (7)$$

Where:

ϕ_1 and ϕ_2 — pinion and gear engagement angles;

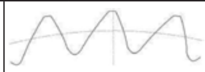
$360/z_1$ and $360/z_2$ — pinion and gear angular pitches.

Low- and Medium-Contact Ratio Gears

Table 1 presents the low- and medium-contact ratio gear pair data and tooth flank optimization results. Three tooth flank modification types (Fig. 3) are considered. A comparison of different types of the drive flank modification optimization indicates that the resulting contact stresses are practically identical, but a parabolic crowning produces a high transmission error reduction and an effective drive contact ratio, while keeping a minimal modification depth.

Figure 6 presents the transmission error charts for gear pairs with the initial nonmodified drive flanks and gears with the optimized drive pinion flanks utilizing three different modification types.

Table 1 Low-to-medium contact ratio gear pair tooth flank optimization

Gear	Pinion 		Gear 
Number of Teeth	27		41
Module (m), mm	3,000		
Drive Flank Pressure Angle	38°		
Coast Flank Pressure Angle	19°		
Pitch Diameter (PD), mm	81.000		123.000
Tooth Tip Diameter, mm	87.090		128.935
Root Diameter, mm	74.393		116.230
Tooth Thickness at PD, mm	4.807		4.618
Face Width, mm	30.00		28.00
Torque, Nm	700		1063
Root Tensile Stress, MPa	415		422
Drive Flank Mesh Efficiency	98.8% (average friction coefficient=0.1)		
Nominal Drive Contact Ratio	1.24		
Effective Drive Contact Ratio	1.46 (no flank modification)		
Contact Stress, MPa	1394 (no flank modification)		
Transmission Error, µm	7.3 (no flank modification)		
Type of Flank Modification	Tip & Root Relief	Arc Modification	Parabolic Crowning
Tip Modification, µm	10	15	13
Root Modification, µm	27	39	3
Effective Drive Contact Ratio	1.28	1.28	1.40
Contact Stress, MPa	1398	1400	1400
Transmission Error, µm	3.7	4.6	3.7
Transmission Error Reduction	49%	37%	49%

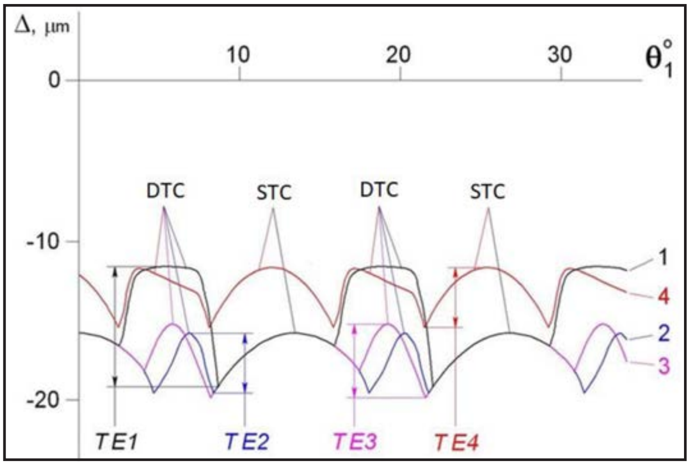


Figure 6 Transmission error charts. 1 – initial unmodified drive flanks (transmission error TE_1); 2 – drive flanks of the pinion with the tip and root relief (transmission error TE_2); 3 – drive flanks of the pinion with the arc modification (transmission error TE_3); 4 – drive flanks of the pinion with the parabolic crowning (transmission error TE_4); STC – single tooth pair contact; DTC – double tooth pair contact.

Figure 7 shows the optimized drive flanks of the pinion for different modification types.

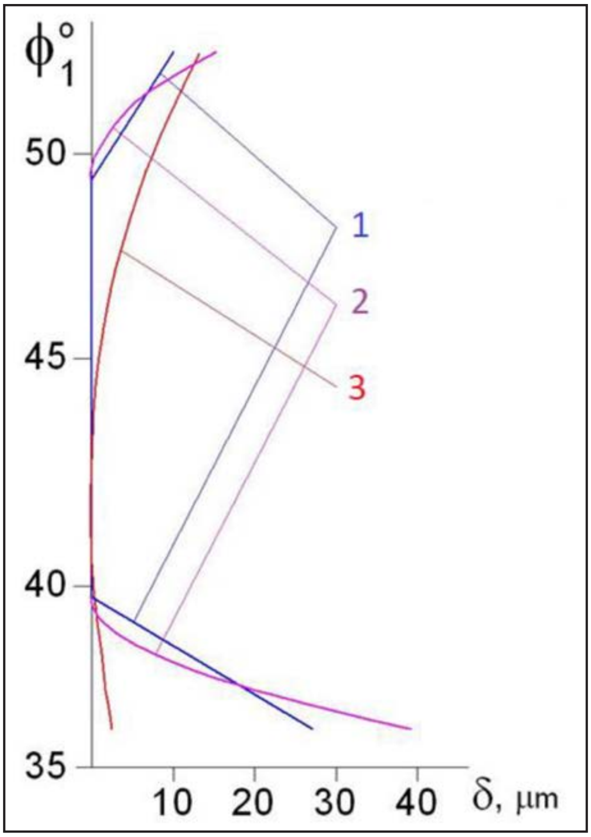


Figure 7 **Optimized drive flanks of the pinion. 1 – with the tip and root relief; 2 – with the arc modification; 3 – drive flanks of the pinion with the parabolic crowning.**

High-Contact Ratio Gears

Table 2 presents the high-contact ratio (HCR) gear pair data and tooth flank optimization results for the parabolic crowning modification. High-contact ratio gears have several advantages over low-to-medium-contact ratio gears due to a much greater contact ratio and load sharing between two and three gear tooth pairs. This results in significantly lower root bending stress and transmission error after the pinion drive flank microgeometry optimization; the contact stress is also slightly lower. However, the drive flank mesh efficiency is lower, because of increased specific sliding velocities.

Figure 8 presents transmission error charts for gear pairs with the initial unmodified drive flanks and gears with the optimized drive pinion flanks. Parabolic crowning of the pinion drive flank of the HCR gear pair is shown in Figure 9.

It is important to understand that microgeometry optimization defines the shape and depth of the drive flank modification for a particular transmitted torque value, for which the resulting modified flank profile provides minimal transmission error. For any other torque value this flank profile is not optimal. For gear drives transmitting a constant torque, this value should be used for driving flank microgeometry optimization. However, there are many gear drives that operate at variable load values. In such cases it is necessary to define which load condition is most damaging or critical for a specific gear drive application and use its value for the optimization.

Table 2 **High-contact ratio gear pair tooth flank optimization**

Gear	Pinion	Gear
Number of Teeth	27	41
Module (m), mm	3.000	
Drive Flank Pressure Angle	24°	
Coast Flank Pressure Angle	14°	
Pitch Diameter (PD), mm	81.000	123.000
Tooth Tip Diameter, mm	89.443	131.542
Root Diameter, mm	71.636	113.877
Tooth Thickness at PD, mm	4.807	4.618
Face Width, mm	30.00	28.00
Torque, Nm	700	1063
Root Tensile Stress, MPa	335	319
Drive Mesh Efficiency	98.0% (average friction coefficient=0.1)	
Nominal Drive Contact Ratio	2.04	
Effective Drive Contact Ratio	2.24 (no flank modification)	
Contact Stress, MPa	1259 (no flank modification)	
Transmission Error, μm	4.4 (no flank modification)	
Type of Flank Modification	Parabolic Crowning	
Tip Modification, μm	15	
Root Modification, μm	12	
Effective Drive Contact Ratio	2.2	
Contact Stress, MPa	1359	
Transmission Error, μm	2.1	
Transmission Error Reduction	52%	

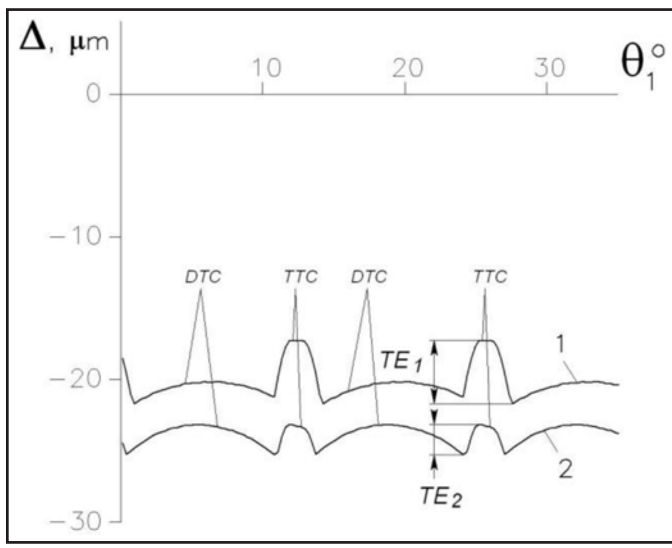


Figure 8 **Transmission error charts. 1 – initial unmodified drive flanks (transmission error *TE*$_1$), 2 – drive flanks of the pinion with the parabolic crowning (transmission error *TE*$_2$); DTC – double tooth pair contact; TTC – triple tooth pair contact.**

