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WHOLE SYSTEM DESIGN

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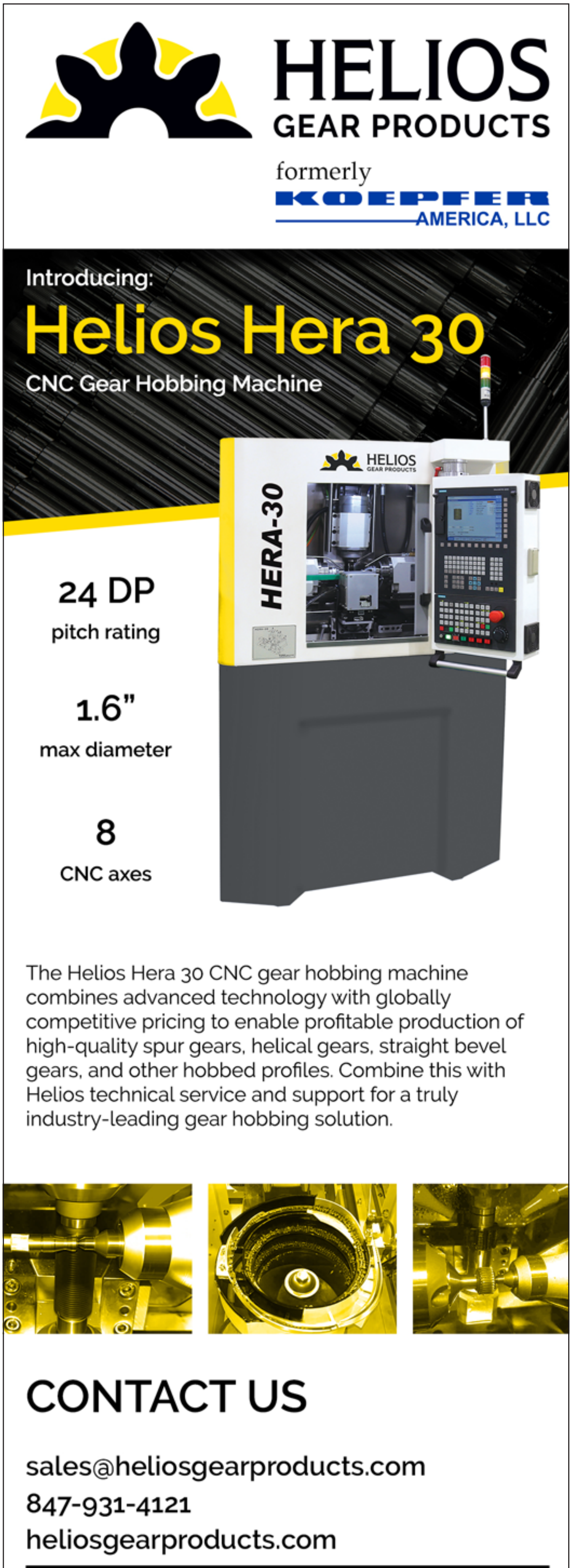

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departments

THE GEAR INDUSTRY'S INFORMATION SOURCE

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Gear Talk: Origin Stories

Our weekly blog has been featuring great stories about how many in the industry first became involved with gears. Read recent entries from Hanspeter Dinner, Dave Hinz, Bob Handschuh, James Richards and others here *www.geartechnology.com/blog*. Be sure to send YOUR gear story to *publisher@geartechnology.com* to be included in future blog entries.

GT Library: Hobbing

Browse the GT Library for articles, technical papers and back to basic submissions on gear hobbing here:

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Event Spotlight:
Motion + Power Technology Expo 2019

The Motion + Power Technology Expo (formerly Gear Expo) connects the top manufacturers, suppliers, buyers, and experts in the mechanical, electrical, and fluid power industries. Over three action-packed days in Detroit, end-users can shop the latest technology, products and services, and compare benefits side-by-side.

MOTION+POWER
TECHNOLOGY EXPO

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Close the Black Hole of Downtime
"What a fantastic bit of kit the GE20A hobber is having run trouble free and 500,000 parts since installation."
— Ken Manners CEO, SP Metal Forging, South Africa
Downtime is a black hole that impairs productivity, kills the bottom line and simply shouldn't happen due to breakdowns. With a philosophy of continuous process improvement, in conjunction with an active reliability and maintainability program, Mitsubishi's gear machine products deliver best in the business quality and predictable production. Experience perfect production systems by visiting www.mitsubishigearcenter.com or contact sales 248-669-6136.

The Do-It-Yourself Mentality

Publisher & Editor-in-Chief
Michael Goldstein

Finding capable, dependable machinists is one of the great challenges of modern manufacturing. Most gear manufacturers we talk to would hire more machine operators — if only they could find them. They lament the fact that their workforce is getting older and grayer, and they don't know what to do.

Just mention the word "Millennial" and the old timers will roll their eyes. The younger generation doesn't have the same work ethic, they say. Millennials are more interested in making YouTube videos and growing their Instagram following than they are in holding a steady job. It's like they're expecting society to just take care of them.

Huh.

It occurs to me that, collectively, we're all doing the same thing. We're waiting for someone else to solve the workforce problem for us. Granted, it's a big problem, and changing the attitudes and expectations of students, parents, school counselors and young workers seems like an overwhelming task. What difference can one manufacturer make?

The answer is quite a lot, actually. At AGMA's recent Strategic Resources Network (SRN) meeting, held in May at MxD in Chicago, one of the presenters was Dave Hataj, president of Edgerton Gear. Hataj talked about a unique pre-apprenticeship program he developed and which is transforming the way manufacturers in Edgerton, Wisconsin are attracting, training and retaining young people to the workforce.

Hataj's program, *Craftsman with Character*, is a pre-apprenticeship program he developed to rescue what he calls the "lost shop kids" — the high school students who enjoy working with their hands but who might not be cut out for a university education. The program includes a partnership with the local high school, and students attend class at Edgerton Gear (or another local manufacturer) for 90 minutes each weekday. Four days are spent job shadowing, allowing students to follow a mentor and be immersed in a culture while gaining knowledge about a trade. The remaining day offers classroom instruction, where students explore their life goals and are encouraged to recognize their unique gifts and talents.

Hataj says the program has helped transform his business. It turns out that the act of mentoring young people has the tendency to bring out better character traits in those doing the mentoring, he says. As a result, the business performs better. More importantly, a third of Edgerton's staff is now under the age of thirty — quite a different situation from the company makeup before the program began.

Complete details about the *Craftsman with Character* program are available from the organization's website (*www.craftsmanwithcharacter.org*). You can see videos describing the program, including testimonials from manufacturers, educators and students. You can see the course outline. And you can find out more about how you can start the program in your area.

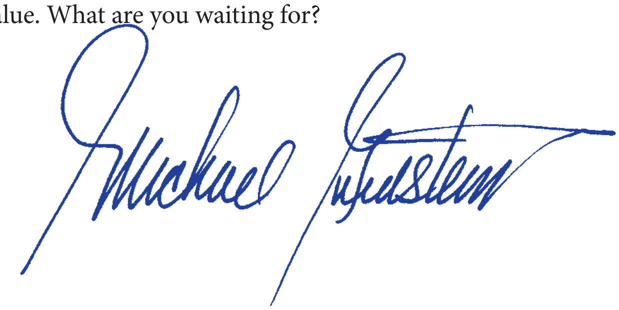
The success of the program at Edgerton Gear is proof that you can make a difference. But if you're not ready to start a full-blown pre-apprenticeship program at your facility, there are still other ways to help yourself.

One of those ways is the AGMA Foundation's *Get Into Gears* employee recruitment toolkit. This free kit was created for anyone who is looking to promote the gear industry as a viable career path in order to recruit new employees. Companies or individuals interested, can download the kit at *www.agmafoundation.org/getintogears*.

The toolkit includes a variety of marketing pieces you can use to attract qualified applicants to your business. They include a PowerPoint presentation, social media and e-mail graphics, a promotional video, a brochure, posters, postcards and advertisement templates. Print materials can be customized with your company name and contact information, and are meant to be customized to your needs.

The AGMA Foundation has done a lot of work for you, so there's really no reason not to at least download the materials, adapt them and make them available to the people who do the hiring at your company. Maybe it's time to reach out to the local high schools, technical colleges and trade schools. Maybe you should participate in local job fairs. When you do, these materials will help you sell the advantages of working in the gear industry.

Solving the workforce problem won't come easy. We have a long way to go. But as manufacturers, you know that it takes dedication, hard work and commitment to build something of value. What are you waiting for?



EMAG

VLC 200 GT OFFERS DIVERSE MACHINING CONCEPTS

EMAG's VLC series covers a very broad range of machining technologies: turning, drilling, milling, gear hobbing, hard and soft machining.

"VLC machines enable us to cover the entire process chain for the manufacturing of transmission components, from blanks to finished parts," explains Peter Loetzner, president and CEO EMAG LLC. "Customers benefit from the unified design of our machines — consistent transfer heights and an integrated pick-up automation system that make it easy to connect machines."

The pick-up automation system is the platform for the success of EMAG machines. Every machine in the VLC series features a parts storage area for raw and finished parts, as well as a working spindle that is automatically loaded and unloaded from this unit. It guarantees minimized non-productive times and high efficiency.

"Of course, these qualities are shared by the VLC 200 GT, a combined turning and grinding machine that we developed specifically for the hard machining at the end of the process chain," Loetzner adds.

The VLC 200 GT was developed primarily with a focus on transmission gears and was first launched in 2016.

"Because of their large production numbers and high quality requirements, transmission gears are ideal parts to be machined on the VLC 200 GT,"Loetzner explains. "When we analyzed the machining process, we found that we could perform the entire machining process in a single clamping operation."

To achieve this, EMAG combines the processes of hard turning and grinding. The shoulder and the bore are hard-turned first. Only a few micrometers of material is then left to be removed from the transmission gear. This ensures a much shorter grinding process using aluminum oxide or CBN grinding wheels, which saves costs in two ways: through lower tool costs resulting in a lower unit cost, and through faster cycle times. 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 Rz of less than 1.6 micrometers can be reliably achieved with the VLC 200 GT.

For more information:
EMAG LLC
Phone: (248) 755-9775
www.emag.com

3M

INTRODUCES HIGH PERFORMANCE, PRECISION STRUCTURED INTERNAL GRINDING WHEELS

Specifically designed abrasive tools require tight wheels, geometry, and tolerance for mass production. Companies that grind in the most complex ID applications need tailor-made solutions that adapt to tool design and specifications, and offer improved outcomes. 3M's new Precision Structured Portfolio for internal grinding brings to market the first product available using 3M's expertise in abrasives, bonding, manufacturing and 3D technology: 3M Precision Structured Vitrified CBN Grinding Wheel 1PVP.

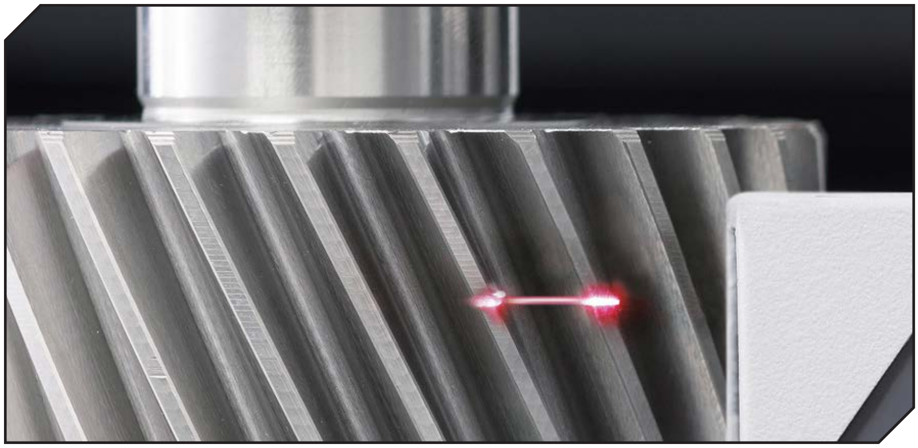
"We listened to customer needs before we pioneered Precision Shaped Grain in Conventional Bonded Wheels, and we've seen significant productivity benefits in ID Grinding for our customers," said Felix Thun-Hohenstein, global business director, abrasives systems division. "But many customers are using Super-Abrasives and are also seeking process improvements—now we're engineering a Precision Structured portfolio of products that could help customers see similar benefits in very challenging ID grinding situations."

Digital modelling, combined with a 3D printing process, allows flexibility in wheel design in terms of wheel shape. This includes unique 3D shapes and structures, surface slots, integrated cooling holes, passages and channels — all key elements that improve outcomes in detailed applications like fuel injectors, rotary bearings, steering components and more.

For more information:
3M
Phone: (855) 809-1710
www.3m.com/us/precisiongrinding

Gleason

PRESENTS GEAR INSPECTION TECHNOLOGIES AT CONTROL 2019



Gleason Corporation presented its 300GMSL Multi-Sensor Gear Inspection System and the GRSL Gear Rolling System with integrated Laser Scanning at the recent Control Show in Stuttgart/Germany.

The versatile platform of Gleason's 300GMSL Gear Metrology System provides the classic tactile probing methods for inspecting conventional gear characteristics on spur and helical cylindrical gears as well as straight, spiral and hypoid bevel gears with a diameter of up to 300 mm. In addition, the new inspection system allows non-contact laser sensor scanning of tooth flanks to support gear development. Complete topography data can be recorded far more rapidly than with conventional tactile probing, with comparable results - depending on the tooth flank surface.

The integration of laser scanning and associated 3D graphics with CAD interface considerably expand both the functionality and the range of applications for this machine platform. The new option makes the 300GMSL the ideal solution for research and development applications, for both prototype and production parts or when reverse engineering is required. Further options include surface finish measurement or Barkhausen noise analysis to inspect grinding burn.

The 300GMSL Inspection System is also an ideal fit for rapid measurement of topography in regular production operation and satisfies the increasingly stringent requirements on gear inspection. Compliant, soft materials (such as plastic gears, for example) can be inspected without sustaining damage. Multiple technologies combined in one single machine platform reduce operating costs, annual maintenance, certification costs and space requirements.

The GRSL Gear Rolling System with Laser allows in-process gear inspection and sets a new standard for throughput where high-speed, high-volume testing

is required. It provides both, double flank roll testing as well as analytical index and involute measurement on all teeth in a matter of seconds.

This new technology is available in manual, semi-automatic or fully automatic configuration depending on the needs of the customer. The index and involute measurements are analyzed using Gleason *GAMA Gear Automated Measurement and Analysis Software* which allows operators to see common charting between a GMS Analytical Inspection Machine and the GRSL Gear Rolling System. With *GAMA*, over fifty analysis packages are available for customers with all major industry standards such as AGMA, DIN, ISO, etc., along with customer specific analysis requirements developed specifically for the *GAMA* Platform.

For more information:
Gleason Corporation
Phone: (585) 473-1000
www.gleason.com

Radix Technology

RELEASES GEAR TOOTH ALIGNMENT ANALYTICS

Radix Technology Solutions, a division of the AIS Technologies Group, released a new vision application at the Automate 2019 trade show and conference. This vision application, called Gear Tooth Alignment Analytics, is designed to automate the process of precisely aligning differential pinion and gears.

This configurable vision application inspects individual gear teeth (drive & coast), precisely calculating gear mesh contact patterns. With real-time feedback to the operator, this stand-alone application ensures the achievement of rapid and accurate pinion and gear alignment. Additional data provided by Gear Tooth Alignment Analytics includes length and width of pattern, position along the flank, total contact area, along with other metrics of value to gear analysis. An additional benefit to this product is that it requires only minimal rouging on each gear — a process and material savings of substantial value.

"Radix is well known for our ability to solve tricky manufacturing problems with clever technologies," says Josh Capogna, vice president, product innovation. "This is one more example of our commitment to innovation in intelligent manufacturing and Industry 4.0."

For more information:
Radix (AIS Technologies Group)
Phone: (519) 737-1012
www.radixinc.ca

Studer

EXPANDS GRINDING MACHINE CAPABILITIES

The new S31 performs complex and varied grinding tasks precisely and reliably. It can be used to produce small to medium-sized workpieces with a distance between centers of 400, 650, 1,000 and 1,600 mm and a center height of 175 mm in individual, small batch and high volume production. With a high-resolution B-axis of 0.00005° the swiveling wheelhead enables efficient external, internal and surface grinding in a single clamping.

The foundation of the universal cylindrical grinding machine is the machine bed made from solid Granitan S103. This provides high dimensional stability thanks to its favorable thermal behavior, while the mineral casting largely equalizes short-term variations in temperature. In addition, the new S33, the CNC universal cylindrical grinding machine from Studer, offers flexibility. With distances between centers of 400, 650, 1,000 and 1,600 mm and a center height of 175 mm, it can be used for grinding small, medium-sized and large workpieces up to 150 kg in individual, small batch and high volume production.