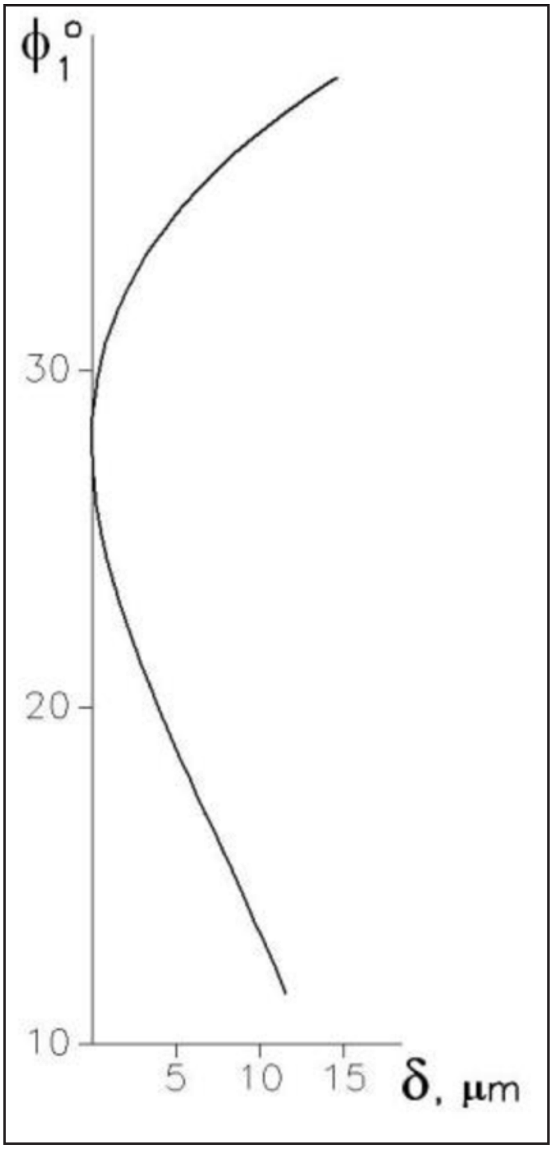


Figure 9 **Parabolic crowning of the pinion drive flank of the HCR gear pair.**

Summary

This article presents a tooth flank modification optimization method for directly designed spur asymmetric gears, considering bending and contact tooth deflections.

The suggested optimization method is applied for three most common tooth flank modification types: a tip and root relief, an arc modification, and a parabolic crowning for both low-medium and high contact ratio asymmetric gears.

Numerical examples of the tooth flank modification optimization indicate a 37%–49% transmission error reduction for low-to-medium-contact ratio asymmetric gears and a 52% transmission error reduction for high-contact ratio asymmetric gears, when compared to gears with unmodified tooth flanks.

The presented tooth flank modification optimization method is equally applicable and can be very beneficial for directly designed, spur symmetric tooth gears.

For more information. Questions or comments regarding this paper? Please contact **Alex Kapelevich**; *ak@akGears.com*.

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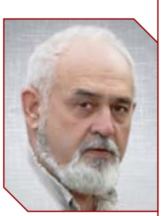
Alex Kapelevich has a Master Degree in Mechanical Engineering at Moscow Aviation Institute and a Ph.D. in Mechanical Engineering at Moscow State Technical University, Moscow. He operates the consulting firm AKGears, LLC, a developer of trademarked Direct Gear Design methodology and software. He has 30 years of experience in custom gear drive development. His areas of expertise are gear transmission architecture, planetary systems, gear tooth profile optimization, gears with asymmetric teeth, and gear drive performance maximization. Alex is author of the book titled Direct Gear Design and many technical articles.



Dr. Yuriy Shekhtman is an expert in mathematical modeling and stress analysis. Drawing upon over 40 years' experience, he has created a number of computer programs based on FEA and other numerical methods. A software developer for AKGears, Dr. Shekhtman is also the author of many technical publications (*y.shekhtman@gmail.com*).

Simulation of Spiral Bevel Gear Tooth Manufacturing to Aid in One-Piece Gear Shaft Design

Scott R. Davidson

Introduction

Many spiral bevel gear applications are implemented with a two-piece gear where the gear and shaft are bolted or inertia-welded as an assembly task. Eliminating a bolted, splined, or welded joint between the spiral bevel gear and shaft can reduce complexity and cost in a transmission design. Simulations of the motion of spiral bevel machine tools have been developed to ensure successful integral shaft designs for helicopters. Awareness of the location of the wheel during spiral bevel gear tooth manufacturing enables a design solution to iterate between the gear shaft and spiral bevel gear tooth design. The simulation was revisited to refine a preliminary two-dimensional tool as well as create a more detailed three-dimensional visualization for use during the design process. The design process was applied to three helicopter bevel gear designs. Physical verification was completed on two designs as a risk reduction in the bevel gear grinding machine before the design was released to manufacturing. The tools used in the design process, as well as verification during manufacturing, are discussed in this publication for three different integral shaft spiral bevel gears for helicopters.

In helicopter applications, spiral bevel gears are used to transfer power and reduce speed from engines to rotors. In order to attain the best performance for helicopters, there is a desire to design a small gearset on stiff shafts supported on bearings in a straddle mount arrangement. A straddle mount arrangement is a shaft design where support bearings are mounted on either side of the gear head. Contrarily, an overhung mount arrangement is where the gear head is at the end of the shaft and the bearings are arranged behind, resulting in a typically less stiff arrangement. If a stiff, straddle mounted support is desired, the gear head and shaft must be designed so that the shaft does not interfere with the cutting and grinding of the spiral bevel gear teeth. In many spiral bevel gear designs, a straddle-mounted gear and shaft are joined after spiral bevel gear tooth cutting and grinding.

In helicopter applications, the two-piece gear is typically joined by welding, bolts, or splines. The tolerances that control the alignment of the shaft to gear head needed for light-weight, high-torque gearing pose a challenging weld manufacturing problem. Welding late in the manufacturing process yields high scrap costs since the majority of the manufacturing has been invested prior to the weld operation. Although very common in the general gear industry, bolted joints can be problematic when applied to helicopters where high reliability is desired. Work has been done to reduce fretting and corrosion in these joints, which can result in crack initiation and torque transfer failure if not detected. In the case of the U.S. Army CH-47D Chinook helicopter, a decision was made to eliminate these joints through the use of integral design (Ref. 1). Integral shaft spiral bevel gears must be designed such that the shaft does not interfere with gear tooth cutting and grinding. This paper discusses techniques that have been updated from those presented in Reference 1to further iterate in the design stage before manufacturing begins. Techniques described were applied to the development of integral shaft designs for a growth project for the CH-47 Chinook and two designs for a new transmission for the SB>1 DEFIANT aircraft for the Joint Multi-Role Technology Demonstrator (JMR TD) Program. Figure 1 shows an integral shaft straddle mount gear and mating overhung mount pinion.

Figure 1 Integral shaft, straddle mount spiral bevel gear and mating overhung pinion.

Preliminary Design

In each of the three integral gear shaft designs, the goal is executing the lightest producible design that meets strength and stiffness design requirements. The gear shaft design process is the same as other design processes, where compromise is the solution. The gear shaft was required to have a large diameter for an integral clutch mounted in the inner diameter in one case and an internal spline in another. A third design consisted of an existing shaft design in which a new spiral bevel gear design was developed. All three designs are straddle mount gear arrangements.

The spiral bevel gear mesh is sized first for durability and strength. The motion of the spiral bevel gear tooth machine is then overlaid to view space available for a shaft design. Both the machine tools that cut the initial gear teeth and the grinding wheel that grinds the gear teeth follow a similar path. Consideration of one or both depends on the envisioned manufacturing process. Capability has improved to the extent that gear tooth grinding machines can be used to grind gear teeth from solid instead of relying on dedicated cutting machines. This allows for less tooling and shorter schedules in fast-paced, low-quantity spiral bevel gear projects. In this case, only the grinding process was considered for the SB>1 DEFIANT aircraft while the CH-47 Chinook gear utilized both cutting and grinding.

The Gleason Works maintains a cutter path plot program that plots the tips of the cutter blades or another point of interest, such as cutter bolt heads of the machine for face milled designs. The program rotates points of interest from the cutter head onto the gear reference frame and plots the distance of each point to the gear axis in two dimensions. Three positions are plotted — one where the machine is at the toe end of the gear tooth; one where the middle of the tooth is in contact; and one where machine is at the heel end. In gear terminology this motion is referred to as "toe," "mean," and "heel roll" positions. The roll positions — defined as a roll angles — are specific positions of the resulting synchronized motion of the cutter head and part during the gear tooth cutting or grinding process (Ref. 2). The program requires the basic parameters of the spiral bevel gear design to be completed in order to draw a path of the point of interest. Points can be exported to overlay on the shaft cross-section in a general computer-aided design (CAD) package. Figure 2 shows an example of a two-dimensional plot overlaid onto a cross-section of the integral shaft gear.

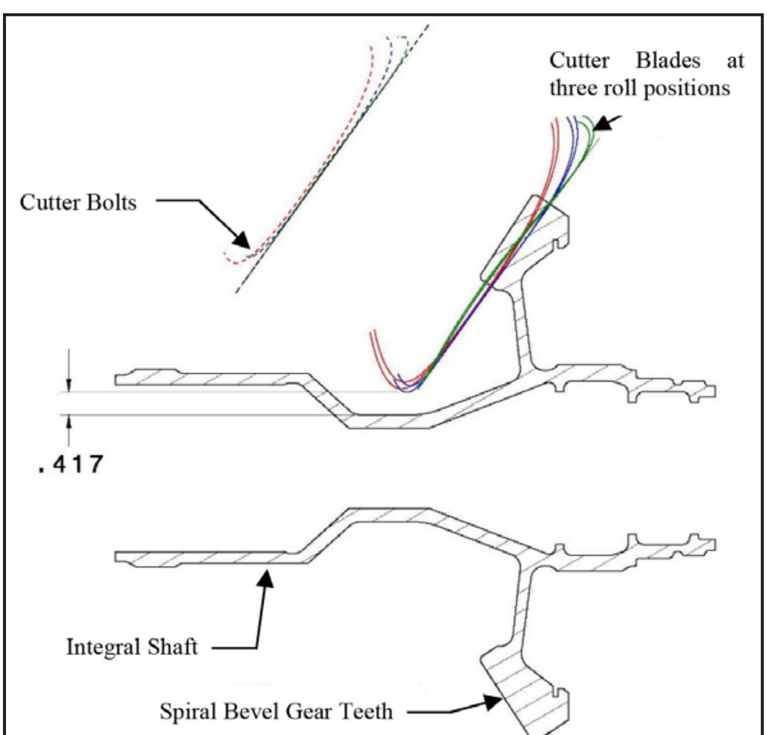


Figure 2 The Gleason Works two-dimensional cutter path plot overlaid onto a cross-section of an integral shaft gear.

At this stage of the design we are primarily interested in the smallest diameter shaft that is clear of the cutter blade tips. In order to speed the cycle time of the process, an inclusive program with fewer inputs was desired that would plot the cutter paths in a two-dimensional shaft reference frame, as well as a shaft diameter of interest to rough in a compromise between the shaft and spiral bevel gear tooth designs. Solutions were iterated between the gear tooth design and the shaft design until the smallest solution gear head with a cutter path design that cleared the shaft by a minimum of .060 inch (1.5 millimeters) was found. Once found, other gear shaft features were located to clear the cutter blade tips and bolts.

Preliminary Two-Dimensional Cutter Path Tool

Reference 1 describes a *FORTRAN*-written tool for drawing the cutter path of a spiral bevel gear design in a two-dimensional coordinate system. The design tool was recreated by applying descriptions detailed by Litvin and Lee (Ref. 2) to a program written in the *MATLAB* software application by The MathWorks, Inc.

The preliminary design tool calculates the path of a point on the cutting tool relative to the axis of the gear shaft. Typically, the path of the blade tips is evaluated, although other points on the cutting tool may be used if desired. The program assumes that the gear is generated using the face milling process with zero cutter tilt. The program takes points $X_c = \langle x_g, y_g, z_g \rangle$ in the cutter coordinate system and transforms those points to the gear coordinate system $X_g = \langle x_g, y_g, z_g \rangle$. The z-axis of the cutter coordinate system is the axis of rotation of the cutting tool with positive *z* pointing into the cutter body. The cutter blade tips are located in the *x-y* plane of the cutter coordinate system. The origin of the gear coordinate system is the apex of the gear. The *z*-axis of the gear coordinate system is the axis of rotation of the gear. Rotation of the gear about its own axis does not affect the cutter path, and is not considered. The simplified coordinate transformation between the cutter coordinate system and the gear coordinate system is:

$$\begin{bmatrix} x_g \\ y_g \\ z_g \end{bmatrix} = \begin{bmatrix} \cos\Gamma & 0 & \sin\Gamma \\ 0 & 1 & 0 \\ -\sin\Gamma & 0 & \cos\Gamma \end{bmatrix} \cdot \left(\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} + \begin{bmatrix} s\cdot\cos(q+\Delta q) \\ s\cdot\cos(q+\Delta q) \\ 0 \end{bmatrix} \right) - \begin{bmatrix} X_{SB}\cdot\sin\Gamma + X_{MCB} \\ E_m \\ X_{SB}\cdot\cos\Gamma \end{bmatrix} \qquad (1)$$

Where Γ is the machine root angle, $(q+\Delta_q)$ is the cradle roll position; X_{SB} is the Sliding Base, E_m is the machine offset; and X_{MCB} is the machine center to back. These values can be found in the grinding machine summary for the gear or for preliminary design they can be calculated from the gear tooth geometry (Ref. 2).

A two-dimensional visualization is created by plotting the distance of each point from the shaft axis $r_g = \sqrt{x_g^2 + y_g^2}$ vs. the position along the shaft axis z_g. The position of the cutting tool relative to the gear changes throughout the generating motion. This motion is a function of the parametric parameter $(q+\Delta_q)$, the cradle roll position; therefore, multiple cradle roll positions should be plotted. For preliminary design, plotting the two extreme positions along with one central position appears to be sufficient. Typically, multiple roll positions are presented on a single plot. Multiple points of interest on the cutting tool can also be plotted simultaneously if desired. Figure 3 shows an example output from the preliminary design tool showing the paths of multiple points on a grinding wheel at three different roll positions.

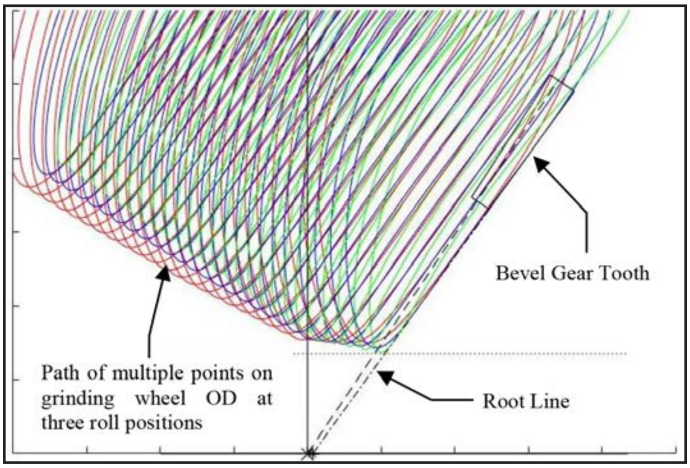


Figure 3 **Sample output from the preliminary design tool.**

Detailed Design

Once a preliminary design has been established, further refinement is needed to verify that the gear tooth cutting and grinding operations will not interfere with the shaft design. At this point further consideration must be given to the geometry of the cutter head and the machine to ensure there is no interference with the design. Coordinate points and unit normals calculated using the updated Preliminary Design tool were used to establish the location of the cutter head in a three-dimensional CAD model of the integral gear. A course representation of the cutter or grinding wheel was drawn in the integral gear CAD model at each of the three roll positions. Figure 4 shows the three cutter positions during the gear tooth machining process.

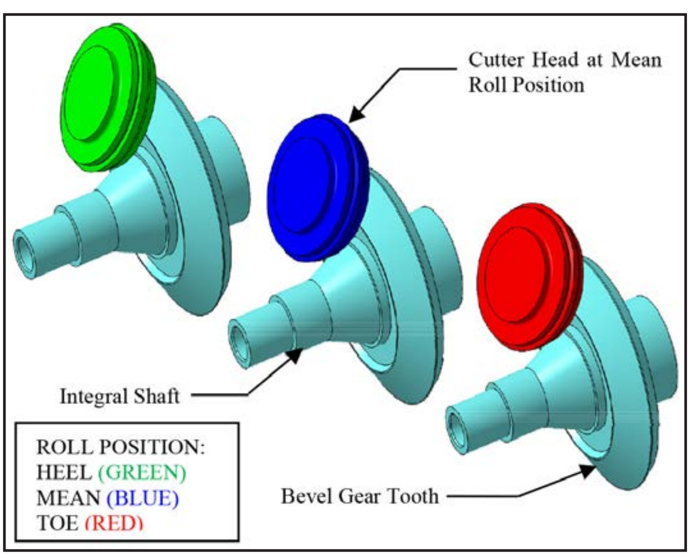


Figure 4 **Cutter wheel located at the three roll positions in the integral shaft gear model.**

The model was used to check clearance with the integral shaft design and to make changes to maintain the minimum clearance while meeting design goals. Changes can also be considered to the blade cutter or grinding wheel. Grinding wheels come in standard sizes, where only a small portion of the wheel is actively used for a job. Extra stock can be removed from the wheel by following the blade angle from the outer blade point or by reducing the diameter of the overall wheel. Reducing grinding wheel outer diameter also reduces wheel stiffness and can impact tooth accuracy, so the effort should focus on fitting the largest-diameter grinding wheel in the space available. The cutter head can be modified by reducing the height of the bolt heads or by using an integral cutter head and blades. Figure 5 details initial grinding wheel interferences and modifications made.

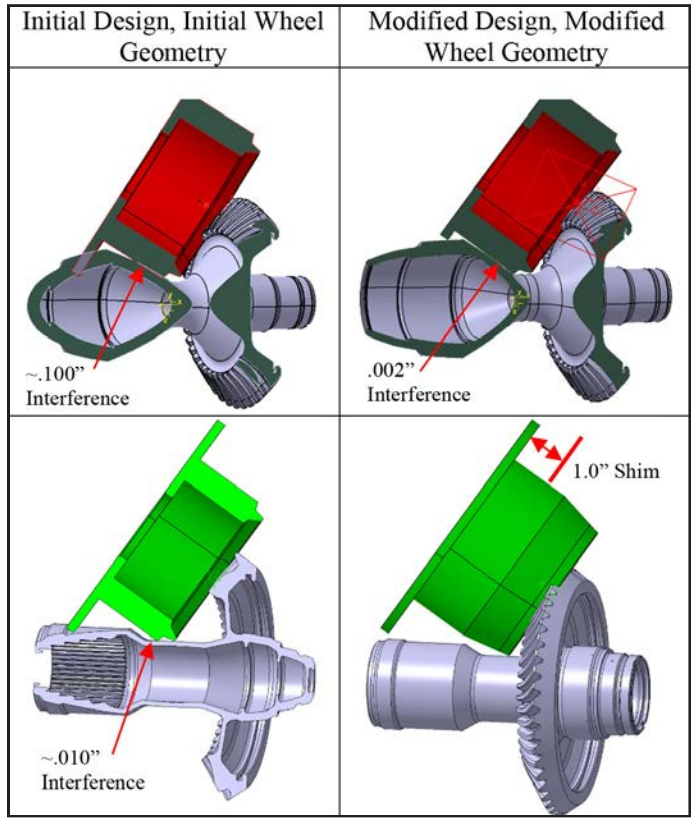


Figure 5 **Examples of initial design integral shaft gears and grinding wheel interferences and modified designs and modified grinding wheels.**

Both the grinding wheel and the cutter head can be shimmed away from the cradle base to eliminate collisions of the integral shaft bevel gear with the machine. In order to maintain accuracy of the bevel gear teeth, shimming should be minimized to keep the rigidity of the head. Care should be taken to fabricate a close tolerance shim that is perpendicular and concentric to the spindle axis to reduce runout and vibration in the spindle. Thought should be given to the number of dresses possible on the wheel before replacement, since with each dress the wheel height shortens and the gear shaft will move closer to the cradle base. Figure 6 shows an example of minimum distance from the cutter to the end of the shaft along the machine spindle axis.