For more information:
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www.studer.com

Scudding Tools by Star SU

Flexibility and High Productivity in Gear Manufacturing

Dr.-Ing. Deniz Sari

The main goal of gear cutting tools is to achieve high productivity while eliminating wasted motion and maintaining high gear quality. Today, through Scudding — a.k.a. Power Skiving — a revived process using CNC controls, it is possible to state that Scudding tools meet all of the above benefits.

Scudding is defined as a continuous cutting operation that uses a tool design similar to a shaper cutter. A great advantage of this technology is that it can be applied to many gear applications, including involute gears, non-involute gears or non-symmetrical gears.

The process is extremely flexible, reduces cycle times and completely eliminates unproductive upstrokes due to the synchronization of the cutting tool and workpiece. Another advantage in using this technology is that you can perform the machining of internal or external gears without the need of an undercut or groove.

Scudding can cut a gear in equal cycle time as hobbing, and can be five to six times faster than shaping an internal gear due to skiving's continuous chip removal capability. It can also be used to hard-finish gears with a carbide cutter and can be applied any time a form can be generated by shaping, hobbing or broaching.

This process is becoming very efficient due to the latest machine technology (direct-drive and stiff electronic gearboxes) and tool technology (complex geometry, material and coating). So, Scudding does not have any wasted strokes and, compared to broaching, can use the machine axes to make lead corrections such as crown and taper.

Cutting speed calculation. Cutting speed is obtained by a combination of workpiece rotation speed, tool rotation speed, and the intersection angle between them. It is generated by the cross-axis angle between tool and workpiece.

Inclination angle:

$$\Sigma = b_0 \pm b_2$$

Cutting speed:

$$v_c = v_{Tool} \cdot \sin b_0 + v_{Workpiece} \cdot \sin b_2$$

- For spur gears, the axial feed f_a is directed in line with the Y axis.
- For helical gear the axial feed f_a is oriented in the y-direction, but an incremental tool rotation n_{Tool} has to be added to tool rotation n_{Tool}.
- A tilt angle can be used to increase the effective relief angles.


The mechanical element that is one of the most important in the industry — now and in the future — is the gear. Due to its versatility and high efficiency, gear drives are used in nearly all areas of powertrain technology. In addition to the design of gears, the production of these is a technological challenge. Therefore, diverse processes and process chains were developed.

A major part in the manufacturing process chain is the soft machining of the gear. The choice of the soft machining process depends on the component geometry, the required quality as well as the productivity. In the automotive and commercial vehicle sector, hobbing, shaping and broaching are the dominating processes for soft machining of gears. A highly productive alternative to the methods mentioned before is Scudding by Profilator.

Due to the geometrical boundary conditions, hobbing can only be used with external gears with enough axial tool travel space. For other cases, gear shaping is required — but this results in decreasing productivity. Another highly productive alternative for machining internal gears is broaching. Due to the process characteristics regarding tool and machine technology, broaching has a low flexibility and requires comparatively high investment costs. Scudding offers the possibility to produce internal and external and gears with and without interfering contours.

During Scudding, tool and workpiece mesh together — like a gear pair; external and internal-external combinations can be implemented. A significant and decisive difference is the cross-axis angle between the two partners that ensures a relative movement along the gear flanks. This relative movement of the cutting edge along the flanks ensures the chip removal. The rotational speeds of the

workpiece and tool are coupled by the numbers of teeth. Under a defined penetration, a tool tooth rolls through the gap of the component to b_e generate the involute. To this movement an axial feed f_a is added, which ensures that the component is machined to its complete face width. The cutting speed results from the rotation speeds of tool and workpiece, as well as the set cross-axis angle.

Today, cutting speeds that are now being implemented with modern machine and tool technology, are up to $v_c = 250$ m/min; using high spindle speeds, high process dynamics occur. To avoid negative effects to the process dynamics on the manufacturing process, it is necessary to design a Scudding machine in a manner tailor-made to the process. This is the only way to ensure that vibrations are minimal and a rigid machine structure provides an optimal quality result.

The process runs continuously until the complete face width of the part is machined. Backstrokes — such as are necessary in shaping — are not required. To reduce the load on the cutting edges of the tool and increase the tool life, today multi-cutting strategies are dominantly used.

Star SU and Profilator have formed a global alliance to offer the market the best tool and machine technology. The experts of the three companies work together for each and every gear project in order to implement the best possible strategy. They can choose among different kinds of tools, like disc type, shank type or wafer Scudding tools, depending on the geometry of the piece. The final decision about the correct kind of tool to be used is taken by Star SU in close cooperation with Profilator. The choice of the combination of material and coating is optimized on the basis of the workpiece. Thanks to their accurate geometric design and high-precision manufacturing, the tools provide the customer with the possibility of repeated reprocessing, which can significantly increase the tool life. Through the use of Wafer Scudding tools, for example, the customer has the possibility to use cost-efficient, non-resharpenable tools for small-to-medium-sized batches.

Together, Star SU and Profilator have many years of experience in Scudding and they successfully supply well-known companies in the gear industry all over the world. David Goodfellow, President of Star SU LLC, sums up: "As a cutting tool manufacturer, we are not just a supplier. With such a high-tech process like the Scudding, we occupy a key position among the customer, the machine manufacturer and the process itself."

Application

Spur and Helical Involute Gears and Splines

Tool Types

- Wafer
- Disc
- Shank

Material

- PM HSS
- Super Alloy HSS
- Carbide

Coating

- Alcrona Pro (AlCrN)
- Altensa (AlCrNX)

Advantages

- Produce predetermined flank corrections
- Taper and crown can be set via machine parameters
- Improve the rolling action of the gear
- High productivity
- High gear quality with low surface roughness
- Reduce cycle times
- Dry cutting
- Hardened workpieces can be machined

Dr.-Ing. Deniz Sari in 2012 received his degree in mechanical engineering from the RWTH Aachen University. He began his career as a research engineer and a group leader of the Gear Manufacturing Group of Laboratory of Machine Tools and Production Engineering (WZL) of RWTH Aachen University. In 2016 he earned his Doctorate — with a core emphasis on gear finish hobbing — in mechanical engineering (Dr.-Ing./Ph.D.) from the RWTH Aachen University. In 2016 he joined Samputensili and its joint venture — Star SU. Sari in 2017 became a gear technology manager and, at the end of 2017, he was named sales manager for gear cutting tool in middle-Europe.

Knowing the System

It's more important than ever to understand the full system your individual components are going into. Here's the latest in how software developers are helping you do that.

Alex Cannella, Associate Editor

No component is ever made in a vacuum. No matter how big a gear you're making, it exists as part of a larger system, and understanding how it does so is paramount to making sure it fits a customer's demands. Whether you're manufacturing a specific gear or building entire gearboxes, your product's parameters are going to be defined at least in part by the other components it needs to interact with.

There's an awful lot to consider, too. There are basic considerations like the application, industry, how many copies you'll have to manufacture, and so on, that will inform design choices like what material and gear shape to use. Is the application mobile? What kind of temperature will it be operating at? How does it interface with the surrounding parts? Any shock loads?

But you also obviously have to consider the components a gearbox will be interacting with directly — the bearings, shafts, and anything else that might be crowding in and limiting design space.

"Your first focus is on the gears," Gunther Weser, general manager, technical support at GWJ, said. "But in the second step, you have to look of course to the shafts and to the bearings."

Part of that is making sure the shafts are strong enough to take the load coming from the gears, but you also need to consider deformation and the shaft's stiffness. And you also need to make sure whatever bearing is getting attached to your gearbox is strong enough, otherwise both components could suffer truncated service lives. In addition, a proper bearing can sometimes compensate for a poor shaft angle.

This is true no matter what you're looking to construct, be it a gearbox for a conveyor system or gear components for a transmission. SMT, whose MASTA software is primarily utilized for simulating transmission systems, be they for automotive, rail, aerospace or otherwise, also sees the industry push towards understanding the entire system said transmission is going to be a part of.

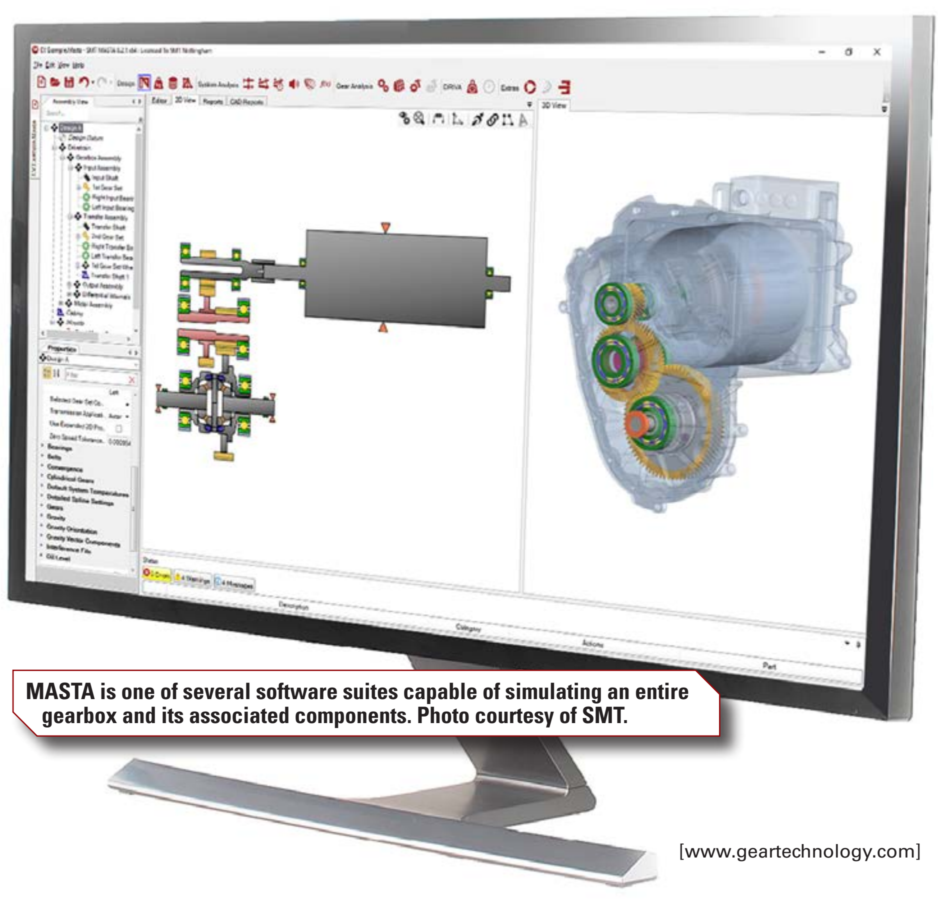
"When designing a heavy-duty automotive transmission, it is critical to understand the conditions it will be used in," Matt Sheridan, senior transmissions engineer at SMT, said. "These transmissions can experience a wide range of environmental temperature, operational gradient and shock loading; these factors need to all be accounted for from concept through to detailed design phases."

Suffice to say, just simulating a gear pairing doesn't cut it. In order to understand and calculate all these parameters, you need software capable of simulating the full system: gearbox, shaft, bearing, and all. Otherwise, you risk missing something that could critically hamstring your component's life expectancy and/or performance out in the field.

"A component's performance is very sensitive to its misalignments and deflections," Sheridan said. "As components are optimized based on their deflections, calculating these incorrectly can significantly impact the durability and noise of each component."

There are already plenty of products on the market that answer this need, as well — SMT's MASTA software being just one of them. MASTA's software is capable of analyzing full system performance, including, just to name a few things: gear, shaft, and bearing static, fatigue ratings, system stiffness and misalignments, and power loss and efficiency, both for individual components and the full system. It's also capable of tracking dynamic responses, modal behavior, and sound power levels of multiple components.

Similarly, MESYS already has extensive solutions for full-system calculations, allowing users to get information



MASTA is one of several software suites capable of simulating an entire gearbox and its associated components. Photo courtesy of SMT.

about contact pressures in bearings, understand load distribution in gear pairs, calculate deflections and housing stiffness, and analyze an entire shaft and/or gearbox system as a whole.

And GWJ offers its System Manager, a piece of software that expands on top of their other software suites to simulate entire gearboxes, including shafts, bearings and gears. Using it allows manufacturers to simultaneously track both system and individual component calculations all at once.

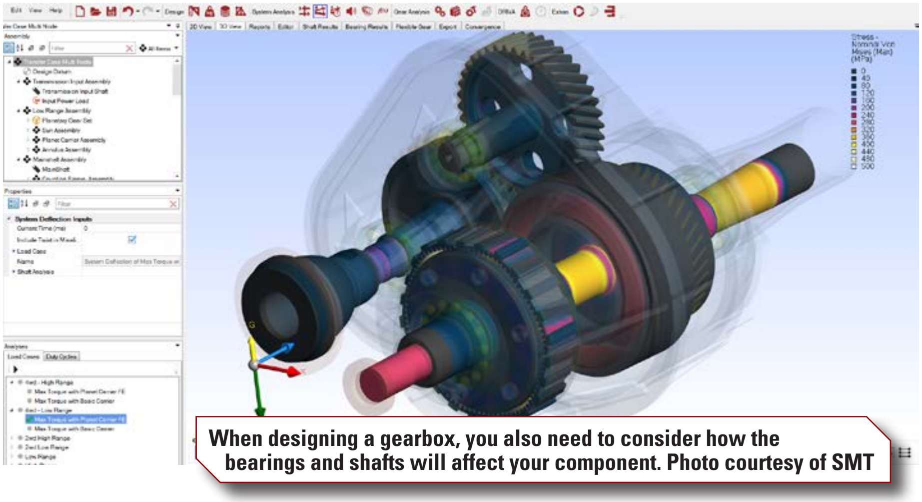
"This is an extension for both calculation software products," Gunther Weser, general manager of technical support at GWJ, said. "The System Manager is a true software application for complete systems of machine elements."

Many of these software suites are focused on speed and ease of use. Part of that is making it so that manufacturers can design components faster and more easily, but just as importantly, they're focused on reducing the computational time required on just a pure performance level, as well. It's all well and good to be able to simulate an entire system of interlocking components, but if it takes an entire day for a program to pump those calculations out, that significantly extends the development process. Cutting down on calculation time can reduce an iteration cycle from days to hours or just minutes.

"Focus for development of this system calculation was to develop an easy to use software that you can use to design very fast," Weser said.

"MASTA streamlines the modeling of transmission systems," Sheridan said. "At SMT we often see customers who, prior to learning about MASTA, are using complex FE modeling solutions which take a long time to run and are difficult to edit. MASTA removes a lot of these frustrations by allowing for analysis results to be calculated within seconds and [using] models that are easily configurable."

Sheridan also pointed to other ways a full system simulation can speed up development time outside of the software itself, as well as make the entire process more affordable, by taking on some of the responsibilities of physical testing.



When designing a gearbox, you also need to consider how the bearings and shafts will affect your component. Photo courtesy of SMT

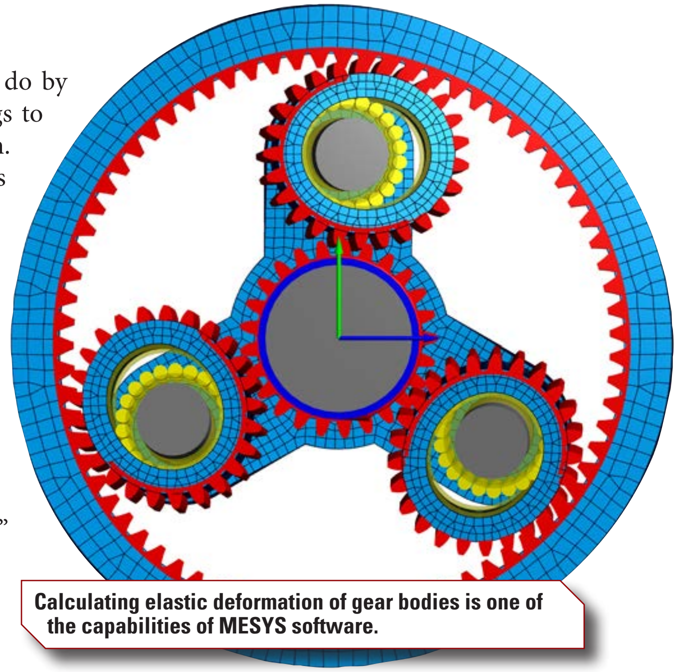
"Whilst it can seem like a large upfront investment to model a full transmission the benefit can be found later in the design and development process when the engineer has greater knowledge and confidence in their system performance," Sheridan said. "Developing a more robust model can reduce the need for expensive physical testing and last-minute development."

One of the most recent advances a lot of software suites have started adopting is in the field of simulating 3d elastic components. MESYS is just one example. But the most recent update to the program has expanded those capabilities further. The focus for this update was on expanding how well the software could simulate 3d elastic parts, namely creating finite element models for elastic bearing rings and gear bodies.