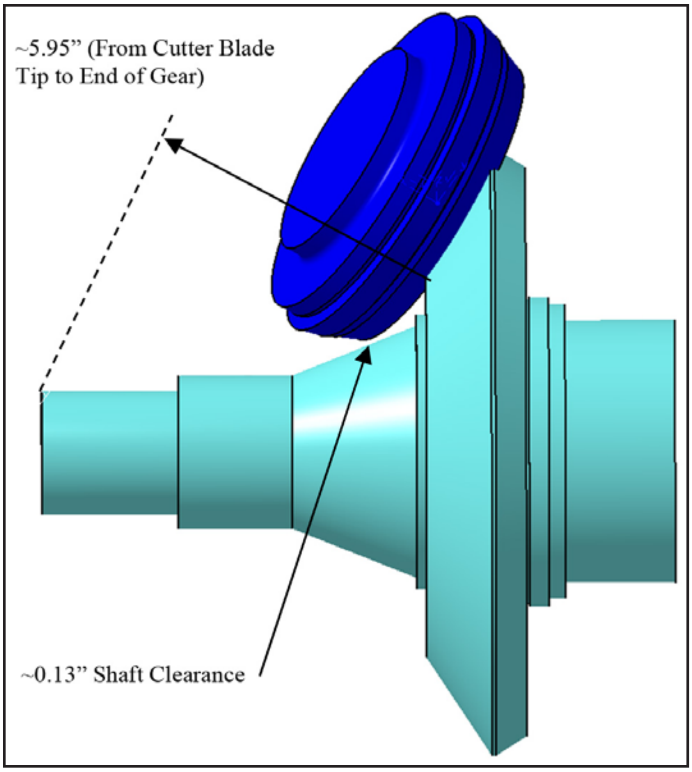


Figure 6 **Minimum distance from cutter blade tip to end of gear along cutter spindle axis.**

Manufacturing Trial

Once a workable solution was reached, trials were conducted in the gear manufacturing machine to verify that a solution had been found. Actual verification reduces schedule risk ahead of fabrication of the first part. As suggested by the Reference 1 paper, a two-dimensional cardboard silhouette, three-dimensional wood, aluminum, or plastic piece are acceptable choices at this step. A test piece was turned from aluminum that replicates the outside shape of the shaft. For the gear head, the test piece was turned to the root cone. Wheel modification suggestions from the computer work were incorporated into the gear tooth wheel. The gear tooth machine summary was loaded onto the machine for the trial so that machine motions will be the same as the actual part.

The trial was conducted by jogging the machine through motion while the spindle is not turning. The machine motion was stopped at toe, mean, and heel roll positions in order to measure clearances between shaft, wheel, and machine. The machine motion was again checked while the coolant bars and nozzles were in place. Figure 7 shows an example of the first and second iterations for the manufacturing trial in a gear tooth grinding machine shown at the toe roll position. In this case, the gear teeth were ground from solid and finish ground in the same machine.

In a different trial, the gear manufacturer planned to rough the gear teeth using a cutting process. Figure 8 shows the resulting integral shaft gear design during the gear tooth cutting process.

Following the Reference 1 paper, the grinding wheel dressing operation was also checked while the integral shaft part was installed. The check proved successful and did not impact any of the designs. One issue noted by the manufacturer was the motion from the home position to the first position before the

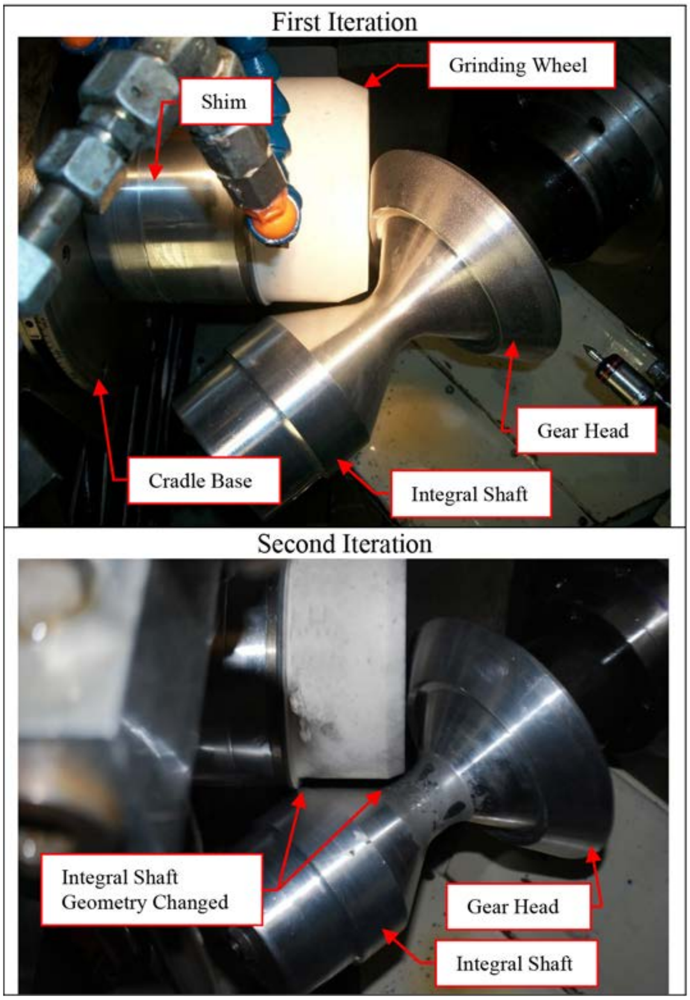


Figure 7 **An example of the first and second iterations for the manufacturing trial in a gear tooth grinding machine shown at the toe roll position.**

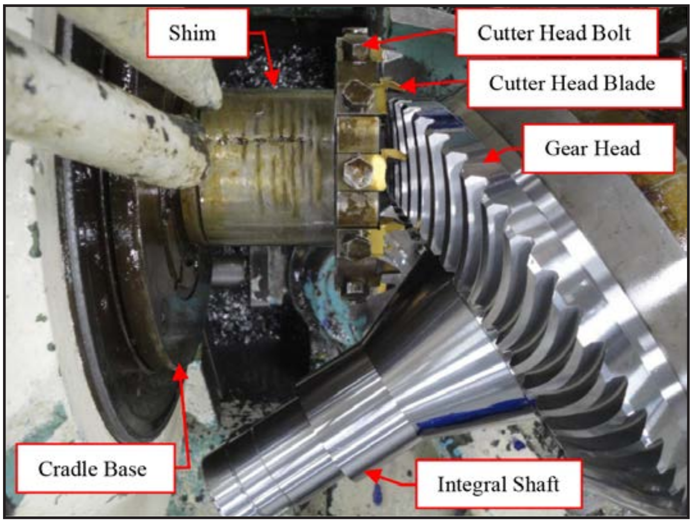


Figure 8 **Example of an integral shaft bevel gear roughed by a cutting machine.**

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wheel enters the tooth. The machines move to the first position by moving in all axes simultaneously. An issue arose in one instance, where the simultaneous motion caused the integral shaft to be in the way during the movement to the first position. The issue was rectified by switching the start and stop roll angles. If a case is presented where the machine tool must follow a path to reach the start position, the machine tool manufacturer would be integral to achieving a solution.

Conclusions

Techniques described were applied to the development of an integral shaft design for a growth project for the CH-47 Chinook and two designs for a new transmission design for the SB>1 DEFIANT aircraft for the Joint Multi-Role Technology Demonstrator Program.

A preliminary design simulation tool for cutter path tools was updated. A detailed design approach was developed to visualize the cutter head in three dimensional spaces in relation to the integral shaft gear design in CAD.

Concluding Recommendation

A successful integral shaft design requires input from design, stress, manufacturing, and the machine manufacturer. Further development in the virtual machine simulations could be used to provide stay out zones in the form of three dimensional surfaces when integral shaft designs are considered.

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The views and conclusions contained in this document are those of the author and should not be interpreted as representing the official policies — either expressed or implied — of the Aviation Applied Technology Directorate or the U.S. Government.

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Scott Davidson is a gear technology engineer in the Dynamic Component Stress Group for The Boeing Company in Philadelphia, PA.

Large Bevel Gears for Crushing Applications

Steve Lovell

Introduction

Large bevel gears drive the crushing machines used to process ores and minerals in the hard-rock mining and aggregates industries. Among the most common machines of this type are gyratory (Fig. 1) crushers and cone crushers (Fig. 2). The gyratory crusher is typically the first process step after initial blasting at the mine, or quarry, with the largest such machines capable of swallowing rocks as large as 72" (1.8 meters) and reducing them to fist-size product. Cone crushers normally see service in secondary and tertiary crushing applications where further size reduction is required. In each case, the gears for the large machines are now approaching 100" (2.5 meters) diameter. Both families of machines are considered quite mature, with only modest design evolution occurring in recent decades. However, during this same period, driven by the need for increased throughput, both speed and power ratings have increased significantly for the same basic machine designs. The challenge for the gear design and manufacturing people is to produce a gearset that performs reliably within the evolving operating conditions of the machines they drive. The following sections are intended to help the reader understand the unique aspects of these machines, and why crushing applications fall outside the traditional automotive paradigm for bevel gears.