According to Raabe, this expansion has been a while coming. While elastic bearing calculations weren't directly requested as a feature, Raabe had come across customers curious about them, as well as elastic planetary gears. Up until recently, it was already possible to simulate an elastic bearing ring in MESYS, but it could only be done as a standalone calculation. This most recent update expands that functionality, which streamlines the amount of work one needs to do by allowing these bearings to be calculated in-system.

In particular, this new feature helps calculate potential deformations in a part.

"If you have [a non-cylindrical shape] gear body for whatever reason, it's difficult to take into account the deformations of the part," Raabe said. "Either you do a full finite element calculation or you just assume it's stiff enough and you don't have to consider that."



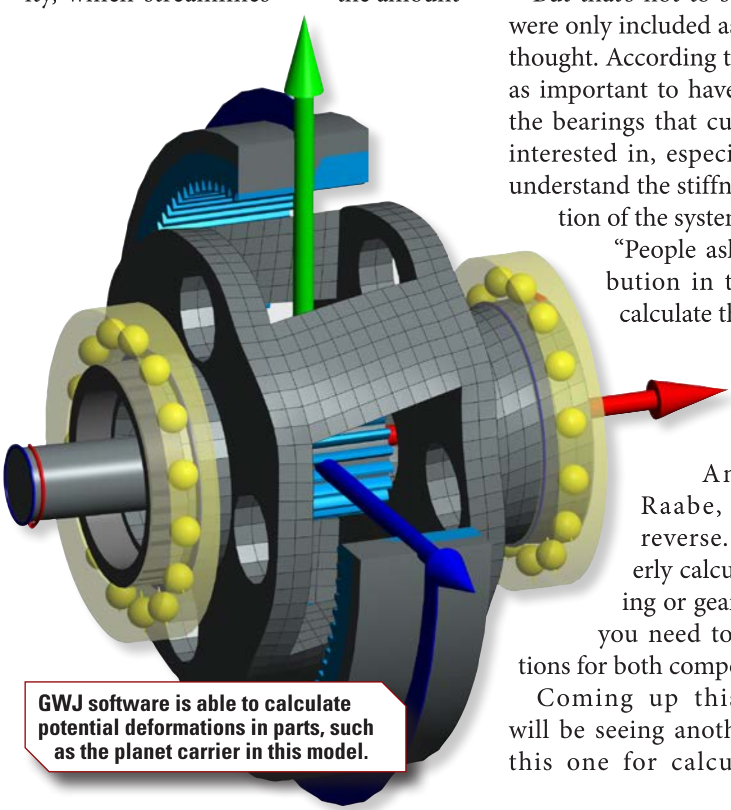
Calculating elastic deformation of gear bodies is one of the capabilities of MESYS software.

The focus for the update was foremost on the elastic bearings, as they were a topic that regularly came up in both the wind and automotive industries. Elastic gear bodies then also got included due to their similar shape, which allowed the software to calculate them similarly. Because both bearings and gears are cylindrical parts that deform, the same basic principles, and thus the same calculations, could apply to both.

But that's not to say that elastic gears were only included as a convenient afterthought. According to Raabe, they're just as important to have calculations for as the bearings that customers were more interested in, especially if you want to understand the stiffness or load distribution of the system.

"People ask about load distribution in the bearing, but to calculate that, you also need to consider the elastic gear in case of planetary gears," Raabe said.

And according to Raabe, it's also true in reverse. In order to properly calculate either the bearing or gear's load distribution, you need to know the calculations for both components.



GWJ software is able to calculate potential deformations in parts, such as the planet carrier in this model.

Coming up this month, MESYS will be seeing another update, as well, this one for calculating the effects of dynamic displacement, such as, for example, vibrations generated by transmission error. Once the update goes live, MESYS will be capable of calculating the dynamic forces placed on both gears and bearings by such vibrations, something that will be helpful for some high-speed applications. The only vibrations it won't cover are vibrations from the housing itself. According to Raabe, the software is capable of calculating vibrations from the housing, but doesn't offer outputs that "could be used easily."

Another company now offering accurate simulations for 3d elastic parts is GWJ Technology. In a February update for their System Manager software, they introduced calculations for 3d elastic and meshed parts. Much like with MESYS, gear bodies and bearings are the central focuses when introducing elastic component simulation, but GWJ's System Manager is also branching out to simulate a gearbox's housing. And here again with GWJ, one of the primary uses for the new simulations is planetary carriers.

Each of these three software suites have seen a positive reception out in the wild. It unsurprising, perhaps, since understanding the full system has become so centrally important to developing an individual component, but each software suite has individually received such a positive reception due to its ease and speed of use.

"Reception to MASTA has been overwhelmingly positive," Sheridan said. "Our customers really value the ease of use of the software. MASTA is quick to learn and we would normally expect an engineer to be creating and analyzing transmissions within their first day of use."

Additionally, Sheridan noted that SMT's consulting staff have been a boon to their customers, which of course means these support staff have also become a central selling point for their software.

"We believe this is an essential part of our business," Sheridan said. "Supporting our customers ensures they are satisfied with our software and engineering services as well as having the additional benefit of allowing SMT to stay abreast of new demands and developments in the field of transmissions."

Weser at GWJ echoed those sentiments with some anecdotal evidence of his own about an application their software was used for. The System Manager was utilized for designing a hoisting gear unit for a crane transporting metal liquids. And in order to properly simulate the entire system, GWJ's software sure had its work cut out for it.

"Comparing the work effort of [each individual component] and the calculation of the entire system, we had 38 calculation files in total generated…" Weser said. "That means we had 12 shaft files, 12 gear calculation files, and 14 calculations of rolling bearings. And all 38 calculations needed to be handled and updated accordingly."

It didn't end there, either, as they also had to track four different torques and two speeds. According to Weser, going through and making all those calculations one component at a time took almost two hours for a single load case. The System Manager calculated all of that in three minutes. And needless to say, the customer appreciated two whole hours of time savings per design iteration.

"The customer was very happy with this calculation because [the development went so quickly]," Weser said. "And on the other side, he had no idea how to calculate all these things with single calculations."

Ultimately, however, more than speed or ease of use, the greatest boon these software suites will provide you is knowledge. Knowledge that prevents breakdowns or malfunctions. Knowledge that will let you adjust designs ahead of time before they're proven faulty in physical testing, or worse, the field. Knowledge that speeds up the iterative design process. The system your component fits into informs so many of the parameters required for that component, and programs like these are how you understand it.

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Identifying Equipment Failure

How Machine Tool Maintenance Has Evolved in Recent Years in Gear Manufacturing

Matthew Jaster, Senior Editor

A quick jump into the virtual time machine (with assistance from the *Gear Technology Library*) will uncover dozens of articles on machine tools. It's actually a fairly entertaining experiment to see what was happening at IMTS in 1996 or Gear Expo in 2011.

23 years ago, machine tool manufacturers were combining tasks like hobbing, deburring and rolling into one unique system that needed a single operator. They were introducing Windows-based software for shaper cutters, broaches, end mills and hobs on a grinding machine. Eight years ago, employment was increasing, lead times were extremely long and the need to make higher quality gears was challenging due to a shortage of gear manufacturing capacity.

No matter the year or the technology in question, the gear industry is only as strong as its equipment and its operators. You can travel back to 1996 or 2011 or fast forward to 2025 and find that machine tool maintenance is vital to manufacturing gears, past, present and future. Lucky for us, it seems to be getting easier as the technology advances.

"Maintaining optimal productivity requires first class machines. This can be further optimized by an investment in operators and maintenance staff training as well as regular maintenance of the machine which shall be carried out by the manufacturer or by the customer's proficient technicians," said Loïc de Vathaire, head of service bevel gears, at Klingelnberg.

Billy Rodgers (a lead gear machine builder at Bourn and Koch) assembling a B&K 100H gear hobber.

Loyd Koch (left, one of the original founders of Bourn and Koch and still works there today) works with personnel on programing a Fellows 10-4 gear shaper.

For Jeff Moore, regional sales manager, Canada, at EMAG, it's all about knowledge. "With practical hands-on training our customers can get the most out of their equipment," he said.

"Foremost, a solid preventative maintenance (PM) program," Adam Gimpert, business manager at Helios Gear Products, said. "This typically begins with manufacturers familiarizing themselves with and following the prescribed PM directions from the machine tool builder or OEM. Additionally, if a manufacturer doesn't have dedicated maintenance personnel, it is wise to have the machine tool's factory-trained technicians perform a basic PM service on an annual or semi-annual basis. Finally, operators must be 'in tune' with their machine tool, which comes with time and experience. This will allow them to raise a red flag when they hear an odd noise, sense an unfamiliar vibration, or see abnormal machine movement."

Personalized productivity is also welcome in the case of Bourn and Koch.

"In order to assist our customers with maintaining the optimal productivity and efficiency of their Bourn & Koch machine tools, we offer personalized Preventative Maintenance Plans (PMP). Individually based on our customer's needs and expectations, our service technicians provide maintenance recommendations, training, and schedule wellness visits either quarterly, semi-annually, or annually," said Rob Swiss, national sales manager—gear machines, Bourn and Koch.

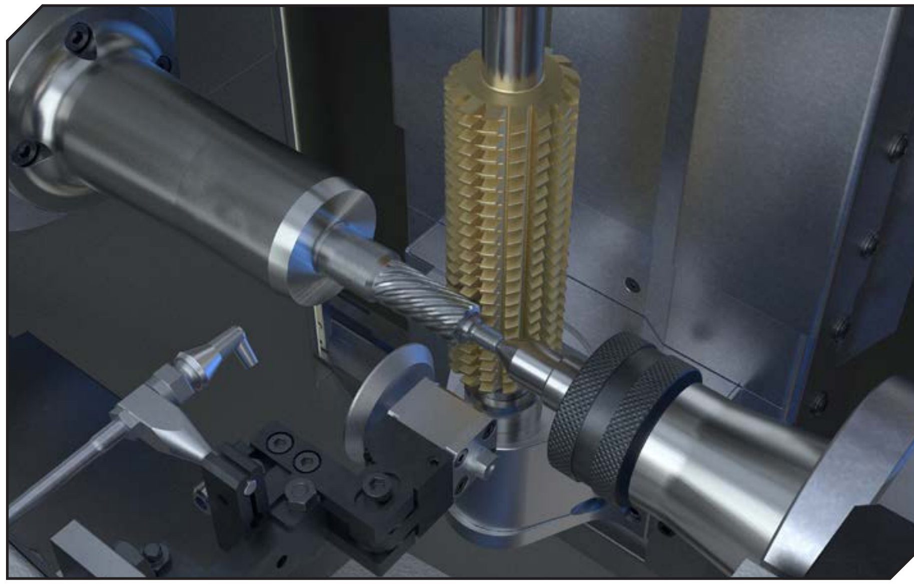
Today's Greatest Hits

To understand how the technology is improving we must first discuss a few of the leading causes of equipment failure in gear production today. Moore said that a lack of basic understanding of the machines can lead to a lack of preventative maintenance, poor basic operation and failure recovery procedures.

Gimpert believes lack of maintenance is number one by far. Chips build up, machines are not cleaned, filters are not replaced, oil turns dirty, wipers wear out, and much more. This lack of simple PM results in the outside world (in this case the shop environment) infiltrating the machine's most important internal construction.

"The consequences are drastic: low-tolerance, mission-critical and expensive components become damaged. These may include ball screws, ways, bearings, motors or linear rails. Often, these damaged parts cannot be fixed by in-house maintenance personnel which means expensive service visits from the machine tool's factory-trained technicians," Gimpert added.

"In our experience most failures result from the non-observance of the manufacturer's visual checks, cleaning and maintenance recommendations which



Hands-on training on EMAG machines is the best way to keep personnel up-to-date on maintenace features and functions.

is often combined with an over-utilization of the machine. Other causes include operators' mistakes due to a lack of training and the installation of lower quality spare parts vs. genuine approved parts," said de Vathaire.

Mechanically, if you properly maintain the oils and lubricants as well as pay mind to common wear components, a machine should hold up for a very long time, according to Chad Webster, sales engineer — gear machines, Bourn and Koch.

"Electrically, the biggest issues we have seen are the obsolescence of components, in older machines. Also, we have noticed that if the consistency & PH of water-based coolant is not maintained, it can breakdown seals and sometimes cause the paint to peel," Webster said.

Like anything else in manufacturing and engineering, success or failure starts with the components.

"We fully understand the challenges of maintenance departments within the gear industry i.e. scarce maintenance resources while production interruptions have serious consequences. Therefore we install the best-in-class components that are fit for purpose within a 24/7 production environment. In addition, we use modern remote maintenance tools and advanced diagnostics features in order to quickly troubleshoot issues and identify worn parts," said de Vathaire.

Gimpert discussed how the technology today helps machine tool maintenance. "Generally, modern machine tools are better engineered, which results in excellent fit and finish, and offers improved design features such as modern enclosures and containment of critical components from potentially damaging production environments," he said.

And IIoT/Industry 4.0 solutions continue to give gear manufacturing the upper hand in machine tool maintenance.

Klingelnberg's Training Center preps machine operators for the latest machine tool developments.

"EMAG machines are ready for the future with our Industry 4.0 Solutions and our ServicePlus app. These services allow our customers to have their machine tools networked with humans as controllers in the value added chain," Moore said.

One example of this is EMAG's Fingertip solution. Fingerprint will help EMAG customers increase machine availability and productivity whilst reducing costs. Prior to shipment of a machine, EMAG can perform a detailed Fingerprint analysis on each of the machine axes. This detailed Fingerprint diagnostic report gives a reference measurement (a baseline) on the condition of mechanical components, which can now be compared in the future to assess machine operation. "The best part is that no expensive dismantling or assembly work is required to perform the evaluation. Using the data provided by Fingerprint, you obtain an up-to-date machine status report," Moore added.

A second example would be the EMAG ServicePlus App (for Android and IOS) together with EMAG Remote Experts. This service can improve downtime with a timesaving's of up to 98%. With the ServicePlus App you can scan the QR Code located on the machine and get connected with EMAG Service at any time, regardless of the location — mobile support always within reach. "Additionally, with Remote Experts our customers are on the fast track to customer help with access to EMAG's entire expertise at the push of a button. With a secure EMAG VPN on-line connection and 24/7 telephone support customers can get help with any machine issues or spares parts needs," Moore said.

The Art of Training Personnel

Klingelnberg currently use multiple channels in order to keep customers informed. This is vital to machine operation.

"We definitely recommend our *Gears Inline* magazine since it includes excellent papers from industry experts. Our applications engineers and service technicians use every opportunity from formal training classes to service calls in order to convey our new developments and how they are adding value for our customers. Last but not least we run Gear Seminars on a worldwide basis. These two-day events are a unique platform for customers to learn about current technologies, trends and innovations from Klingelnberg experts," said de Vathaire.

EMAG hosts open houses at its corporate headquarters in Salach, Germany introducing its latest technology innovations.

"We also host local Technology Days at EMAG LLC in Farmington Hills, MI every other year during even years. During the Technology Shows, we have presentations from our EMAG technology experts, as well as, industry experts," Moore said.

Gimpert said that job shop customers tend to place maintenance low on a scale of importance and do not take advantage of this type of learning. On the other hand, the availability of such content is limited. Nevertheless, preventative maintenance (PM) of machine tools does not require highly skilled personnel.

"The challenge is implementing a system where such PMs are performed accurately and with adequate frequency. For job shops without dedicated maintenance personnel, a simpler solution is often to allow the OEM to perform the PMs, so the shop's team can focus on manufacturing gears," he added.

Swiss at Bourn and Koch continued the discussion on personalized preventative maintenance.

"These tools can be very helpful to customers, keeping them up-to-date with their routine maintenance. We always include training at the time of machine run-off and offer additional training during installation of their machine. However, we believe it is more effective to customize each training program and

PMP based on the individual customer, rather than create a generalized webinar."

Additional Tools in the Toolbox

What else is available for job shops to optimize their gear equipment and keep personnel up-to-date on the latest technology available in the industry?

"There are many courses available from major control manufactures that can help customers maintain their CNC system and operate their machinery more effectively. Also, by joining AGMA you will stay up-to-date on anything involving gear manufacturing and new technology. We constantly update our website and our machine sales team is always available to answer any questions or concerns," said Webster.

Gimpert said it is important to communicate with their machine tool supplier and get to know their service team.

"This can be an invaluable resource to ensuring they get the most out of their gear equipment. Secondly, trade shows such as the upcoming AGMA MPT Expo offer a one-stop source to see the latest in equipment, learn modern methods of maintenance, and compare different supplier solutions." he added.

Moore said that utilizing the latest media resources available to every company is another great way to keep personnel informed and current on machining technologies.

"We have an EMAG YouTube Channel where we often post new videos. We also do postings on LinkedIn making our customers aware of EMAG product releases and new technology news as well as classes through our EMAG Academy. These courses can be taken to keep your team up to date on the latest technologies and how to use them," Moore said.