Crusher Operating Principal

Both types of crushers consist of a tapered, conical crushing chamber that's created by a fixed conical housing that surrounds a gyrating conical mantle. With the mantle placed inside, and in close proximity to the housing, these two main components form a tapered crushing chamber having a maximum opening at the top — where the raw feed stock enters the machine — and with the tapered chamber opening gradually necking down as the feed stock is crushed and reduced in size. The crushed material progresses its way down thru the tapered crushing chamber by gravity feed, and is finally discharged out the bottom after the desired size reduction has been achieved.

Machine Motion

Crushing action results from the unique motion of the mantle as it gyrates about the machine's vertical centerline. It is perhaps simpler to envision the motion of the mantle as a rotating pendulum, i.e. fixed at the top and tracking a circular sweeping path at the bottom. The heart of the machine is the eccentric, which creates and transmits the gyrating motion to the mantle. The bore of the rotating eccentric is radially offset and inclined on the necessary angle to produce the desired pendulous motion during operation. The machine's main shaft fits into the bore of the rotating eccentric and, working together, these two components form the axis for the path of the gyrating mantle. Finally, drive power is transmitted by the bevel gear, which is firmly mounted to the eccentric wherein plain rotary motion is transformed into the gyrating motion.

Bearing Design

The vast body of knowledge about bevel gears has been built around experience with automotive-type applications including cars, trucks, agricultural equipment, and heavy off-road vehicles. These applications all utilize rolling element bearings to produce hard/fixed mounting points for the gearset. And in these more typical applications, the engineer must consider the anticipated deflection and elastic deformation of the various fixed and moving components of the drive system under load.

The unique part about crushing applications is that the gearset, in nearly all cases, is held in alignment with plain bronze bushings. And with most of these applications falling within boundary lubrication parameters, the resulting bearing clearances tend to be quite large. For example, a large gyratory crusher may have an eccentric bearing clearance exceeding .100" (2.5 mm), with the resulting floating centerline determining the operating centerline for the bevel gear. Now, imagine an automotive-type application, with an 8" (200 mm) ring gear that's mounted in sleeve bearings with .009" (0.23 mm) radial clearance, and consider where the contact pattern might want to go under intermittent load conditions. Making things more interesting, imagine a radial load on the ring gear carrier that, with each revolution, moves in an orbital path about the housing's fixed centerline by an amount equal to the total bearing clearance.

Therefore, in addition to the inherent separating forces and elastic deflections that always occur, crushing applications must also anticipate the effects of generous bearing clearances and a bevel gear that follows an orbital path relative to the fixed centerline of the pinion. Some machine designs serve to mitigate the extent of the gear's orbital path by offsetting the gear radially — off the eccentric's centerline — by an amount equal to the design bearing clearance. However, this compensating feature does not account for the inevitable bearing and shaft wear that naturally occurs, where the total bearing clearance can reach 150% of the design clearance between service intervals.

Material Combinations

For many years, both gears and pinions were made from thru-hardened materials. As throughput and power ratings increased, thru-hardened gears got harder and the pinions became carburized and hardened. Hard cutting of pinions came shortly thereafter, once the necessary tooling and skiving techniques could be developed. But carburizing and hard cutting of the gear component, having many more teeth, was deemed impractical due to period cutting tool technology and machine tool rigidity.

In more recent years, carburized and hard cut versions of the larger gears have become a viable option with the advent of larger cutting machines reaching the market, and particularly with the introduction of five-axis milling technology to the gear industry. However, distortion control during heat treatment continues to be a limiting factor due to the lack of quench presses capable of handling the very large pieces. For this reason, many of the larger crushers continue to utilize thru-hardened gears in conjunction with carburized and skived pinions.

Induction hardening of the large gear component has also been utilized to achieve surface hardening, with significantly less distortion than would be seen in a free-quenched, carburized gear. However, this requires specialized equipment for the inductor to perfectly track the spiral angle and radius of curvature in spiral tooth designs.

Figure 1 **TS Gyratory Crusher. (Illustrations property of FLSmidth A/S, used with permission.)**

Tooth Configurations

Following the chronological evolution of tooth configurations, the oldest crushers utilized straight bevel gears, and a considerable number of these machines remain in operation today. As throughput and power ratings increased, and along with increases hardness, the industry further responded with skew tooth designs. Numerous skew tooth cutting machines also remain in operation today — the "senior citizens" of the bevel gear shop — producing good quality components on busy production schedules. Spiral bevel gears appeared later and, until more recent years, only a few cutting machines were capable of producing spiral bevel gears in the larger sizes. This situation has been largely remedied with the introduction of high-precision 5-axis milling machines, along with the sophisticated software that supports them.

Design Considerations

The challenge for the engineer is to produce a design that will accommodate the wandering contact that naturally occurs in these soft bearing applications. This accommodation includes: 1) lowering traditional expectations for contact patch area relative to total available tooth flank area; 2) compensating for the reduced contact patch area thru the augmentation of other design attributes; 3) increasing static backlash and root clearance values to prevent hard mesh conditions as the gear follows its orbital path relative the pinion's fixed centerline and 4) applying a contact test method and acceptance criteria that provide satisfactory operation and life expectancy given the unique operating characteristics of these machines.

Testing

The contact testing technique for crushing applications needs to account for the wandering contact that naturally occurs as the gear's rotational axis, mounted in soft bearings, follows an orbital path with respect to the pinion's fixed centerline.

When utilizing a test machine with

both horizontal (H) and vertical (V) axes adjustment capability, the H and V axes are sequentially adjusted to mimic the orbital motion of the gear, and to simulate the resulting contact patch movement that naturally occurs during operation. This results in contact tests being performed at five different test machine settings as follows: 1) with the gear and pinion both set on basic centers; 2) with the pinion moved out (H-plus); 3) with the pinion moved in (H-minus); 4) with the pinion moved up (V-plus); and 5) with the pinion moved down (V-minus). In each of the five tests, the gear remains set on basic centers, with each pinion offset movement being equal to the uncompensated bearing clearance.

At each of the five test machine settings, the contact patch should be of an acceptable shape and size, and remain within the allowable window of movement; and, observing the prescribed standoff values (no-go zones) with respect to the tooth extremities. In addition, minimum backlash and root clearance values must be observed at each of the four test machine settings to ensure that adequate clearance exists and that hard mesh conditions will not occur during operation. With straight and skew tooth designs, contact patch movement and changes in backlash are greatest when test machine settings are adjusted in the V-plus and V-minus directions. With spiral tooth designs, contact patch movement and changes in backlash are greatest with test machine adjustments in the H-plus and H-minus directions.

When using a test machine with no vertical axis of adjustment (V-plus/minus), the gear is radially offset, relative to the test machine's horizontal axis of rotation, by an amount equal to the uncompensated bearing clearance. This arrangement produces radial runout of the gear, simulating its orbital path relative to the pinion's fixed centerline. Once the proper offset (radial runout) value has been accurately set, the gear tooth that best aligns with the maximum runout value is identified, as are the teeth that best align with the remaining three cardinal coordinates around the gear. Testing is then a straightforward proposition, with contact patch size and location being evaluated, along with backlash and root clearance values, at the four pre-marked tooth positions representing the four cardinal coordinates around the gear. And prior to this offsetting routine, the contact patch should first be evaluated with the gear runout set at zero, thereby producing the five test results described in the foregoing procedure for a test machine with both H and V axis adjustment.

With either of the above testing arrangements, an additional test can be performed with offset values set to represent operating conditions when bearing/shaft wear reach the point at which bearing replacement should occur. As a practical matter, the scope of such testing should be limited to evaluating the extent to which the contact patch intrudes on the tooth extremities, and whether backlash and root clearance values are diminished to dangerous levels at these extreme settings.

Design simulation programs can predict what happens to the contact patch and backlash as the gear moves around its orbital path. They can also aid in predicting what type of crowning and tooth thinning is required to achieve the desired results. However, these simulations provide only an informed starting point for the tooth cutting programs; actual results of software outputs should always be validated thru one of the above-described testing regimens. Fortunately, cutting programs produced directly from simulation software will typically allow adequate opportunity for further development and tweaking, once the initial contact test results are observed.