Klingelnberg is currently testing the usefulness of augmented reality (AR) glasses, basically the integration of digital information in real time as opposed to an artificial virtual reality.

"We support a significant number of machines and the required expert may not always be able to immediately travel to inspect the machine. However, with smart glasses we can virtually put him in front of the machine so that he can immediately understand the issue and share his knowledge," said de Vathaire.

Smarter Resources, Clever Machines

We've discussed the benefits of remote access programming for machine tools for many years in the pages of this magazine. Today, it is becoming the norm to use these tools for preventative maintenance. This resource is also less expensive—which is a great way for smaller companies to keep up with the technology.

"Remote access programming is readily available technology and extremely useful to smaller shops. The remote access allows the machine tool builder to log into the machine offsite, via the Internet, to diagnose any particular issue the customer may be experiencing. This technology is fairly inexpensive and allows for a quick solution," Swiss said.

Moore said that large and even medium to small customers can take advantage of EMAG's Industry 4.0 solutions. In fact, the smaller shops with less service staff and limited budgets would benefit the most. With the ServicePlus app and Remote Experts it's like having a service expert on call available 24/7 days a week. For those times when service technician is needed, EMAG has multiple personnel stationed in key markets.

Philipp Becher, product management and sales gear tooling, at Klingelnberg GmbH said that the digital twin can be used for maintenance optimization of production equipment as well. It allows visualizing condition and status of every integrated component. During production the machines interlinking the count of produced parts with the used production equipment on the machine. Also incidents like crashes or comments noted by the machine operator are documented an assigned to the production equipment on the machine. This information gives a pretty clear view on the current condition and allows optimizing the reconditioning and replacement of customer's production equipment. (*Editor's Note: He discusses this in length in the May 2019 issue of* Gear Technology *magazine.*)

While some of the latest innovations are coming down in price, Gimpert said that many analytics are still prohibitively expensive to implement for smaller shops.

"An industry-leading cloud IoT (Internet of Things) platform costs tens of thousands to utilize *on an annual basis*. Additionally, a manufacturer needs to develop or purchase software integration. And the last barrier is that a pre-internet machine tool likely has no way to offer IoT connectivity," Gimpert said. "Until the economics of these solutions 'trickle down' to smaller shops, we see a more immediate solution in "clever" machines (maybe not fully smart). These

The Bourn and Koch gear team standing by a Fellows HS1280 gear shaper.

machines offer self-diagnostics and self-monitoring solutions that are not powered by the Internet, the cloud, or big data, but offer powerful maintenance guidance and assistance."

Everyone will be connected to the virtual world in the future, added Moore at EMAG. "With real-time machine production data that includes machine downtime, OEE%, production numbers per-shift. per-machine that are available on your desktop computer, tablet or phone," he said.

"We believe that automated solutions will be on the rise. Innovations like smart sensors, big data analytics and fast communications will enable machine tool users to identify issues before it is too late and to schedule maintenance tasks as required," said de Vathaire. "Down the road, machines will proactively seek assistance when they sense that their condition has been deteriorating."

Machine technology will one day be fully-connected to the Internet, according to Gimpert.

"Machine tools in the future will be fully connected to the Internet, which will allow them to feed data to suppliers of predictive and real-time analytics. This will all be performed securely and seamlessly," Gimpert said. "But that's the future, and we feel *that time* is many years away before becoming the norm."

"In 2019, we see shops still reluctantly rolling out Internet access points in production environments, but this is a critical first step. Suppliers of data analytics still grapple with selling security; the technology is there, but it is uphill work of making manufacturers comfortable with the solutions. And 2019 will still be a year of new smart solutions, so manufacturers will continue to vet what's new, what's existing, and what's proven. In the meantime, existing maintenance programs will likely continue without significant change," he added.

But change *is* coming, and planning now will benefit your components in the future.

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Fine Grinding on Klingelnberg Bevel Gear Grinding Machines

Dr. Rolf Schalaster, head of Klingelnberg's Competence Center for Bevel Gears

One way to implement the growing performance requirements for transmissions is by optimizing the surface finish of the gearing. In addition to increasing the flank load capacity and the transmittable torque, this also allows for improvements in efficiency. On Oerlikon bevel gear grinding machines from Klingelnberg, fine grinding can be implemented efficiently in bevel gear production—even in an industrial serial process.

High efficiency and power density are basic requirements for a transmission. Particularly in highly dynamic applications in vehicle transmissions, however, the permissible dimensions, weights and inertia torques for the moving parts are strictly limited. Parameters such as material, heat treatment, inherent stress and surface finish are therefore considered with a view to increasing the permissible stress of a gear set. Specifically the last aspect—surface finish—is the focus of attention at Klingelnberg. In the area of aviation components, surface requirements for ground bevel gearings of $Ra < 0.3\,\mu m$, $Rz < 1.5\,\mu m$ or finer are standard. The experience and competence the company has acquired in the area of aviation applications form the basis for implementing fine grinding of bevel gears on Klingelnberg bevel gear grinding machines—and thus also for a technology that can be applied in an industrial series setting.

Stress and Permissible Stress of Gearings

When considering the fatigue life of gearings, the focus is always on the comparison of stress and permissible stress. Stress arises from the external load conditions, the gear macrogeometry, and the tribological system of the tooth contact, which is also influenced by the surface quality of the tooth flanks. The permissible stress of the gearing, in turn, is defined by the material, its heat treatment and inherent stress condition, as well as the macro- and microgeometry.

If the stress on the gearing exceeds the permissible stress, the required fatigue life is not achieved. If the options for adapting macrogeometric variables such as gear geometry, curvature radii and flank topography aimed at reducing stress and increasing permissible stress have been exhausted, the only remaining option is to increase the permissible stress through material or surface effects.

Increased Load Capacity Through Finer Surfaces

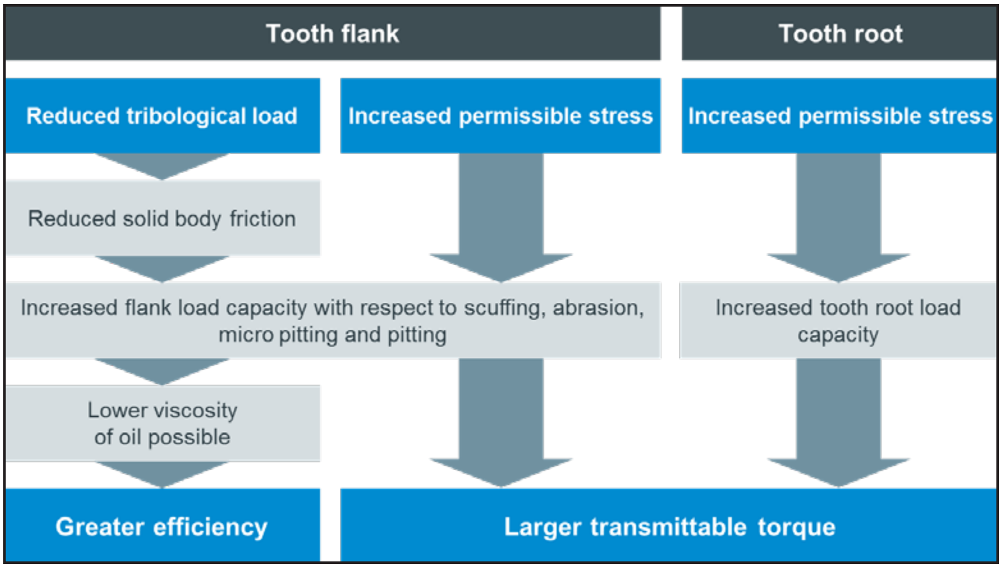
In principle, the permissible stress of mechanical components can also be improved by improving the quality of the surface finish. This is true for mechanical stress, such as bending fatigue under fluctuating load, as well as for breakdown and abrasion in tribocontact.

With respect to gearings, a higher quality of the surface finish of the tooth flank means a decrease in the tribological load due to reduced friction (Fig. 1). It also means increased permissible stress due to a reduced notch effect; moreover, an increased micropitting capacity is expected. All of this together leads to an increased load capacity of the tooth flank. A tooth root with a higher-quality surface finish also demonstrates a greater permissible stress due to the reduced notch effect. This also increases the tooth root strength. The potential gained can be used for a larger transmissible torque. If an increase in flank load capacity is not required, this can also be converted to greater efficiency through the use of a lower-viscosity lubricating oil.

Superfine Surfaces in Cylindrical Gear Transmissions

Studies of the influence of surface finish on flank load capacity have already been conducted for cylindrical gear transmissions. Ground surfaces were improved through trowalizing from $Ra = 0.30\,\mu m$ to $Ra = 0.11\,\mu m$ and $Ra = 0.07\,\mu m$, respectively. In this way, the continuously transmittable torque was improved by 20% and 40%, respectively.[1] With one variant, which underwent

Klingelnberg Oerlikon G 30 Bevel Gear Grinding Machine.



Advantages of higher-quality surface finish in gearings.

shot peening followed by trowalizing ($Ra = 0.07$ µm), an increase in torque of 70% was achieved.[2] Moreover, tests on large gearings have shown that micropitting below a roughness of $Ra = 0.3$ µm is avoided altogether.[3] By trowalizing cylindrical gearings, roughness parameters of less than $Ra = 0.06$ µm can be achieved.[4]

With conventional gear grinding processes, roughness values of approximately $Ra = 0.3$ µm are achieved. Through fine grinding processes, surfaces up to approximately $Ra = 0.2$ µm can be realized. To achieve finer surfaces, additional grinding wheels with an elastic bonding system can also be installed on the tool spindle of the grinding machine. Conventional gear grinding is then followed by polish-grinding, with very little stock removal. Roughness values of approximately $Ra = 0.1$ µm are possible in this case. Polish-grinding performed as part of a research project even achieved values of up to $Ra = 0.05$ µm ($Rz = 0.25$ µm).[5,6]

Special Case: Bevel Gear Transmissions

A characteristic feature of cylindrical gear transmissions is that at the generating circle only rolling occurs without any sliding. In the direction towards tooth tip and root, the sliding velocity increases such that — depending on the rotation speed — mixed friction always occurs in one section of the tooth flank. By contrast, hypoid gears (bevel gear transmissions with an axis offset) show a sliding velocity at every point on the tooth flank during operation — at least in the face width direction. For this reason the lubrication condition in tooth flank contact is more favorable, but the efficiency is lower in principle.

In terms of production, bevel gearings also differ fundamentally from cylindrical gearings. Ground bevel gears typically have a curved longitudinal tooth line; as a matter of principle, cup grinding wheels are used to manufacture them. Due to their low form stability, elastic-bonded tools are unsuitable for this purpose.

Fine Grinding of Bevel Gear Transmissions — a Challenge

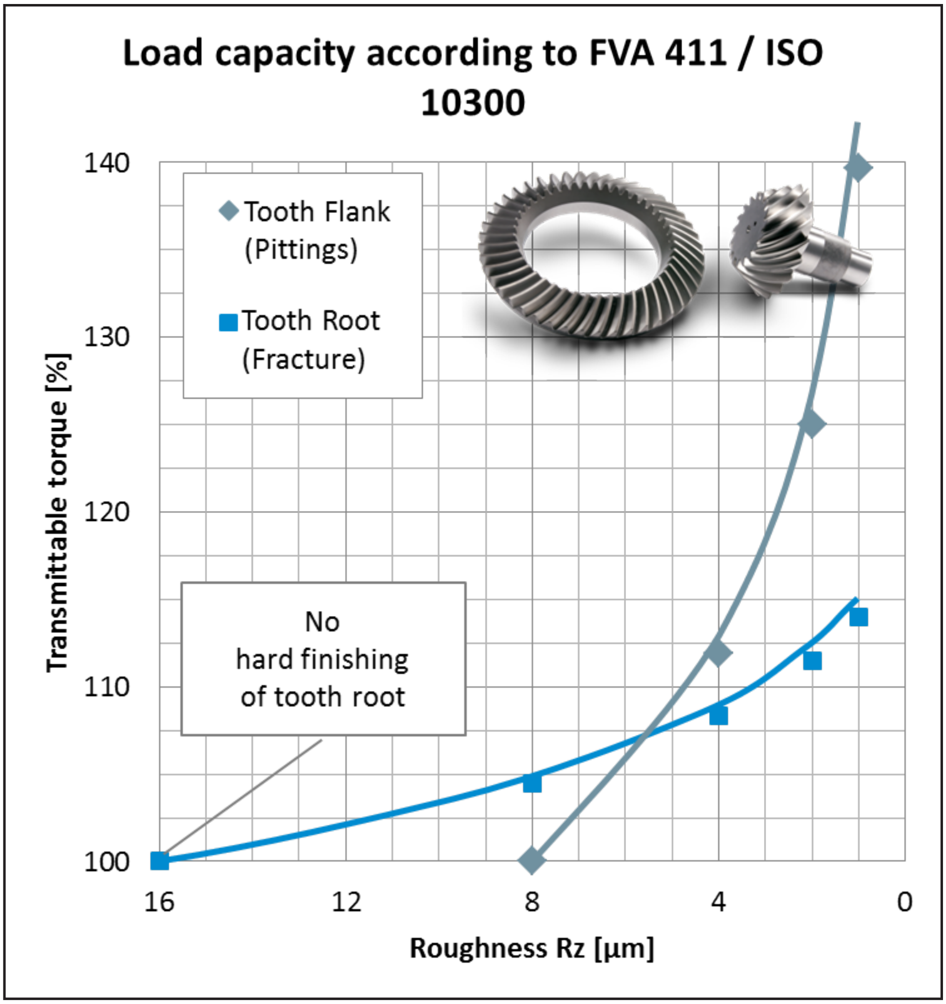
Klingelnberg's strategy is based on the use of a grinding tool that allows both a high-quality surface finish and a satisfactory machining performance. The particular charm of this solution is that fine grinding in this manner can be implemented in existing manufacturing sequences with minimal intervention.

With the appropriate dressing tools, modern grinding tools can be conditioned for a broad range of applications. In the first instance the grinding wheel is dressed in order to reach a very abrasive surface that is capable to remove the bulk of the grinding allowance effectively. Prior to the final grinding, the dressing parameters are chosen such that the desired surface finish can be reliably achieved with the appropriate process control. With the bevel gear grinding machines of the Oerlikon G 30-type designed for machining automotive gears and the G 60-type for the truck applications, machines meeting all these requirements are available on the market. The rigid construction of the machines in the vertical concept and the high precision provide optimal conditions for implementing the fine grinding process. An allowance control unit monitors the geometry of the series components without disrupting the production process to rule out thermal joint damage due to variations in the grinding allowance. Routine automatic inspection of the stock removal ensures the desired distribution of the allowance between the two tooth flanks during the course of the series.

Fine Grinding on Klingelnberg Bevel Gear Grinding Machines Enables Improved Performance of Bevel Gear Sets

Experiments conducted on an Oerlikon G 30 bevel gear grinding machine (Fig. 2) show that with ceramic-bonded grinding wheels used to grind typical automotive bevel pinions, surface parameters of approximately $Ra = 0.11$ µm and $Rz = 0.75$ µm can be achieved. For comparison: Typical requirements for the tooth flank surface of ground automotive hypoid gears today are in the range of $Ra = 0.8$ µm to 1.6 µm or $Rz = 4$ µm to 10 µm. Thus the conducted experiments make it clear that when grinding bevel gears in serial applications on Klingelnberg machines, there is significant potential available for increasing the quality of the surface finish. According to the standard calculation, the flank load capacity of the gearing can be increased through the improved quality of the surface finish by at least 25% to 40%, compared with the series standard (Fig. 3).

The permissible load on the tooth root can still be increased by approximately 15% starting from an unground surface. An improvement in the surface finish thus evidently has the potential to optimize the performance of bevel gear sets. With the Oerlikon bevel gear grinding machines from Klingelnberg, this load bearing potential for the bevel gear can be efficiently utilized in series production.



Influence of surface finish on standard load carrying capacity of an automotive hypoid gear set.