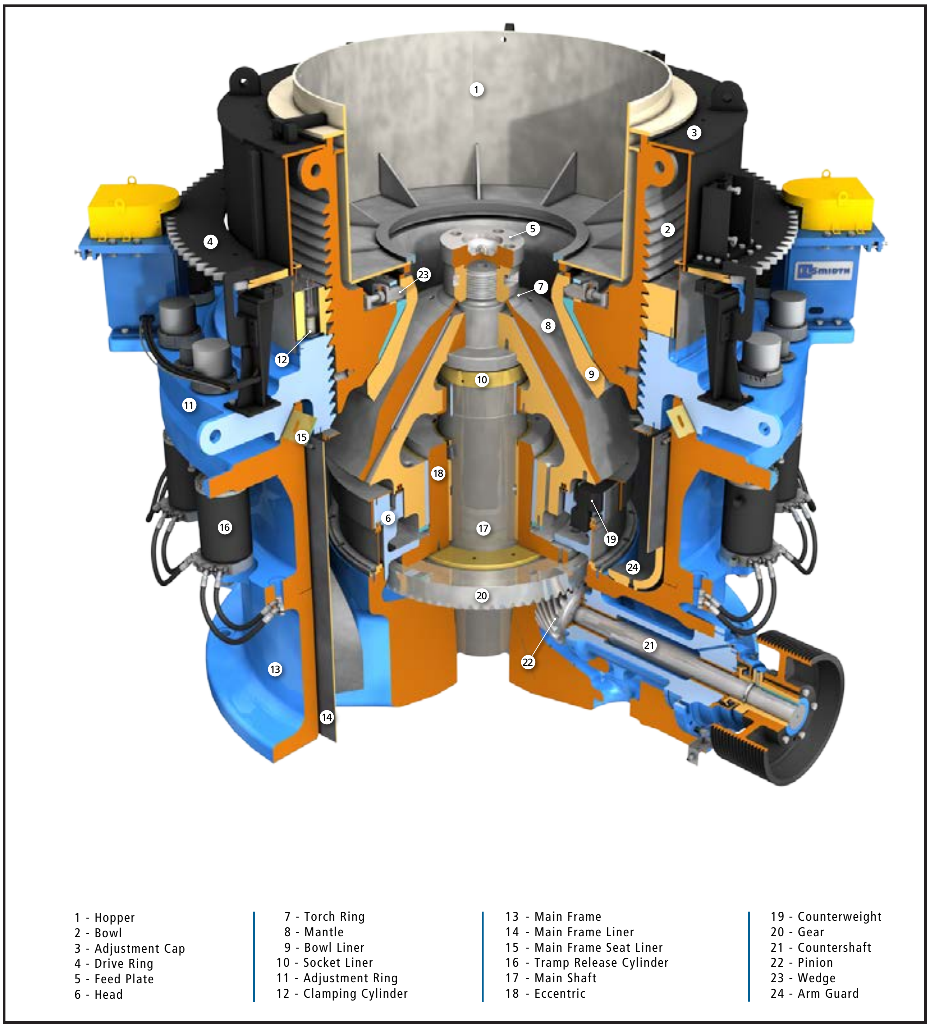

Figure 2 Raptor 2000 Cone Crusher from FLSmidth.

Summary

Although all bevel gears share many commonalities in design and manufacturing, those destined for crushing applications must possess certain key characteristics that fall outside the automotive paradigms routinely observed by the greater bevel gear industry today. These key characteristics are not widely understood within the engineering community, and it goes without saying that far fewer gear manufacturers are adequately informed on the technical requirements for these applications.

For crushing applications, the gear's operating axis depends on plain bronze bushings to maintain alignment, and these require generous oil clearance to survive under boundary lubrication conditions. The wide bearing clearances, working in tandem with gyrating crushing forces, cause the gear's pitch cone to take on an orbital path relative to the pinion's fixed operating centerline.

The resulting wandering contact imparted on mating pitch cones requires special attention to 1) avoid overload conditions at tooth extremities and 2) prevent dangerous hard mesh operating conditions. To avoid these unwanted consequences, mating components are machined with additional crown and backlash, and are finally tested by a method that simulates the gear's orbital path relative to the pinion.

The advent of precision 5-axis milling has extended the effective size range and improved efficiency in manufacturing of large bevel gears. As a positive result, this new technology has introduced many new sources for the buyers of large bevel gears. Conversely, a broader supplier base also serves to further dilute an already-limited understanding of what's required for crushing applications.

The preceding sections of this article are aimed at improving the reader's depth of knowledge with respect to these unique applications and, hopefully, serve as the impetus for more dilligent research when approaching that next crusher gearset order.

Steve Lovell is a journeyman machinist, having learned his trade in Navy and civilian machine shops, with brief career excursions working as a foundryman and a welder. Following early years as a craftsman, he held various management positions at Ingersoll-Rand (Pump Group) and the Fuller Company (Minerals Processing), and most recently as director of quality for FLSmidth Minerals. Having worked with more than 30 suppliers of large open gearing on all six inhabited continents, he is an innovator, technical writer, mentor, and recipient of awards in technological leadership. Following retirement from full-time employment in 2010, Lovell remains active today as a consultant for organizations in and around the global mining and cement industries.
Stephen.lovell1@gmail.com

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GMTA

REPRESENTS WEMA GLAUCHAU GMBH

German Machine Tools of America (GMTA) is now the North American distributor of WEMA Glauchau GmbH.

WEMA's internal grinding machines maximize operating times with more efficient and integrated procedures. A repeatedly allocable tool and workpiece headstock are guided on up to six axes with an accuracy of 0.1 µm. WEMA SI is scalable and is adapted to the clients' needs through specific mounting for the greatest machining efficiency. Powerful drives ensure quick availability with additional work and peripheral modules reducing costly non-productive times. Available in 4 different series (S2I, S3I, S6I and S10I), it offers machining of chuck and shaft-shaped parts. In addition, the internal grinding machines are equipped with internal cylinder/ cone, internal polygons, internal screw threads, up to 4 applicable grinding tools and high rigidity through the use of cast beds/hydropol beds.

With WEMA SU, universal grinding machines are available for the complex task of three-way machining of all major workpiece sizes. The machines are equipped with external and internal grinding units. Clamping operations provide decisive efficiency and precision benefits. WEMA's technology enables machines to perform highly complex operations, while peripheral modules permit greater flexibility. These machines' features include up to 3 swivel axes, machining of 4 sides in one clamping operation, machining of chuck and shaft-shaped parts and external grinding wheels with a maximum diameter of 600 mm. WEMA SU also offers additional features such as: 4 insertable internal grinding tools, 4 external grinding tools and cones, polygons, etc.

The company's external grinding machines can machine parts up to 1,500 kg with external lengths of Ø600 mm and 2,700 mm. Grinding wheels are available in Ø500, 600, and 750 mm. Typical workpieces include railway axles, rollers, pipes and shafts.

Assemblies of the roller bearing grinding machines feature a strict modular structure used for various operations. One is for sequential internal, external and rim machining operations. Another is for simultaneous internal and external machining operations. Other modular structures are used for external machining operations, internal machining operations and rim machining operations. Machining jobs can be carried out on single or multi-row outer rings (OR) and inner rings (IR) of diverse bearing types. Notable features on these WEMA machines include three different types of milling centers (SW3, SW6, SW10), grounding of borings and tracks of inner rings, as well as tracks and outer diameters of outer rings. Outside rings have a diameter of approximately 300 mm to 900 mm. Shoulders, rims, etc can also be ground and different grinding operations can be performed in sequential or simultaneous grinding procedures.

Although the company's grinding machines cover a wide range of possible applications, they also build and design grinding machines to order ranging from more or less customized adaptations to complete designs of the machine. (*www.gmtamerica.com*)

Solar Atmospheres

PROMOTES PAPONETTI TO SOUTHEAST SALES MANAGER

Solar Atmospheres South Carolina facility proudly announces that **Mike Paponetti** has accepted the position of Sales Manager. Prior to accepting this position, Mike was the Regional Sales Manager at our Hermitage, PA facility. Mike will lead the sales efforts to maintain and promote sales for Solar Atmospheres in the Southeastern United States and we are confident Mike will provide our customers with exceptional support.

Solar Atmospheres Southeast President, Steve Prout says, "We are excited to have Mike as a part of the Solar Atmospheres Southeast team. With over 20 years of thermal processing experience, his heat treating and brazing expertise will be a tremendous resource for our customers." (*www.solaratm.com*)

Methods Machine Tools

APPOINTS GENERAL MANAGER FOR MEMPHIS TECHNOLOGY CENTER

Methods Machine Tools, Inc., North America's foremost supplier of leading-edge precision machine tools and automation, has announced that **Jon Dobosenski** has been appointed as general manager of Methods' new state-of-the-art Memphis Technology Center. A ribbon cutting was recently held on November 14th, 2018 to celebrate the center's opening.

For over 30 years, Dobosenski has held various roles at machine tool and manufacturing companies ranging from executive level positions to operations, service, application management and sales. He has also been well established at Methods, including a successful run as regional sales manager, leading up to his current role of general manager for Memphis operations.

"We are thrilled to have Jon at the helm of our new modern Memphis Technology Center," said Jerry Rex, president and CEO Methods Machine Tools, Inc. "Jon brings a unique skill set and excellent leadership abilities, combining extensive machine tool and manufacturing knowledge with a genuine passion for the industry." (*www.methodsmachine.com*)

Bodycote

HOLDS OPENING CEREMONY FOR NEW FACILITY

Bodycote recently held an official opening ceremony at its brand new facility on the Advanced Manufacturing Park (AMP), Rotherham, Yorkshire.

The new advanced heat treatment center, now fully operational and supporting customer requirements, offers a range of heat treatment services and has been established to support the aerospace and power generation markets in the U.K. and Europe.

The Rotherham facility was officially opened by Andy Greasley, executive vice president of Rolls-Royce's Turbines Supply Chain Unit, in recognition of the enduring partnership between Bodycote and Rolls-Royce. Greasley commented: "Heat treatment and processing is a vital part of our supply chain and Rolls-Royce are delighted to be supported by Bodycote on the Advanced Manufacturing Park in Rotherham. Close coupling of this capability to our own Rolls-Royce business is critical for our future success and our relationship with Bodycote is one that we truly value."

Also speaking at the event, AMRC (Advanced Manufacturing Research Center) CEO, Colin Sirett, said the new center will bring a key capability to the Advanced Manufacturing Park: "We've got everything from aircraft parts through to carbon fiber chassis for supercars all being manufactured on this site; the one piece of the process that was missing was materials processing. We can cast, we can forge, we can assemble, we can machine, but the one key element that was missing is exactly what Bodycote brings to the park. So it's great to welcome the Bodycote team here and we are looking forward to working with them for many years to come."

VIP delegates were also the first to hear about Bodycote's plans for significant expansion of the new site, which includes the securing of extra units on the Advanced Manufacturing Park. Tom Gibbons, president of Bodycote's Aerospace, Defense & Energy division, commented: "Due to customer demand and interest since the announcement of this new plant in July, we are investing in further capacity and technology. The additional space we secured here at Rotherham is nearly three times the size of our existing unit. We are committed to ensuring we are able to meet our customers' demand in the years ahead."

Additionally, Bodycote recently announced plans to open a new heat treating facility in Elgin, Illinois. The new facility will include advanced heat treating technologies such as low pressure carburizing and carbonitriding, vacuum nitriding and ferritic nitrocarburizing, Bodycote's proprietary Corr-I-Dur process, and traditional carburizing of large parts. The facility, scheduled to be operational by late 2019, will support the automotive, agricultural, mining, construction and various other manufacturing supply chains in the upper midwest region.

Dan McCurdy, president automotive and general industrial, North America & Asia division, adds: "This investment demonstrates Bodycote's commitment to serving the Midwest with the services our customers ask for and require."

(*www.bodycote.com*)

Ingersoll

OFFERS LIVE CUTTING TOOL SEMINARS

Ingersoll Cutting Tools is offering seminars in 2019 to learn how cutting tools can work for you. These seminars will include informative product presentations with an emphasis on ways to increase productivity, discussions on cutting tool theory and application, and live demonstrations in a state-of-the-art Technology Center in Rockford, Illinois, showcasing product capabilities and performance. The Ingersoll Cutting Tools Seminar covers a full range of cutting tool applications, including milling, hole-making, turning, grooving, threading and more. They feature presenters/instructors with decades of industry experience. There is no charge for the seminar, and lodging and meals are provided.

A quick look at the upcoming schedule: (Gold Productivity Seminars: Feb. 6–7, March 13–14, April 3–4, May 8–9, Aug. 7–8, Oct. 3–4, and Dec. 4–5), (Turning Seminar June 5–6), (Die & Mold Seminar July 17–18), (Swiss Seminar Sep. 4–5), and (Automotive Seminar Nov. 6–7). Vist the website below for additional details. (*www.ingersoll-imc.com/seminars/live?qwikcuts=20181204&source=external*)

3M

DEVELOPS GLOBAL ADHESIVE SOLUTIONS LAB

As more and more industries are moving towards automation, design engineers are being challenged to increase production efficiencies and solve assembly challenges. Exploring new solutions and pushing the boundaries of what's possible is the everyday expectation. That's why 3M has developed the Global Adhesive Solutions Lab — to provide one-on-one attention and individualized solutions designed to advance its customers' overall manufacturing processes.

3M Science. Applied to Life.™

"Pushing the envelope with your designs takes time and effort, and it can be a very intimidating process if you're unsure where to start," said Pauline Allison, global business director, 3M. "The Global Adhesive Solutions Lab is 3M's way of offering its expertise so that our customers can exceed the expectations of their customers."

Located in St. Paul at the 3M global headquarters, the Global Adhesive Solutions Lab encourages collaboration and engagement with live, professional application engineers who are at the ready to support customers in a personalized setting. On-site, automated dispensing equipment and robotic cells from various manufacturers are also available, giving customers the chance to observe adhesive applications firsthand and interact with available tools to help ensure optimization.

"At 3M, we are constantly striving to improve the overall assembly solutions process by working directly with our customers to help them overcome issues and advance their process efficiencies," continued Allison. "We understand our customers and they appreciate having a room full of problem-solvers at their disposal to explore options and test new and creative ideas."

Every business has its own inherent challenges. This state-of-the-art laboratory will serve as a useful tool for customers interested in identifying solutions specific to their business. Users will benefit from personalized product and process recommendations, including help identifying adhesive solutions for their applications.

"We are excited to have Nordson technology and products featured in the new customer lab facility at 3M," said Justin Hall, general manager, Nordson Sealant Equipment. "This collaboration will give 3M the unique ability to demonstrate both the performance of their materials and the application process to their customers, creating confidence in the total dispensing solution. Nordson looks forward to supporting 3M in their testing allowing us to continue to strengthen our material and application expertise, leading to innovative, highly valued solutions for the market." (*www.3m.com*)

CTI Berlin

PRESENTS YOUNG DRIVE EXPERTS AWARD

Once again, three candidates qualified for the CTI Young Drive Experts Award at the 17th CTI Symposium: "Automotive Drivetrains | Intelligent | Electrified." The finalists Lukas Pointner (Technical University of Munich), Marc England (Leibniz University Hannover) and Ruben König (Technical University of Darmstadt) first presented their work in the form of Pecha Kucha presentations to an audience of 1,000 industry representatives. Then the Applausometer determined who placed first, second and third.

Lukas Pointner received the greatest response from the expert audience for his work "Multibody Simulation for Characterization of High-Dynamic Form-Fit Shifts of Alternative Shifting Elements for Automatic Transmissions". He was referring to a project in which the TU Munich, together with the company Hoerbiger, developed the so-called

"TorqueLINE Cone Clutch" in order to increase the efficiency of ATs and DCTs. In this context, Pointner has developed a multi-body simulation that can be used to predict the influence of various clutch geometries and wear on operating behavior. He has thereby made an important contribution to the design and control of this innovative transmission component. Dr. Ing. Ruben König was also able to win the crowd with his Master's thesis on "Gear Shifts and Mode Changes in Electric and Hybrid Electric Powertrains with Dog Clutches", and secured second place and the recognition of the experts that were present. Jaw clutches can make an important contribution to cost savings and increased efficiency. In order to ensure comfort when switching and changing models at a level comparable to AT/DCT, he has investigated a parallel hybrid concept with a double electric motor. In his work, he presents the corresponding vehicle simulation model, as well as the implementation, in a demonstrator vehicle.

Last but not least, M.Sc. Marc England provided an automated method for optimally designing the wiring of multi-layer hairpin windings in his Master's thesis entitled "Automated Design of Hairpin Windings as Tabular Winding Diagrams". The use of electric motors with hairpin windings makes it possible to produce high torques and power in confined spaces. This is particularly successful when the number of layers is high. With regard to electrical vehicle systems, his work provides an attractive approach for installing cost-effective e-machines with hairpin windings in passenger car propulsion systems. (*www.transmission-symposium.com*)

Weiler Abrasives

APPOINTS NEW DIRECTOR OF SALES-WEST

Weiler Abrasives, a provider of abrasives, power brushes and maintenance products for surface conditioning, has announced the promotion of **Jennifer Hawkins** to director of sales — west.

Hawkins has been employed with Weiler Abrasives since August 2013 when she joined the company as a district sales manager covering Houston and the surrounding areas. Since then, she has served in additional sales capacities of increasing responsibility at the company. In her prior sales roles, Hawkins successfully built end-user and distributor partnerships focused on growth and was successful in launching new product categories to markets she served. She has also been a critical part of the successful execution of the Weiler Vision and Strategy across the United States.

In her new position, Hawkins will lead a team of district sales managers that are focused on executing the Weiler Vision and Strategy with distributor business partners at the local level. She will also be responsible for delivering the Weiler Value Package in a way that creates mutually beneficial growth for Weiler Abrasives, distributors and end users by providing value-add solutions, innovative new products, marketing support, and training focused on safety and proper use of Weiler products.

"Since Jennifer joined Weiler Abrasives, she has excelled in every sales role she has held of increasing responsibility. Jennifer understands the needs of our distributor business partners, and she has seen the challenges that our end users face every day. She is an expert at delivering the Weiler Value Package so that it leads to growth and formidable distributor partnerships," says Jason Conner, vice president of sales — U.S. and Canada. "We are very excited and fortunate to have such a strong, experienced leader like Jennifer in this important role." (*www.weilerabrasives.com*)

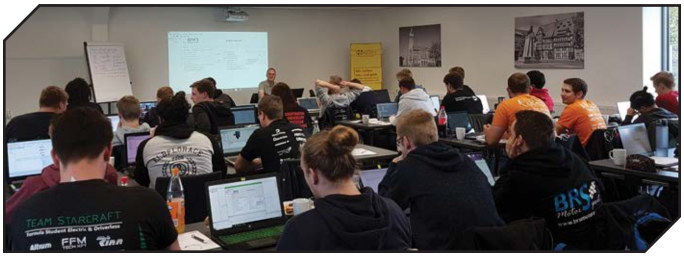
GWJ Technology

OFFERS CALCULATION WORKSHOP FOR FORMULA STUDENT TEAMS

At the end of October 2018, GWJ Technology, a provider of software solutions for gear and gearboxes, organized a workshop for the second time for Formula Student Teams addressing "Gear Calculation, Dimensioning and Optimization System Calculation."

Attracting attendees from more than 20 racing teams, the students enjoyed two insightful days of sharing knowledge, learning and networking. The first day kicked off with an introduction to gear calculation and the calculation software eAssistant. Basics for calculation and dimensioning of the geometry and the load capacity of cylindrical gears were the focus of the first workshop day.

Topics covered in this workshop included also planetary geartrains in addition to cylindrical gear pairs. The students received tips and tricks as well as optimization strategies. The theoretical basics were illustrated with examples and deepened with practical exercises. The second day was another concentrated day of learning which focused on system calculation using the eAssistant SystemManager to configure and calculate complex systems with just a few mouse clicks. This workshop provided attendees with a hands-on introduction to the SystemManager basics and the students got the idea of what they could do with the software.



The workshop included a series of practical exercises, especially multistage cylindrical gears as well as different forms of planetary geartrains. Advanced features such as the import and automatic meshing of housings and planet carrier were introduced following free-practice time at the end of the workshop. The workshop gave attendees the chance to work on their concrete transmission concepts and additional guidance was provided if needed. In 2019, GWJ Technology will continue its support of Formula Student Teams. (*www.gwj.de*)

February 12–14—IPPE 2019 Atlanta, Georgia. The International Production & Processing Expo is the world's largest annual poultry, meat and feed industry event of its kind. A wide range of international decision-makers attend this annual event to network and become informed on the latest technological developments and issues facing the industry. The 2019 show will expand to all three halls of the Georgia World Congress Center. It will bring more than 1,200 exhibitors and 30,000 attendees to Atlanta to discuss innovations in production and processing. Note that the date has been moved to accommodate the Super Bowl coming to Atlanta in 2019. For more information, visit *www.ippexpo.org*.