References

1. Steigerung der Zahnflankentragfähigkeit durch Kombination von Strahlbehandlung und Finishingprozess. [Increasing flank load capacity through a combination of shot peening and a finishing process.] Abschlussbericht zum Forschungsvorhaben Nr. 521 I der FVA, 2010 [Final report for FVA research project no. 521 I, 2010].
2. Tragfähigkeit gestrahlter und gleitgeschliffener Zahnflanken unter besonderer Berücksichtigung der Randzonen- und des Schmierfilmzustands. [Load capacity of shot- peened and fine ground tooth flanks with particular consideration to the peripheral area and lubrication film condition.] Sachstandsbericht zum Forschungsvorhaben Nr. 521 II der FVA, 2017 [Progress report on FVA research project no. 521 II, 2017].
3. Graufleckentragfähigkeit von Großgetrieben III. [Micropitting capacity of large transmissions III.] Abschlussbericht zum Forschungsvorhaben Nr. 286 III der FVA, 2010 [Final report for FVA research project no. 286 III, 2010].
4. Krantz, T. L. The Influence of Roughness on Gear Surface Fatigue U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio, 2005.
5. Profilschleifen von Verzahnungen mit höchsten Oberflächenqualitäten. [Profile grinding of gearings with ultra-high-quality surface finish.] Zwischenbericht zum Forschungsvorhaben Nr. 654 der FVA. [Interim report on FVA research project no. 654.] In: Forschungsreport 2012 der FVA, 2012 [FVA 2012 research report, 2012].
6. Diskontinuierliches Zahnflankenprofilschleifen zur Erreichung höchster Oberflächengüten und Verzahnungsqualitäten — Superfinishing II. [Discontinuous tooth flank grinding for achieving ultra-high-quality surface finish and gearing quality — superfinishing II.] Zwischenbericht zum Forschungsvorhaben Nr. 654 II der FVA. [Interim report on FVA research project no. 654 II.] In: Forschungsreport 2016 der FVA, 2016 [FVA 2016 research report, 2016].

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Method for High Accuracy Cutting Blade Inspection

Haris Ligata and Hermann J. Stadtfeld

Introduction

Inspection of the cutting blades is an important step in the bevel gear manufacture. The proper blade geometry ensures that the desired gear tooth form can be achieved. The accuracy of the process can be compromised when the blade profile consists of several small sections such as protuberance, main profile, top relief and edge radius. Another common obstacle — are outliers which can be caused by dust particles, surface roughness and also floor vibrations during the data acquisition. This paper proposes the methods to improve the robustness of the inspection process in such cases.

Figure 1 Face cutter head (Face Milling) with stick blades (Ref. 2).

The authors propose a procedure for using larger (combined) portions of the blades to evaluate the properties of the small features. This method was inspired by the standard AGMA/ANSI ISO 1328-1-B14 for the evaluation of tooth profiles on cylindrical gears. An example of the application could be the assessment of the pressure angle and blade distance in case when the blades have large toprem and flankrem sections (short cutting/ clearance edge portion).

In cases where the measured data contains outliers, the filtering is proposed using the random sample consensus (RANSAC) procedure. The authors show the effectiveness of the procedure using the actual measurement data.

Finally, the proposed methods were

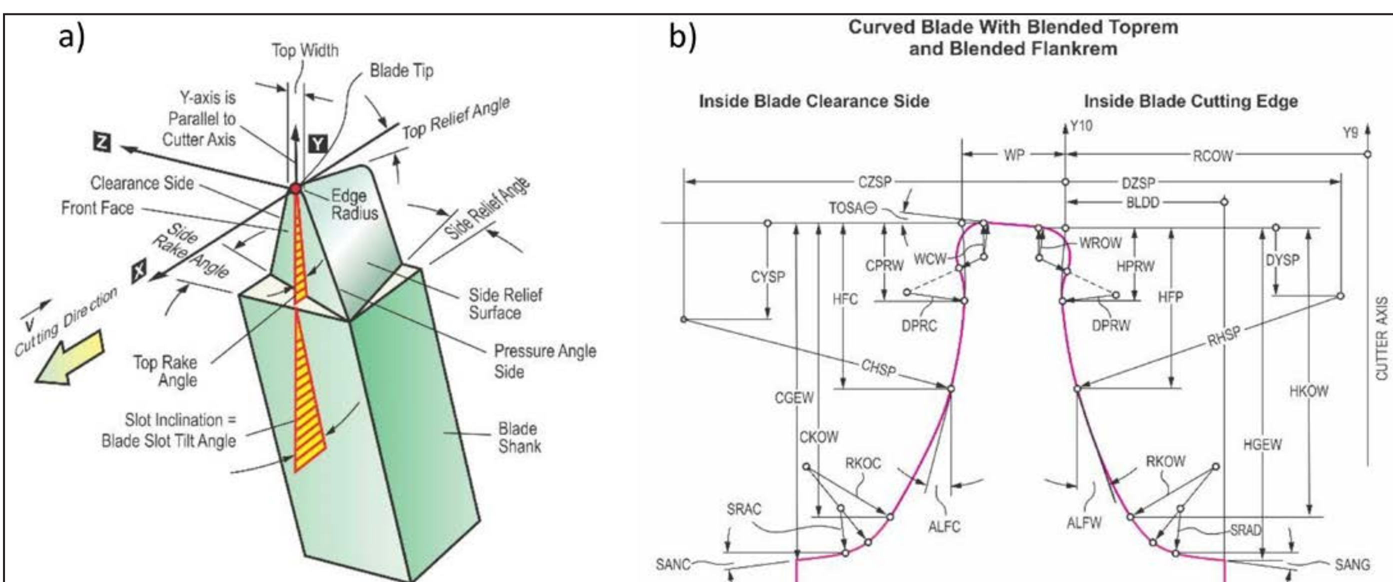

Figure 2 Stick blade geometry (Ref. 3); (a) three-face stick blade, (b) blade geometry definition.

implemented on a blade inspection machine, and the improved accuracy and robustness demonstrated using several examples.

Accuracy of the bevel gear tooth form depends on the accuracy of the cutting blades. The cutting blades are sticks which are positioned in a face cutter head as shown (Fig. 1) (Ref. 2). The accuracy of the blades is usually verified by analyzing and comparing the measurements from the specialized coordinate measurement machines to the nominal (theoretical) coordinates created by the blade definition program. Detailed inspection of a typical stick blade is a demanding task due to the rather complex geometry shown (Fig. 2) (Ref. 3). Accurate analysis of the measured (actual) data can be a challenging task when the data contains short sections, or when it is compromised by the conditions in the inspection environment.

The authors in this work propose the procedure which can be helpful in evaluation of the measurements containing outliers and for the treatment of the short blades with the small number of measured points.

Overview of the Stick Blade Measurement Procedure and Its Challenges

A bevel gear geometry is defined through the basic settings and the "tooth forming contour" (Refs. 4–5) of the stick blade. The contour is defined by projection of the actual blade, placed in its cutting position, onto the cutting plane, as shown (Fig. 3) (Ref. 6). The same figure also shows the minimum number of points (five) needed for the blade evaluation. The blade consists of three major parts (as shown Fig. 2a): pressure angle side, clearance side and blade tip. The pressure angle side consists of (Fig. 2b):

a) ***edge radius***: portion of the blade which together with the blade tip, cuts the root and fillet portions of the gear (part of circle with WROW radius)
b) ***toprem***: part which creates the relief (transition) between the fillet and flank (part from edge radius to HPRW)
c) ***main cutting edge***: the largest part of the blade which creates the main portion of the gear flank (from HPRW to HKOW)
d) ***flankrem:*** part which creates relief between flank and the gear tip (from HKOW to shoulder radius start)
e) ***shoulder radius:*** transition portion between main cutting edge/flankrem and shoulder (part of circle with SRAD radius)
f) ***shoulder:*** transition from the stick geometry to the ground blade portion (part from shoulder radius to HGEW)

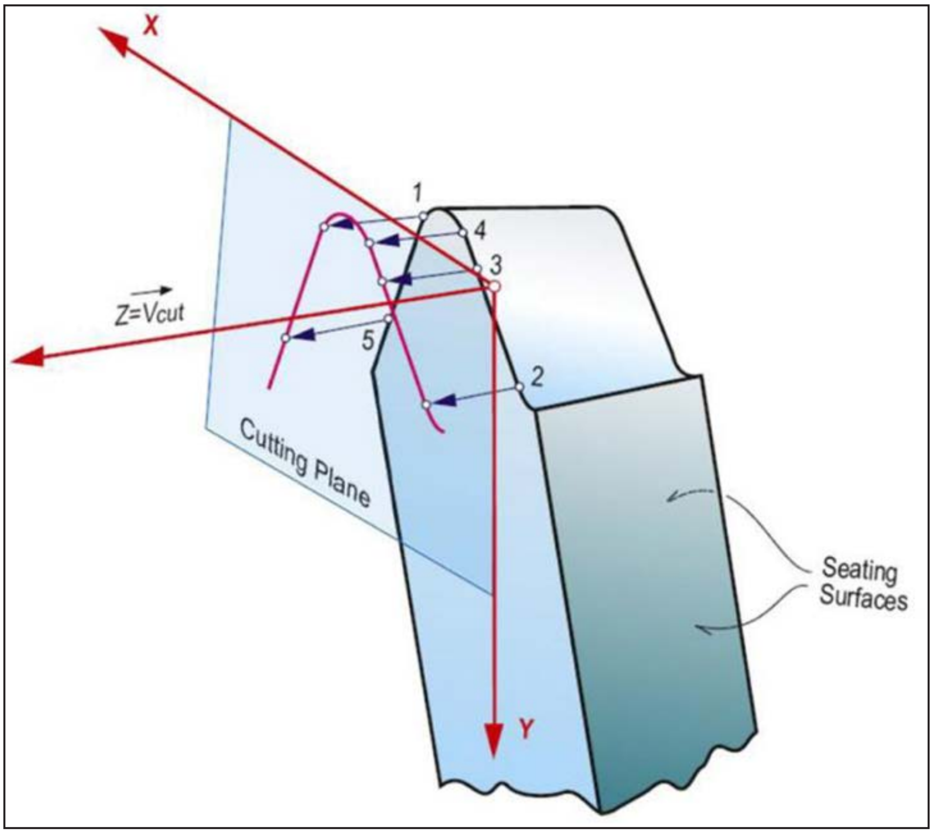

Figure 3 Projection of blade profile onto the cutting plane (Ref. 6).

The sections, as defined in the cutting plane, can have either circular or straight line geometry. Exceptions are the edge radius and the shoulder radius, which are always circular.

Traditionally, blade inspection was performed using manually operated machines and comparison checkers. Today, it is usually performed using a three-dimensional coordinate measurement machine. Lately, the laser curtain principle (Ref. 6) was utilized, together with the automatic clamping and loading to minimize the effects of the probe size and reduce the influence of the operator on the measurement results.

Blade inspection process can be summarized in several steps:

1. Nominal (theoretical) coordinates and normals of the blade profile points are created and provided to the machine prior to the inspection.
2. Cutting blade is positioned in the machine which performs measurement and returns the actual coordinates.
3. The results (actual coordinates) are compared to the nominal coordinates and the necessary corrections are reported to the user.

The corrections include necessary adjustments to the form (radii of curvature and inclination angles) and position (blade distance and the starting positions of the features). Recently, a closed loop system was developed where the corrections are shared automatically with the specialized blade grinding machine and implemented in the regrinding of the blades to their proper geometry.

The described inspection procedure seems to be straightforward. However, there are several sources of the errors embedded in the procedure itself. They need to be addressed in order to ensure that the inspection results accurately represent the geometry of the inspected blade. The inspection errors can be divided in three main groups, based on the source:

– ***errors due to the operator***, which mainly include the variation in the blade handling (placement);
– ***errors due to the environment***, caused by the placement of the machine in the production environment where the

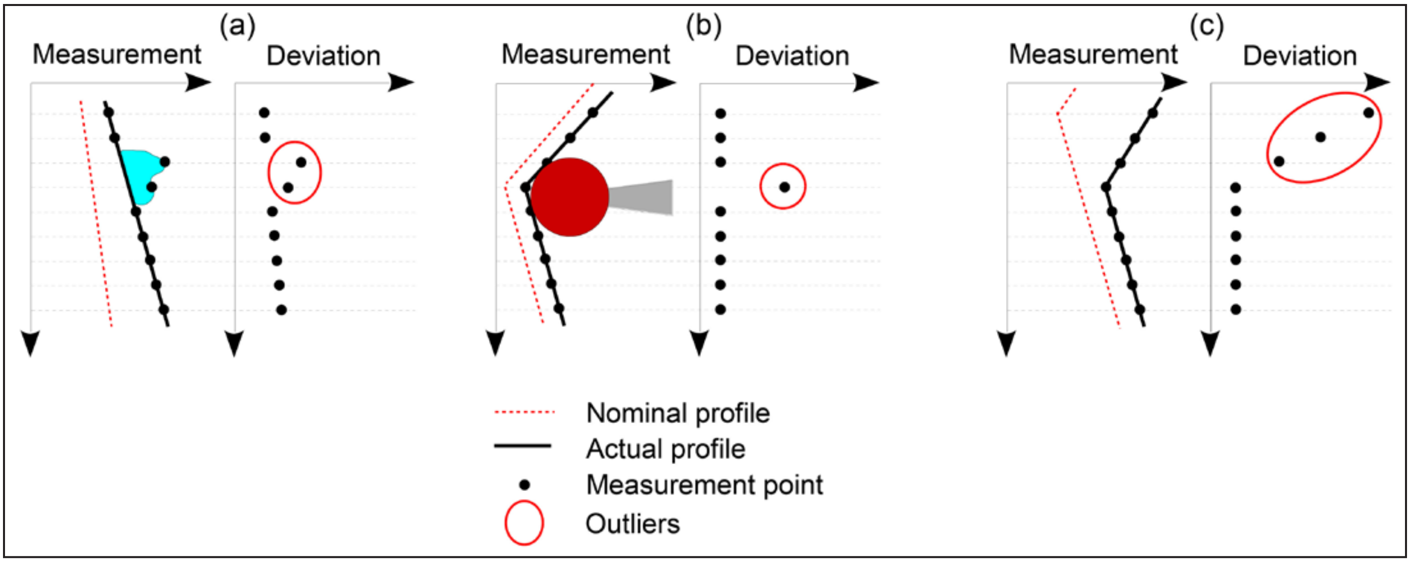

Figure 4 **Common sources of the large date deviation (outliers); (a) dust particles, (b) inadequate probe size and (c) position error of neighboring sections.**

machine vibration can distort the measurements, or where dust and oil can contaminate the blade surfaces;
– ***errors due to the inspection machine capability***, caused by the probe size and resolution limits of the inspection equipment.

The first source of the errors can easily be detected and rectified as it leads to the obvious deviation from the blade geometry. The latter two errors lead to the erroneous data (outliers) which can usually be detected only by carefully reviewing the measurement results. They often lead to the misinterpretation of the blade geometry and faulty geometry corrections, at the end resulting in the wrong blade geometry which will have to be reground. The detection and removal of the outliers is one of the main tasks of this work.

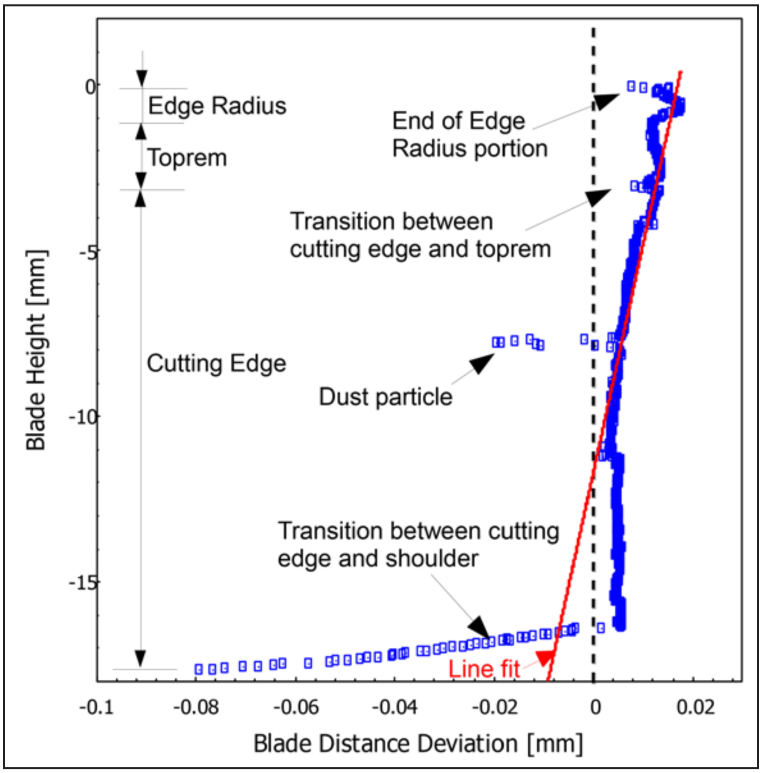

Figure 5 **Example of the deviation of the actual from the nominal data for the blade the common outliers.**

Treatment of the Outliers

Inconsistent data can be detected as the deviation from the expected (nominal) form. Unlike the actual blade geometry error which varies gradually, the outlier deviation tends to vary rapidly and be localized. Figure 4 illustrates some common sources of the outliers. The difference between nominal and actual (measured) profile is usually not larger than 10–20 micrometers and small dust particles, chips left after cutting, or lint from the cloth used for blade cleaning can create large discrepancy in the measurement data, Figure 4a. Another common example would be the inability of the probe to access the actual points due to its size, providing the erroneous measurements, as shown (Fig. 4b.) Such a problem is often encountered between two adjacent sections of a blade. Finally, neighboring sections could have position error in the vertical (axial) direction which can be recorded as a large deviation (Fig. 4c). While this measurement accurately captures the blade geometry, it can still lead to the inaccurate interpretation of the evaluated blade portion geometry. Namely, the inclination angle and the horizontal position of a section are usually calculated using regression analysis, which considers all points measured over the nominal range for that particular section. Using the results from Figure 4c could lead to the conclusion that the sections have inclination and position error — which is *not* correct. Common practice in the past was to reject certain portions of the end points to avoid the situations described in Figures 4b and 4c.

A typical blade used in the automotive industry is considered as the first example (Example #1). The blade has axial (total) grind depth of 19 mm and its tooth forming contour consists of edge radius, toprem and cutting edge. Figure 5 shows the deviation of the measurement from the nominal data. The expected deviation would be a smooth line (either straight line or a curve). The position of the outliers can be clearly seen, particularly at the transition between the cutting edge and the shoulder section. The figure also shows the line fit (red line) to the deviation data, when all points (including outliers) are used in the fitting procedure. It should be apparent that the line fit does not accurately describe the inclination of the actual sections. In this particular case, using all data in the calculation of the necessary corrections would lead to the incorrect results. The outliers need to be removed in order to obtain more accurate results.

A simplified application of the Random Sample Consensus (RANSAC) (Ref. 7) algorithm is used by the authors to detect and remove the outliers from the measurement data. It is an iterative algorithm which finds and removes the outliers based on their departure from the behavior of the majority of the points. The expected behavior, or shape (e.g. straight line or circle) must be known in advance, and it would be represented by a parametric model. In the case of the blade geometry, the models are the (parametrized) equations of line, or circle, depending on the shape of the blade section. The algorithm starts by creating random set of two (for line) or three (for circle) inspection points and finding the parameters for the equation. It calculates the distance of all other inspection points to the line or circle and compares it to the predefined allowed margin. The points which are outside the given margin from such a line or circle are designated as potential outliers, i.e.—the outliers for that particular case. The procedure is repeated for a number of iterations (point sets), with the aim of finding the equation of the line, or circle which describes the behavior of the largest number of inspection points (the smallest number of outliers). Once the equation is determined, the outliers from such a case are removed from the data set. While the total number of the possible inspection point combinations can be prohibitively large, good results can be obtained using a relatively small number of non-repeating combinations (e.g. up to the total number of points).

RANSAC analysis is applied separately to each section of the blade profile, using the shape (line or circle) of the section and the margin (distance) of the allowed deviation from the fit. In the particular example shown in Figure 5, three sections were analyzed:

- cutting edge, with the circular profile
- toprem, with the straight profile
- edge radius, with the circular profile

The allowed margin of deviation from the fit was set to 0.001 mm for all sections. The result of the analysis is shown in Figure 6. Comparison to the original deviations (Figure 5) clearly shows that the outliers were removed. The numbers of the removed outliers for each section are:

- cutting edge: 99 outliers removed from 488 starting points
- toprem: 6 outliers removed from 67 starting points
- edge radius: 8 outliers removed from 33 starting points

As mentioned above, the analysis also provides parameters of the fitted model (equation of line or circle), which describe the position and shape of the measured sections. It should be noted that the RANSAC algorithm uses sets of the data points, forcing the fitted equation to pass through these chosen sets of points. Because of that constraint, the RANSAC analysis does not provide the best-fit line which generally does not have to pass through any of the points. Accurate fit, appropriate for the calculation of the corrections, can be obtained by using the filtered (outlier free) data in a specialized procedures. In case of the example shown in Figures 5 and 6, the radius of curvature of the cutting edge was determined by RANSAC and Taubin fit (Ref. 8) as 869.554 mm and 870.113 mm, respectively. The radius of curvature of the Edge Radius was calculated as 1.824 mm (RANSAC) and 1.838 mm (Taubin fit).

Usual spacing of the blade inspection points varies between 30 and 100 μm in a typical automotive application. However, the spacing step can be increased for the large blades. The number of outliers under normal circumstances should not exceed 25% of the total number of

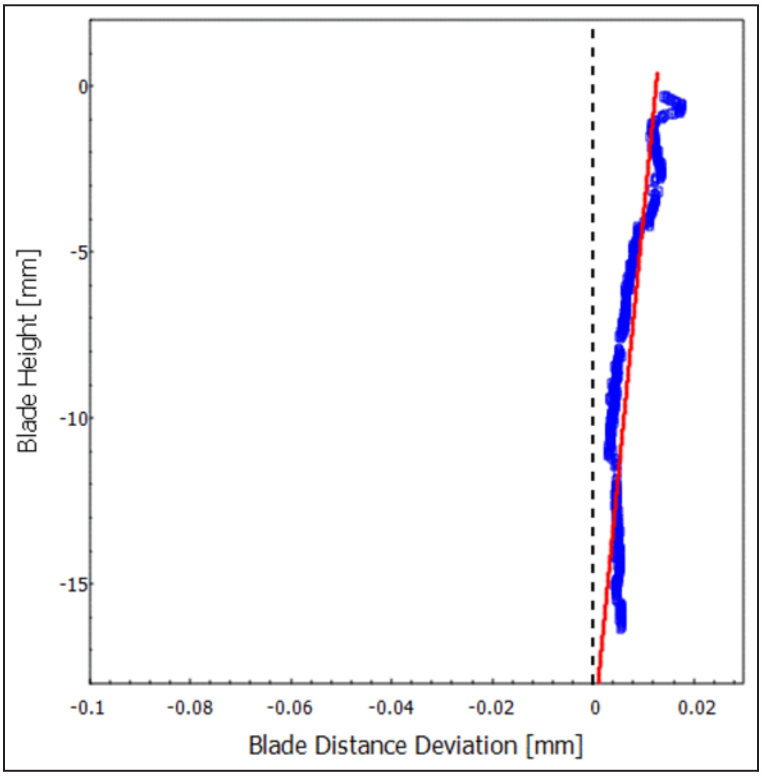

Figure 6 Data deviation after removal of the outliers.

points in each section. Large number of outliers could also point to the problems with the blade definition. As an example, the inspection of a blade with the curved main cutting edge, with the inspection settings for the straight cutting edge would result in a large number of outliers. The value for the filtering margin used in the analyses could be determined from the angular tolerance and the length of the analyzed section. In the above example, shown in Figure 5, the length of the cutting edge section is equal to approximately 15 mm. The pressure angle tolerance for the application (typical automotive industry blade) is equal to ±2 minutes — yielding the appropriate filtering margin of 0.009 mm. A considerably smaller margin (0.001 mm) was used in the example to show the effectiveness of the method in removing the outliers.

Measurement of the Blade Parameters

Figure 2b shows the parameters used in definition of a blade geometry in the cutting plane. Number of the variables in the complex cases can as high as thirty. This work concentrates on two main parameters — Pressure Angle and Blade Distance — designated as ALFW and BLDD, respectively, in Figure 2b. Pressure angle is defined as the angle between the tangent to the cutting edge and vertical line. Blade distance is the distance between the side of the blade and the point where the tangent to the cutting edge intersects y = 0 line (Fig. 2b).

It is more convenient to determine the deviation of the parameters from their nominal values, instead of determining their absolute value. These deviations are called Blade Distance Error and Pressure Angle Error. The values are the corrections which are applied in regrinding of the blades to their satisfactory geometry.

Measured points generally have both, x and y coordinates different from their nominal values. The process of calculating the deviations starts with recalculating the nominal coordinates at the y coordinates of the actual points. Then, the deviations of the actual from the nominal points in x (horizontal) direction are calculated for each I = 1…N points, where N is the total number of points.

$$E_i = x_{a,i} - x_{n,i} \quad i = 1\ldots N \qquad (1)$$
$$y_{a,i} = y_{n,i} = y_i$$

Pressure Angle Error, E_{ALFW}, can be calculated as the average angle between the neighboring points, Figure 7a:

$$E_{ALFW} = \tan^{-1}\left(\sum_{i=1}^{N-1} \frac{E_i - E_{i+1}}{y_{i+1} - y_i}\right) \qquad (2)$$

Alternatively, the value for EALFW can be calculated by using regression analysis.

Blade Distance Error, E_{BLDD}, can be determined by first calculating the centroid of the data points, $C\ (x_C, y_C)$, Equation 3. Then, the intercept with the y = 0 axis can be easily found by using Equation 4. Alternatively, Blade Distance Error can be found as the intercept of y = 0 line and of the line obtained from the linear regression analysis of the deviation points.

$$x_c = \frac{1}{N}\sum_{i=1}^{N} x_i \quad , \qquad (3)$$
$$y_c = \frac{1}{N}\sum_{i=1}^{N} y_i$$

$$E_{BLDD} = x_c - y_c \cdot \tan(E_{ALFW}) \qquad (4)$$

Using Multiple Sections for Pressure Angle and Blade Distance Measurement

The parameters determined in the previous section rely on the data points collected in cutting edge section (Fig. 3). A particular problem is encountered when the short blades are inspected, or when toprem and flankrem sections occupy sizable portion of the total blade height, making the cutting edge portion very short. Determination of the blade distance and pressure angle can be a challenging task in such cases, due to:

a) reduced number of the inspection points
b) sensitivity of the short sections to the small measurement variations

An effective approach in such cases could be to combine the neighboring parts of the blades into the larger sections. The approach is inspired by the inspection of parallel axes gear flanks in the standard AGMA/ANSI ISO 1328-1-B14 (Ref. 1).

The procedure used up to this point will need to be modified in order to be able to use the complete tooth forming portion of the blade in the evaluation of the Blade Distance and Pressure Angle. In certain cases the toprem, flankrem and edge radius sections have rather high deviations, not caused by the outliers. Blade Distance and Pressure Angle Errors would not be determined correctly in such cases, if the data for these sections was used in the calculations. Instead, the authors propose using the second filtering to automatically remove potential large deviations from the linear regression line fitted to combined sections. The tolerance on the pressure angle could be used as the margin of allowed deviation for the second filtering.

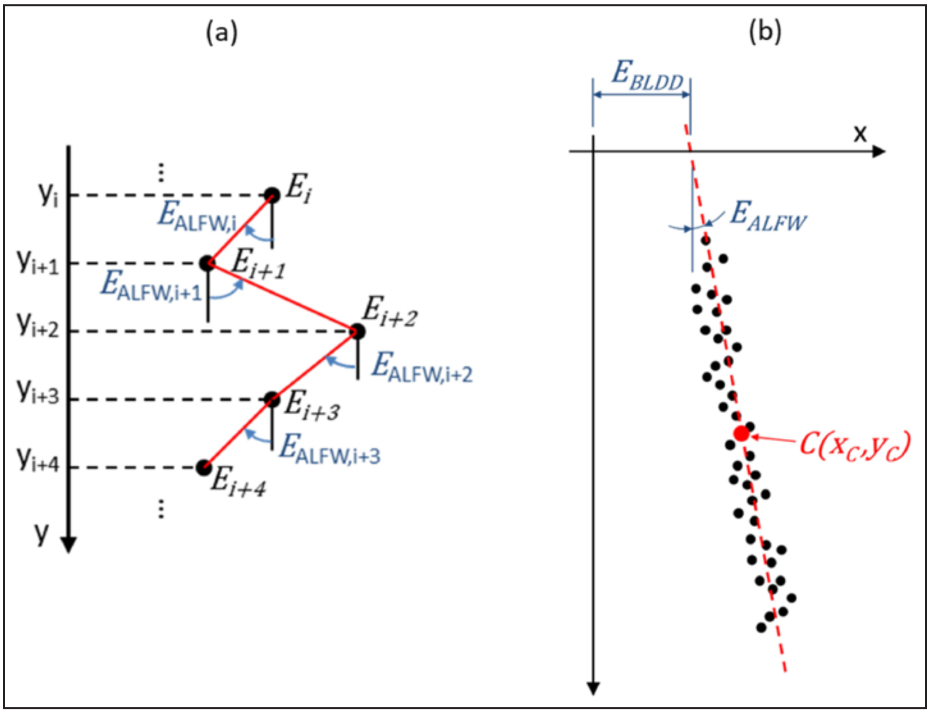

Figure 7 Calculation of (a) Pressure Angle Error, and (b) Blade Distance Error.

The examples shown (Figs. 5–6) will be used again to demonstrate the method. Unlike the first time when it was used on each section separately, RANSAC analysis is now used on all points remaining after removing outliers. With the axial grind depth of 19 mm, and the pressure angle tolerance of ± 2 minutes, the second filtering margin is set to M2 = 0.01 mm. The result of the second filtering is shown in Figure 8. The variation, mostly in the toprem and edge radius sections, was removed. Linear regression line, shown in red, describes the behavior of the large portion of the cutting edge rather well.

The described method could be particularly useful in the inspection of short blades. As the second example (Example #2), Figure 9a shows the deviation of the actual from the nominal points for the blade with the axial grind depth of less than 4 mm, and the inspected portion of the blade equal to 1.2 mm. The blade has three inspected sections — cutting edge, toprem and edge radius — all with the circular profile. The deviation data for all sections overall seems not to have a large scatter, but the number of the inspection points is relatively small (40 starting points for complete blade), Figure 9a. Using the first filtering of outliers with 0.0005 mm allowed margin, only three outlier points were removed, Figure 9b. The second (overall) filtering with the margin of 0.002 mm (2 minute deviation over 4 mm length), removed an additional seven points, as seen in Figure 9c. As expected, the scatter of the points was further reduced. It should be noted that more than 40% of the remaining points come from outside the cutting

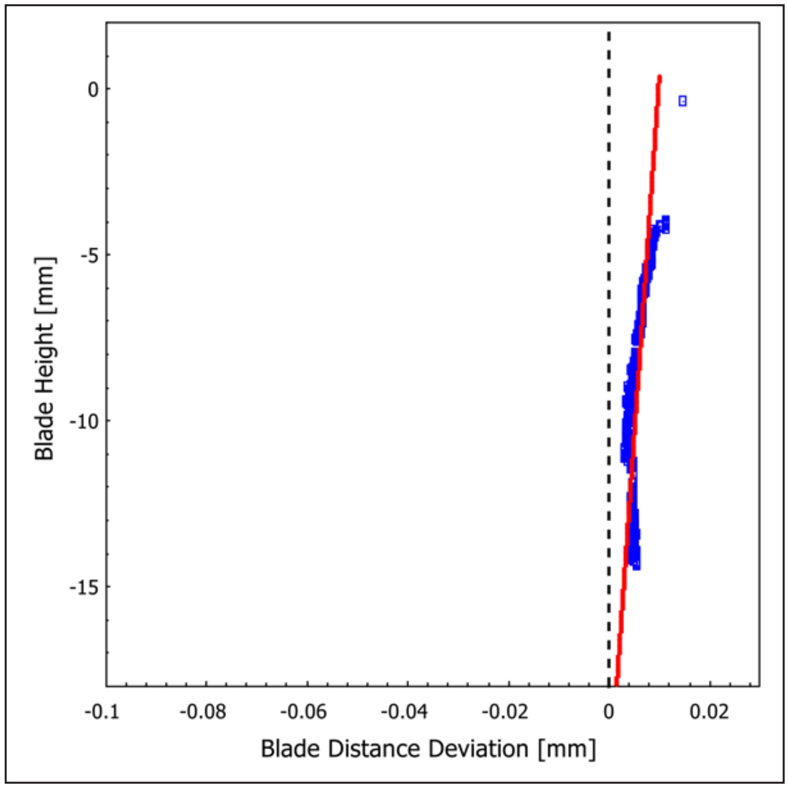

Figure 8 Data deviation (Example #1) and linear regression fit after the second filtering.