February 20–22—Gearbox CSI Hotel Indigo Old Town Alexandria, Alexandria, Virginia. Gain a better understanding of various types of gears and bearings. Learn about the limitation and capabilities of rolling element bearings and the gears that they support. Grasp an understanding of how to properly apply the best gear-bearing combination to any gearbox from simple to complex. Gear design engineers; management involved with design, maintenance, customer service, and sales should consider attending. The course instructors are Raymond Drago and Joseph Lenski, Jr. For more information, visit *www.agma.org*.

February 26–28—Houstex 2019 George R. Brown Convention Center, Houston, Texas. Houstex 2019 examines everything from additive manufacturing to robotics, machining centers to welding, and dozens of technologies in between. With more than 58,000 square feet of exhibit space, Houstex 2019 will showcase products of all types, Lunch & Learns to Brew & Views, Keynotes to Knowledge Bars, attendees will hear about hot topics and best practices they can put to use immediately. Explore aisle after aisle of the latest manufacturing products, software and services. This event is brought to you by SME and AMT. Industries represented include aerospace, automotive, industrial, medical, oil and gas, plastics and more. For more information, visit *https://houstexonline.com/*.

March 2–9—IEEE Aerospace Conference 2019 Big Sky, Montana. The international IEEE Aerospace Conference, with AIAA and PHM Society as technical cosponsors, is organized to promote interdisciplinary understanding of aerospace systems, their underlying science and technology, and their application to government and commercial endeavors. The annual, week-long conference, set in a stimulating and thought-provoking environment, is designed for aerospace experts, academics, military personnel, and industry leaders. The 2019 conference is the 40th in the conference series. Conference topics include aerospace systems, military, civilian or commercial aerospace endeavors, government policies and aerospace engineering and management. For more information, visit *www.aeroconf.org*.

March 6–9—The Mfg Meeting 2019 Tucson, Arizona. Hosted by two major manufacturing trade associations, AMT—The Association for Manufacturing Technology and National Tooling and Machining Association (NTMA), The MFG Meeting brings together the complete manufacturing chain for a unique conference experience. This event provides unparalleled opportunities to network with industry leaders and the agenda topics are designed to address key business challenges and provide actionable solutions. The event is intended for senior leadership, executives, vice presidents, senior sales directors, manufacturing technology's builders, distributors and end users. Learn about the future challenges and opportunities facing the American manufacturing industry, discover new ideas and participate in interactive discussions. For more information, visit *www.amtonline.org*.

March 19–21—Gear Materials, Selection, Metallurgy Hilton Garden Inn, Las Vegas, Nevada. Learn what is required for the design of an optimum gear set and the importance of the coordinated effort of the gear design engineer, the gear metallurgist, and the bearing system engineer. Investigate gear-related problems, failures and improved processing procedures. Gear Engineers, gear designers, application engineers, people who are responsible for interpreting gear designs, technicians and managers that want to better understand all aspects of gear design should attend. The course instructors are Raymond Drago and Roy Cunningham. For more information, visit *www.agma.org*.

April 1–5—Basic Training for Gear Manufacturing – Spring Hilton Oak Lawn, Chicago, Illinois. Learn the fundamentals of gear manufacturing in this hands-on course. Gain an understanding of gearing and nomenclature, principles of inspection, gear manufacturing methods, and hobbing and shaping. Utilizing manual machines, develop a deeper breadth of perspective and understanding of the process and physics of making a gear as well as the ability to apply this knowledge in working with CNC equipment commonly in use. This course is taught at Daley College. A shuttle bus is available each day to transport students to and from the hotel. Instructors include Dwight Smith, Peter Grossi and Allen Bird. For more information, visit *www.agma.org*.

April 1–5—Hannover Messe 2019 Hannover, Germany. In 2019, the integration, digitization and interconnection of industrial technologies will transform the world's manufacturing industries more than ever before. In recognition of this, the Integrated Automation, Motion and Drives (IAMD) show at Hannover Messe will feature the full range of products and solutions for the factory of the future, including factory and process automation systems, industrial IT, robotics, smart drives, and intelligent hydraulics and pneumatics systems. The unifying theme this year, "Industrial Intelligence," will focus on eliminating production downtime and ensure the seamless integration and operation of all the parts that make up smart factories. Companies like Siemens, ABB, Festo, Bosch Rexroth, Schneider Electric, Phoenix Contact and Beckhoff—have already registered display space. Confirmed exhibitors of intelligent power transmission and fluid power technology solutions include SEW Eurodrive, Schaeffler, Continental, Aventics, Hydac, KTR, Parker Hannifin, Trelleborg and ZF Friedrichshafen. For more information, visit *www.hannovermesse.de*.

April 8–11—Automate 2019 McCormick Place, Chicago. Held once every two years, Automate features the latest in cutting-edge robotics, vision, motion control, and related technologies, the event attracts thousands of visitors from around the world looking for ways to enhance their processes, improve product quality, lower costs, and sharpen their competitive edge. More than 400 exhibitors participate with technologies in drives, motors, actuators, robots, controls, metrology equipment, sensors, software, system integrators and more. For more information, visit *www.automateshow.com*.

ad index

Hyperloop is Coming!
But When?

Jack McGuinn, Senior Editor

Before Dr. Who, there was Professor Quartermass (a 1950s BBC TV and film creation). And, in the-here-and-now, there is **Elon Musk** — a flesh-and-blood living legend in his own time — or mind: take your pick. But the point here is that he's for real — not a fictional sci-fi icon.

And when he's not at work burning millions of dollars developing under his Tesla brand a commercialized electric car, he and his other company — SpaceX — are on the one hand figuring out how to colonize Mars and, on the other, how to transport goods and people to their earthbound destinations at the "speed of flight" — both above and below ground. He introduced this concept of aerodynamic subway and elevated trains in a 58-page white paper in 2012. He named it "the Hyperloop." Elon Musk's version of the concept incorporates "reduced-pressure tubes in which pressurized capsules ride on air bearings driven by linear induction motors and axial compressors." Seven years out, Musk's concept is that much closer to fruition.

SpaceX launched a "Hyperloop Pod" competition in 2015. There have been three events — two in 2017, one in 2018.

Looking for backers and believers, and perhaps overwhelmed with running both Tesla and SpaceX, Musk invited anyone interested in making the Hyperloop a reality to join the quest. Virgin Hyperloop One (originally known as Hyperloop Technologies) and CEO Richard Branson came aboard as one of the companies that agreed to give it a shot.

Meanwhile, there has been significant progress since the Hyperloop sparked a frenzy in 2013, when it was just another Elon Musk Big Idea, i.e. — very exciting, maybe possible, definitely hard to believe. Today, a prototype of the futuristic, tube-based transportation system is taking shape in the Nevada desert — "a world just isolated enough for Virgin Hyperloop One to build a giant white tube and not attract too much attention," according to Virgin Hyperloop One. "We did this whole construction in around 10 months," says Kevin Mock, Virgin Hyperloop One senior test engineer. "It's similar to a water pipe, but it was made to our specific specifications."

While the Hyperloop is indeed a "big idea"-type undertaking — especially for this country, with its woeful transportation infrastructure — those involved say it won't take a (technological) revolution to build one. It is, rather, merely an amalgam of existing transportation and industrial technologies. It is, boiled down — part elevated structure, metal tube, bullet train, pressure vessel, and a vacuum system. The challenge lies in making it work without killing anyone. And despite the not-so-hush-hush aura surrounding the project, it can be reliably reported that the prototype tube — or "DevLoop" — is one-third of a mile long and nearly 11 feet in diameter.

Most recently, incorporating its prototype pod with the tube last summer, Hyperloop One has completed some 200 test runs — at varying speeds — and collected data on every trackable variable. Last December, in a test run of the pod's real speed, the module attained a record speed of 240 mph in a matter of a few seconds.

More on the recent demo: To decompress the DevLoop, Hyperloop One used a row of small pumps, housed in a metal building to one side. These are off-the-shelf components, typically used in steel factories or meat processing plants. They can drop the pressure inside the tube to under 1/1000th of atmospheric conditions at sea level, or the equivalent of what you get at 200,000 feet. By that point, the few air molecules left are not going to get in the way of a speeding vehicle. At the right-hand end of the tube, one section of pipe, about 100 feet long, operates as an airlock. A 12-foot steel disc slides across to separate that chunk from the longer tube, so that pods or other vehicles can be loaded in and out without having to pump the whole tube down to vacuum, which takes about four hours.

Indeed, there is plenty of competition in the race to realize Musk's fever dream. For example, Arrivo, founded by Hyperloop One co-founder and former top engineer Brogan BamBrogan, is planning to build a "hyperloop-inspired system" in Denver. What's more, student teams worldwide take up the challenge, using the short tube Musk built in Los Angeles. And Musk is now on recent record saying he'd like to utilize the Hyperloop in the tunnels he's digging around the country (like Chicago). Deep tunneling, i.e. — the Boring Company (tunnels, i.e. *boring* — got it) — another Musk enterprise.

Here's the thing: this is complex engineering and logistics, with a large number of players — too complex to cover in 850 words. We haven't even touched on Hyperloop-like projects in India and Dubai — which — no surprise — are ahead of U.S. efforts. So not unlike the messy but ultimately realized meeting of East-West rail a century ago, much work of all kinds — political and technological — remains before the Hyperloop becomes the transportation mode of choice. For more information, check out *hyperloop-one.com; spacex.com/hyperloop; en.wikipedia.org/wiki/Hyperloop*.