Table 1 Pressure and Blade Distance Error for the provided examples

	Blade Distance Error (E_{BLDD}) [mm]	Pressure Angle Error (E_{ALFW}) [°]
Example #1	–0.0098	0.026
Example #2	–0.0014	–0.512

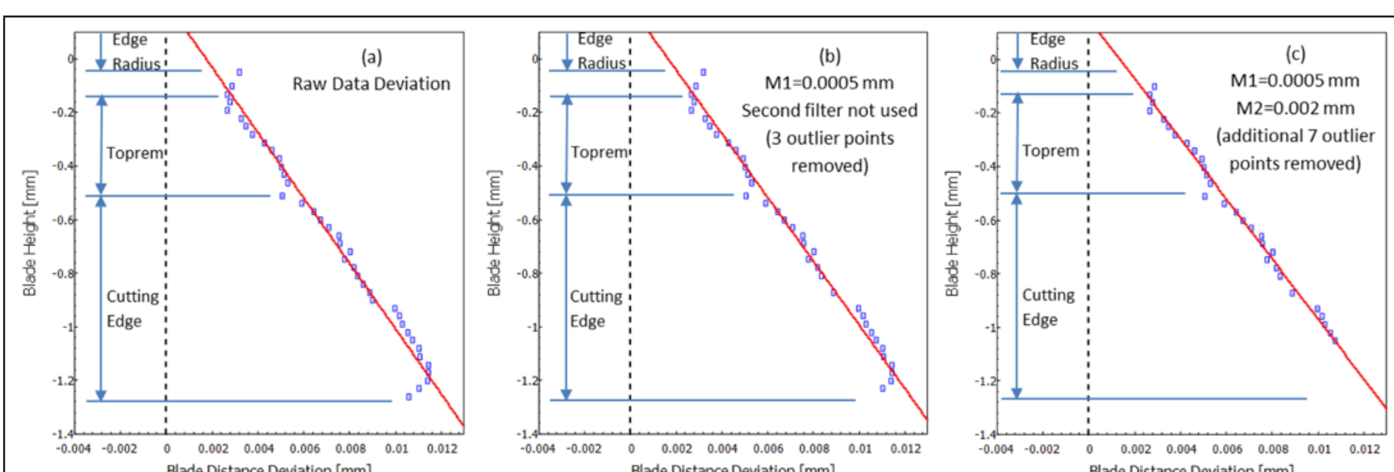

Figure 9 Treatment of the short blade; (a) raw data deviation, (b) deviation after the first filtering (outlier removal) and (c) deviation after the second filtering.

edge section, showing that using multiple of the sections can be useful method when inspecting short blades.

As the final step, the filtered data was used for the Blade Distance Error and Pressure Angle Error calculation by using Equations 2–4. The values are summarized in Table 1, and the deviation of the data before and after correction is shown (Fig. 10).

Summary of the complete process is provided (Fig. 11). In the current form the process is suited for the linear nature of the corrections. However, the process could be modified in the future to handle the non-linear response of the system to the intended corrections.

Conclusion

The authors of this work present a novel method of evaluating blade geometry deviations. The method would be particularly useful in cases with large number of outliers and when the small number of data is created during inspection (typical for short blades). Two major deviation parameters were considered, Pressure Angle and Blade Distance.

The method relies on the RANSAC algorithm to remove the outliers from each section separately, based on the allowed deviation from the predetermined mathematical model. Actual example was used to demonstrate the effectiveness of the proposed procedure.

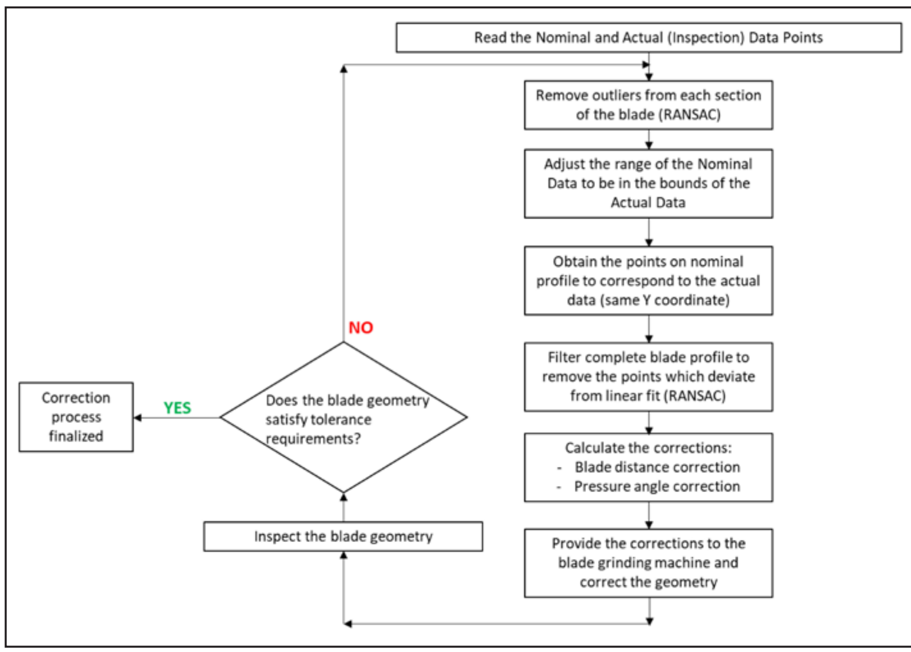

Figure 11 Summary of the proposed procedure for blade correction.

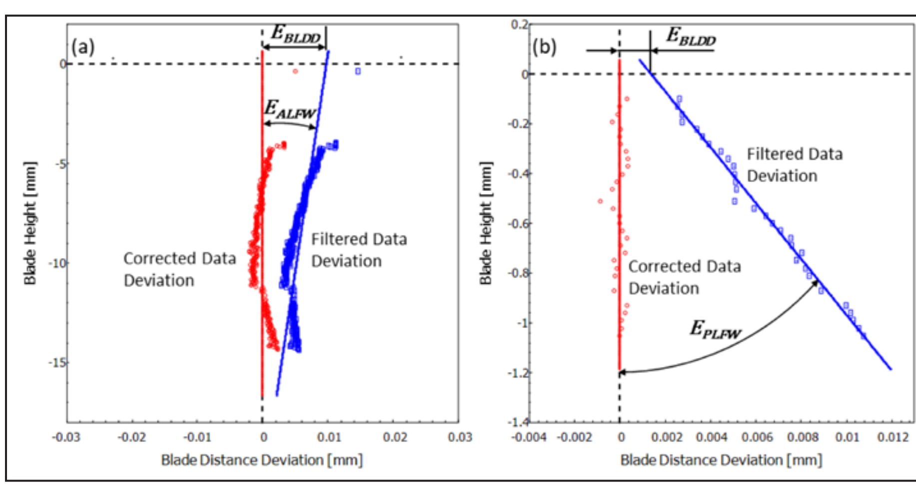

Figure 10 Final data correction; (a) Example #1 (blade with the large number of outliers), and (b) Example #2 (short blade).

The RANSAC algorithm was applied again to the complete blade profile in order to automatically remove the large portion of data, or complete sections, deviating from the linear behavior. Such approach makes it possible to utilize the data from several sections in calculation of the Blade Distance and Pressure Angle. The effectiveness of this method was demonstrated through a short blade example where the starting number of points is relatively low.

As a future task, the authors will apply the proposed methods in the actual blade inspection process, followed up by the geometry correction (grinding) and verification of the corrections (re-inspection). While the proposed method looks simple, the complete process might not be linear, and several iterations, performed automatically, might be necessary in order to obtain proper blade geometry. The study will include the possibility of improvement of the process by using a simple transfer function for scaling of the correction values in case of the non-linear behavior.

References

1. ANSI/ AGM. "Cylindrical Gears — ISO System of Flank Tolerance Classification, Part 1: Definitions and Allowable Values of Deviations Relevant to Flanks of Gear Teeth," AGMA/ANSI ISO 1328-1-B14, 2014.
2. Stadtfeld, H. J. *Pentac Mono-RT, High Performance Face Milling Cutter Heads*, Gleason Company Publication, 2016.
3. Stadtfeld, H. J. "Bevel Gear Cutting Blade Measurement," *GearSolutions*, March 2012, pp. 42–51.
4. Stadtfeld, H. J. *Stick Blade Definition Manual*, Gleason Company Publication, 2014.
5. Stadtfeld, H. J. "Three-Face Blade Technology," *GearSolutions*, November/December 2017, pp. 82–90.
6. Stadtfeld, H. J. and T. Matsubara. *Bevel Gear Cutting Blade Measurement in Past, Present and Future,* Gleason Company Publication, 2015.
7. Fischler, M. A. and R.C. Bolles. "Random Sample Consensus: A Paradigm for Model Fitting with Applications to Image Analysis and Automated Cartography," Communications of the ACM, v 24(6), 1981.
8. Taubin, G. "Estimation of Planar Curves, Surfaces and Nonplanar Space Curves Defined by Implicit Equations, with Applications to Edge and Range Image Segmentation," *IEEE Trans. Pattern Analysis Machine Intelligence*, 13:1415–1138, 1991.

Haris Ligata joined Gleason's R&D Department (Rochester, NY) in 2017 as a Senior Gear Theoretician, working on cutting blade inspection and bevel gear technology. Prior to Gleason, he worked in GE's Global Research Center (Schenectady, NY) on a wide range of projects related to rotating machinery, and in American Axle & Manufacturing (Detroit, MI) on straight bevel and helical gear differential technology. He obtained his Ph.D. degree in Mechanical Engineering from the Gear Lab at The Ohio State University in 2007.

Dr. Hermann J. Stadtfeld is the Vice President of Bevel *Gear Technology* and R&D at the Gleason Corporation and Professor of the Technical University of Ilmenau, Germany. As one of the world's most respected experts in Bevel *Gear Technology*, he has published more than 300 technical papers and 10 books in this field. Likewise, he has filed international patent applications for more than 60 inventions based upon new gearing systems, gear manufacturing methods, as well as cutting tools and gear manufacturing machines. Under his leadership and guidance, the world of bevel gear cutting has converted to, environmentally friendly, dry machining of gears with significantly increased power density due to non-linear machine motions and new processes. Those developments also lower the noise emission level and reduce the degree of energy consumption. Over a span of over 35 years, Dr. Stadtfeld has had a remarkable career within the field of Bevel *Gear Technology*. Having received his Ph.D. with summa cum laude in 1987 at the Technical University in Aachen, Germany, he became the Head of Development & Engineering at Oerlikon-Bührle in Switzerland. Dr. Stadtfeld held a Professor position at the Rochester Institute of Technology in Rochester, New York From 1992 to 1994. In 2000 as Vice President R&D he received in the name of The Gleason Works two Automotive Pace Awards, one for his high- speed dry cutting development and one for the successful development and implementation of the Universal Motion Concept (UMC). The UMC brought the conventional bevel gear geometry and its physical properties to a new level. In 2015, the Rochester Intellectual property Law Association elected Dr. Stadtfeld the "Distinguished Inventor of the Year." Between 2015 and 2016 CNN-Networks featured him as "Tech Hero" in a Website dedicated to technical innovators for his accomplishments regarding environmentally friendly gear manufacturing and technical advancements in gear efficiency. Currently, he continues in his Senior Management position at Gleason Corporation to mentor and advise graduate level Gleason employees, and he supervises Gleason-sponsored Master Thesis programs as Professor of the Technical University of Ilmenau, helping to shape the future of gear technology.

For more information.
Questions or comments regarding this paper? Contact Haris Ligata at *hligata@gleason.com*.

CORRECTION

In the March-April issue, the technical paper — Experimental Study on the Pitting Detection Capabilities for Spur Gears Using Acoustic Emission and Vibration Analysis Methods — by M. Grzeszkowski, C. Gühmann, P. Scholzen, C. Löpenhaus, S. Nowoisky and G. Kappmeyer — an incorrect biography and photo were used for one of the co-authors — **Sebastian Nowoisky**. For the correct information, please refer to the online version of the paper at *www.geartechnology.com*. *Gear Technology* regrets the confusion.

Oil-Off Characterization Method Using In-Situ Friction Measurement for Gears Operating Under Loss-of-Lubrication Conditions

Aaron C. Isaacson and Matthew E. Wagner

Introduction

The oil-off (also known as loss-of-lubrication or oil-out) performance evaluation of gears is of significant interest to the Department of Defense and various rotorcraft manufacturers, so that the aircraft can safely land in an accidental loss-of-lubricant situation. However, unlike typical gear failure modes such as pitting or bending fatigue where early detection is possible, gear failure in an oil-off situation is very rapid and likely catastrophic. Failures rapidly result in the loss of torque transmission and the inability to control the aircraft.

Interest in loss of lubrication gearbox performance testing is not new. In 1978, Hudgins and Schuetz described the need for improved survivability of helicopter drive systems based upon loss of lube events in the Vietnam conflict due to combat damage (Ref. 1). They noted that typical times to failure were five to nine minutes and that failure modes were inconsistent. Five to nine minutes is not enough time for an aircraft to escape hostile environments and land safely. A requirement of 30 minutes of operation after lubrication system failure was established and is still used today as outlined in the Title 14 Code of Federal Regulations: Airworthiness Standard (Ref. 2.)

Today's helicopters and tiltrotors are commonly used for missions where 30 minutes of loss of lube operation is insufficient, such as long range, over water flights to access drill rigs or aircraft carriers. This has led to review of this longstanding benchmark and the standard is currently being revised. Indications are that test survivability times for full gearboxes will be between 36 and 67 minutes and that more test repetitions will be required.

Related Research

Between 1978 and the early 2010s, there was very little related to oil-off testing reported in the open literature with the exception of some work done by NASA Glenn (Ref. 3) and Kaman Aerospace (Ref. 4), both of which focused on improvement of gearbox performance through auxiliary oil supplies. There were many lessons learned, the most obvious were that there are a large number of variables that can affect the result of the test and that the possibility exists for gearboxes to operate for a long time with minimal lubrication.

Many of the test reports available are for full-scale gearboxes (Refs. 1; 4–8). The complexity involved is staggering. The variables that can affect the outcome of each test are: gear arrangement (planetary vs. non-planetary); gear backlash; gear material; housing design (provides locations for oil to pool); type of oil leak (pressure loss vs. hole in sump); bearing and shaft clearances; bearing type; bearing material; surface roughness of sliding surfaces; ability to generate mist; heat transfer properties; and more. It is clear that component-level testing to optimize gear-related variables is a valuable step before undertaking a costly full-scale test.

Several computational tools have been built to model aspects of lubrication loss to a gear mesh (Refs. 9–15). The most sophisticated is likely the multi-physics-based approach taken by McIntyre, et al., incorporating aspects of contact mechanics; tribology; computational fluid dynamics modeling for the gearbox flow; conduction within the gears; housing and components; and free convection to the environment (Ref. 14). The model is based upon a component test rig at NASA Glenn and predicts temperature distribution across the teeth and time-to-failure (Refs. 13–14). Efforts are currently underway to correlate model output with temperature data collected at Penn State University. While useful insights can certainly be observed, the available models cannot currently account for variables such as oil mist variation, carbonaceous oxidation deposits that develop during testing, gear tooth profile loss and any other unknown influences.

Gear Failure Mechanisms

The lubricant inside of a gearbox serves two primary functions — to separate sliding metal surfaces and to distribute and remove the heat generated due to this sliding. Components begin to heat up immediately when the lubricant supply is removed. This leads to the thinning of the remaining oil film and the prompt occurrence of metal-to-metal contact, which is accompanied by a sharp rise in friction. Increased friction causes more heat generation, exacerbating the problem. Without oil, the system relies on conduction through the components and convection inside and outside the gearbox for heat dissipation. Most reported test results show a period of metastable thermal equilibrium after loss of lubrication where the gearbox operates at higher than design temperatures (Refs. 3, 5, 15–17). The gear teeth are often reported to be the initial component to fail (Refs. 1 and 7). Scuffing initiates immediately upon metal-to-metal contact (breakdown of lubricant film). The high heat eventually causes the steel to soften and leads to plastic deformation under load (Ref. 18). The extreme temperatures also result in thermal expansion that can cause seizure of the gears if backlash is insufficient. The gear backlash can typically be increased to account for the high temperatures expected during oil-off cases.

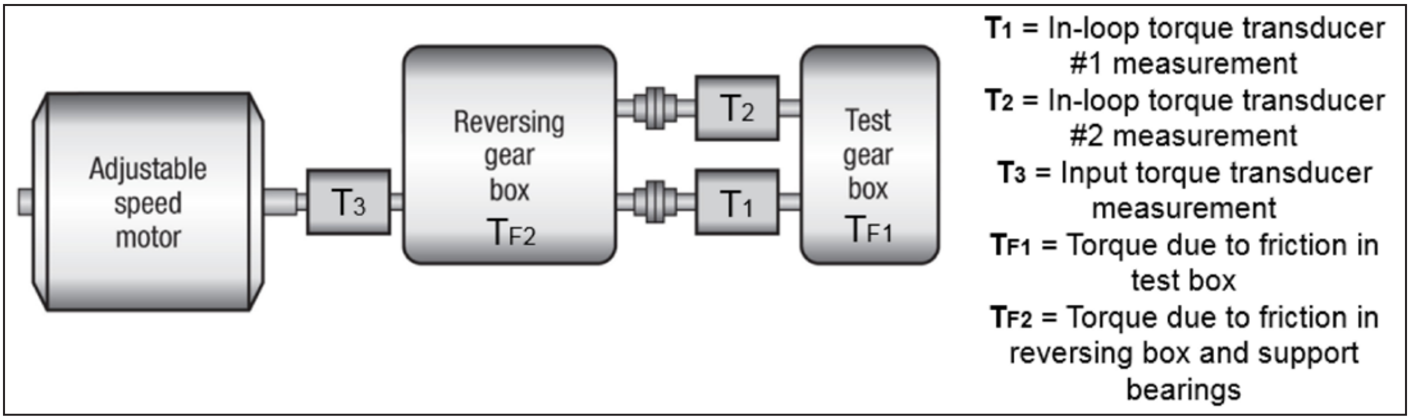

Figure 1 Test rig layout.

Scuffing

The previously discussed work identifies scuffing as a key part of the oil-out failure process for gears (Refs. 1, 3, 5, 7, 9–10, 15, 17–19). Scuffing is a physical failure of the elastohydrodynamic lubrication (EHL) mechanism (Ref. 20). It can be described as the repeated welding and tearing apart of surface asperities due to insufficient lubrication. Scuffing resistance has traditionally been increased by improving surface finish, using EP additives in lubricants or other means of reducing the friction between the contacting surfaces (coatings for instance) (Ref. 20).

Scuffing has been studied using coupon level tests by many researchers. Tests such as pin-on-disc; four-ball; block-on-ring; twin-disc; ball-on-ring; and ball-on-disc are used to generate scuffing under controlled, specific test conditions (Ref. 19); the influence of roughness, oil additives, etc. can be quantified. There has been significant work done at both the U.S. Army Research Lab and Wedeven Associates, Inc. using ball-on-disc testing to evaluate loss-of-lube performance. While scuffing is the primary failure mechanism, some performance differences exist and are the subject of continued research. These differences are likely attributable to the variable stresses and variable sliding inherent to the involute gear tooth geometry and the fact that the meshing action of the gear teeth allows even the smallest amount of residual lubricant mist (or even vaporized carbon (Ref. 21)) to provide continued lubrication to the mesh.

Scuffing failures demonstrate a specific progression that is consistent — regardless of test type. The onset of scuffing, called "micro-scuffing" by Yagi, et al. (Ref. 22), is followed by a period of stability. What is occurring during this period varies depending on test type, roll/slide ratio and amount of residual lubricant present. It is most likely an oxidative wear phenomena (Ref. 23) created by the oxidation of the residual lubricant and the metal at high temperature, resulting in a high carbon deposit that reduces the friction between the contacting bodies. This is where the metastable thermal equilibrium occurs. The length of this period depends on a number of factors, but is essentially determined by how well the system is able to absorb and remove the generated heat from the contact. Eventually, the temperature rise is too much to overcome and another transition occurs where the friction and temperature rise sharply, leading to catastrophic failure (Refs. 19, 22–24).

Gear Testing

A gap exists between coupon testing and full-scale gearbox testing, allowing more realistic, cost-effective oil-out screening tests to be conducted using a component level test. These tests are currently being used to characterize the performance benefits of the most advanced gear steels, surface treatments, lubricants and even non-involute tooth profiles for oil-out operation (Refs. 17 and 25). The remainder of this paper outlines the test rigs and procedure developed for oil-out performance characterization.

Test Rig Hardware

A 3.5" center distance power recirculating four square test rig capable of speeds up to 10,000 RPM was used for the oil-off testing described in this paper. This test rig uses a dedicated reversing gearbox that hydraulically applies torque to the four-square loop, which enables torque changes during test operation. A schematic layout of the system is shown (Fig. 1). Several modifications to the test rig were necessary to allow for oil-off operation and are described in detail below.

Oiling System Modification

During typical oil-on testing, the test gearbox uses jet lubrication to supply oil to the test gears. Additionally, the test gear shafts are supported on each end by bearings which require a pressurized oil feed. The test box bearings use the same oil that is supplied to the gear mesh for lubrication, and the bearings drain to the interior of the test box. It was necessary to modify the oiling system of the rig to allow shutdown of oil flow to the gear mesh while maintaining lubrication to the test box bearings. The test box bearing oil feed lines was also equipped with needle valves so bearing oil flow could be controlled in order to ensure oil mist in the test box during oil-off was identical and repeatable from test to test. Bearing temperature limits were continuously monitored during testing to verify proper operation.

Oil Control Shroud

The test rig was also modified to shroud the perimeter of the test gears in order to control residual oil after lubrication flow is stopped. The shroud was based on the design shown (Ref. 9) and has 0.06"radial clearance from the shroud to the tooth top land, as well as 0.06" clearance to each end face. Slots positioned radially outward from the gear rotation allow residual lubrication to exit during the oil-off event. The assembled shroud (without front cover installed) is shown (Fig. 2).

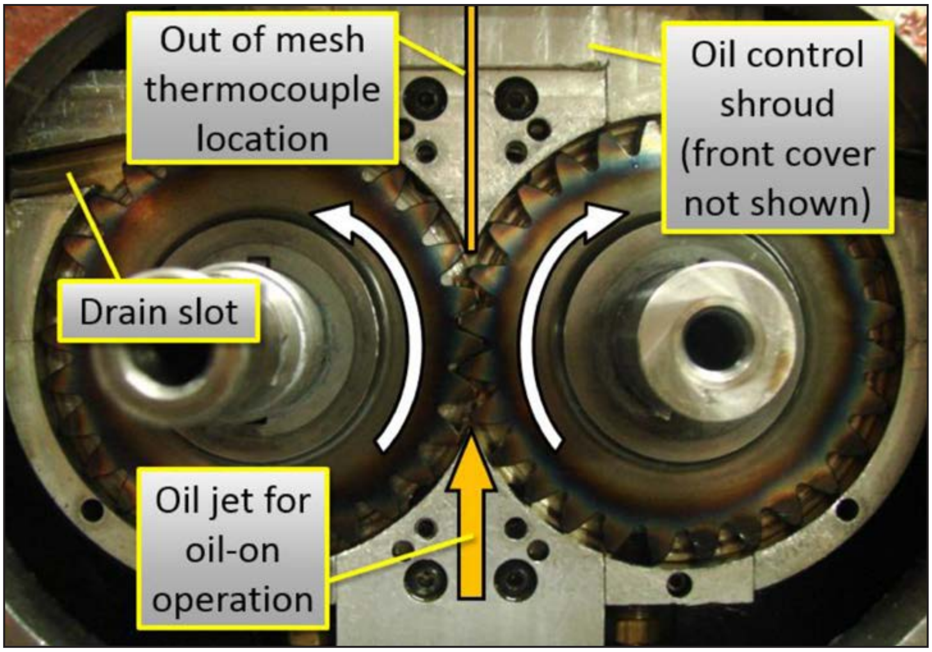

Figure 2 **Oil control shroud.**

Table 1 Oil-off test result cases

	Case	Description
Least Severe	I	No scuffing (runout)
	II	Scuffing without progression to catastrophic failure (runout)
	III	Scuffing with progression to catastrophic failure
Most Severe	IV	Immediate catastrophic failure

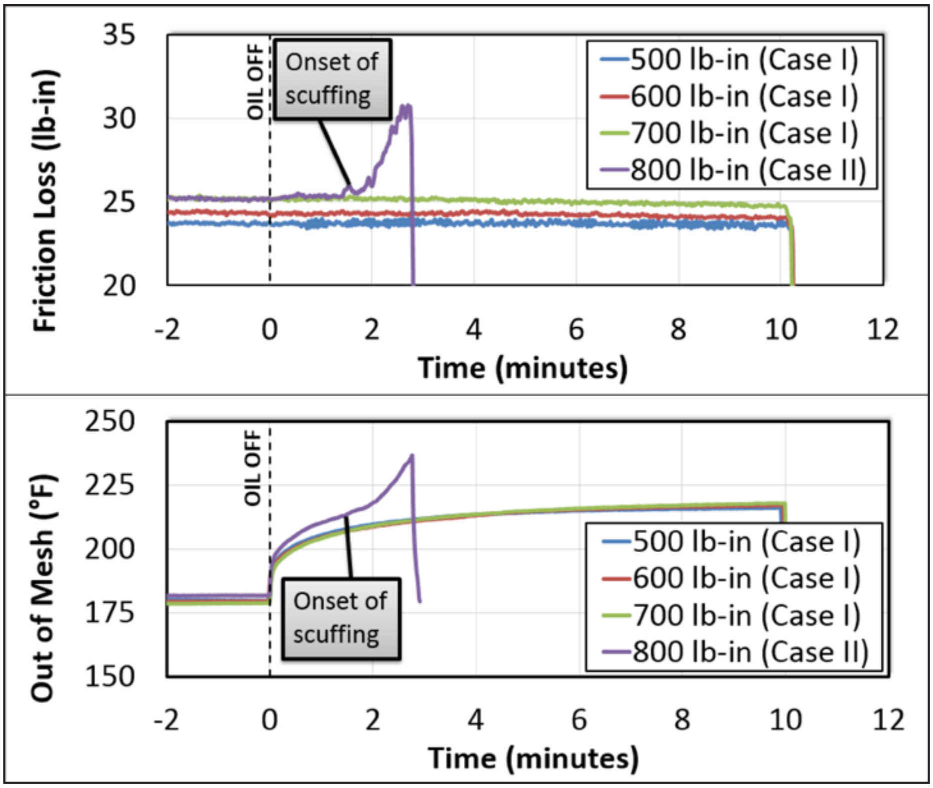

Figure 3 **Detecting onset of scuffing.**

Out-of-Mesh Temperature Measurement

A 0.125" diameter out-of-mesh thermocouple was incorporated into the oil-off shroud, as shown in the location shown (Fig. 2); it was positioned axially as close as possible to the rotating gear teeth. This thermocouple measures out-of-mesh oil temperature during oil-on break-in, but is also used to measure temperature of the entrained air near the gear tooth surfaces during oil-off. Although the absolute temperature reading of the entrained air does not directly predict tooth temperature, it was found that the temperature trend is a valuable metric for monitoring progression of gear failure during oil-off.

Friction Measurement

As shown (Fig. 1), the test rig was also instrumented with three torque transducers. Two transducers monitor torque inside the four-square loop, and an additional transducer monitors input torque from the drive motor. These measurements are then used to compute frictional losses in the test box and reversing box. Details of the loss calculations and friction measurement techniques were presented previously by the authors (Ref. 26). Test box friction loss measurements were found to be the most effective metric for monitoring oil-off progression to failure, and were also found to correlate well with out-of-mesh temperature measurement trends during catastrophic failure. To the knowledge of the authors, in-situ measurement of gear mesh friction during oil-off gear testing has not previously been reported in open literature.

Test Procedure

The oil off test procedure is defined as follows:

1. ***Break-in step #1*:** Run with oil on at break-in torque for 30 minutes.
2. ***Break-in step #2*:** Ramp to test torque, continue running with oil for 60 minutes.
3. ***Oil-off*:** Continue running at test torque and turn off oil; monitor for catastrophic failure.
4. ***Runout*:** If runout time limit is reached (typically 30 minutes), turn on oil and increase torque.
5. ***Stabilize*:** Allow to run at increased torque level with oil for 10 minutes.
6. ***Repeat*:** Repeat oil-off and continue to run up to runout time limit. If necessary, repeat steps 4 through 6 until catastrophic failure occurs.

Typical Test Results

Through extensive testing, it was found that oil-off results typically fall into one of the four cases summarized in Table 1, based on the severity of test conditions. Details and examples of each case are presented below.

Case I: no scuffing. In the least severe case, gear teeth can last the oil-off test period without scuffing. This can be caused by residual oil mist in the test box or test torques that is too low. This condition does not occur frequently, but is presented here to illustrate the friction loss and out-of-mesh temperature trends when the onset of scuffing is detected.

Figure 3 shows four tests which were completed at increasing torque levels with the same gear pair. These tests were part of an initial development effort to evaluate the effectiveness of friction loss and out-of-mesh temperature to detect scuffing. Tests were stopped for visual inspection after each torque step, and the 500, 600 and 700 lb-in steps did not show any scuffing. This indicates that the residual lubricant and/or tribological film were sufficient to prevent scuffing initiation under these conditions.

Case II: scuffing without progression to catastrophic failure. In Figure 3, continuing testing to 800 lb-in showed a significant change in both friction and temperature trends, and visual inspection confirmed that scuffing occurred at this torque; the scuffed gear tooth surfaces are shown (Fig. 4). In a typical test sequence this test would have been allowed to continue to catastrophic failure or runout, but this test was stopped after friction and temperature trends indicated scuffing had occurred. This test result demonstrates the effectiveness of using friction and out-of-mesh temperature to detect the onset of scuffing.

As conditions increase further in severity, scuffing typically occurs rapidly after oil flow is stopped. This is shown in the friction loss trend in Figure 5, which peaks immediately after oil-off. Since heat generation increases with friction, this suggests that the maximum heat generation at the mesh interface occurs during the scuffing event immediately after oil-off. After the initial scuffing event, the friction loss and out-of-mesh temperatures stabilize as the test continues to run. In this case, the conditions are not severe

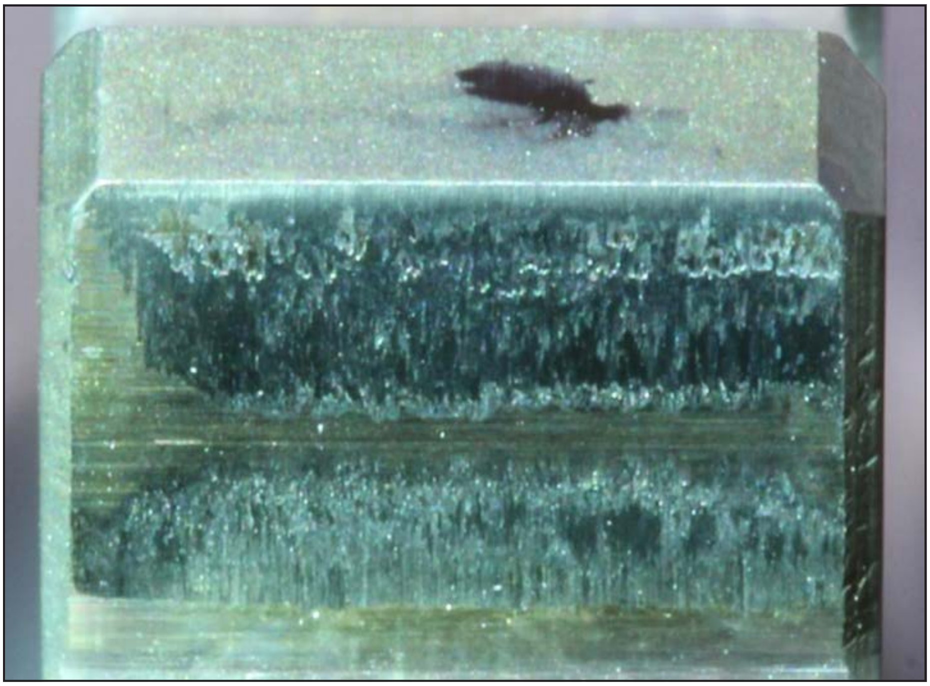

Figure 4 Scuffed gear tooth.

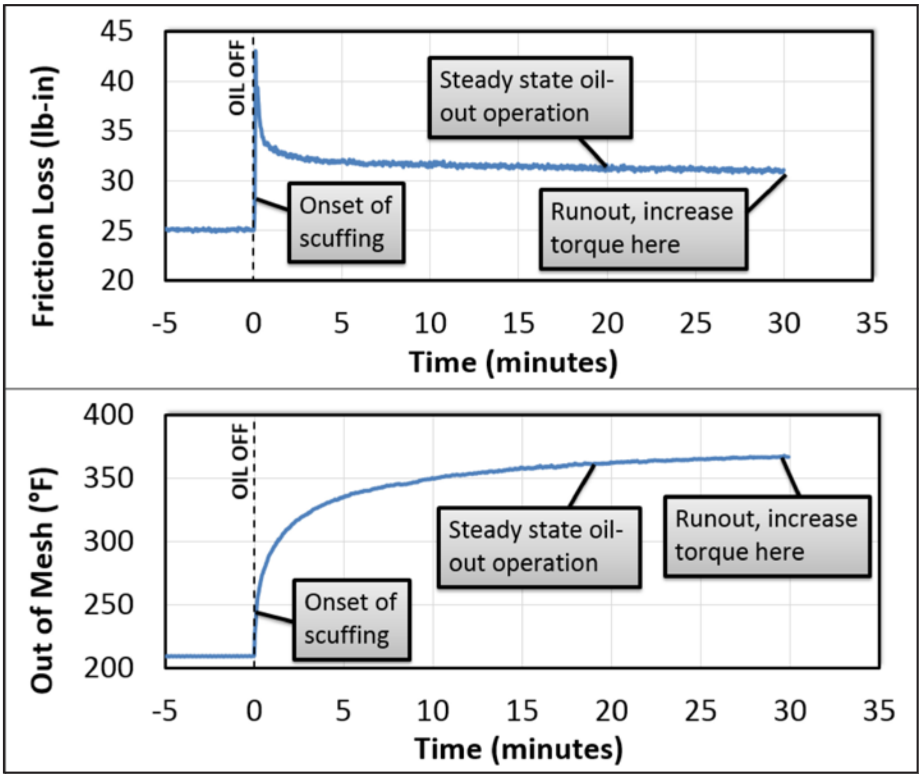

Figure 5 Scuffing and runout.

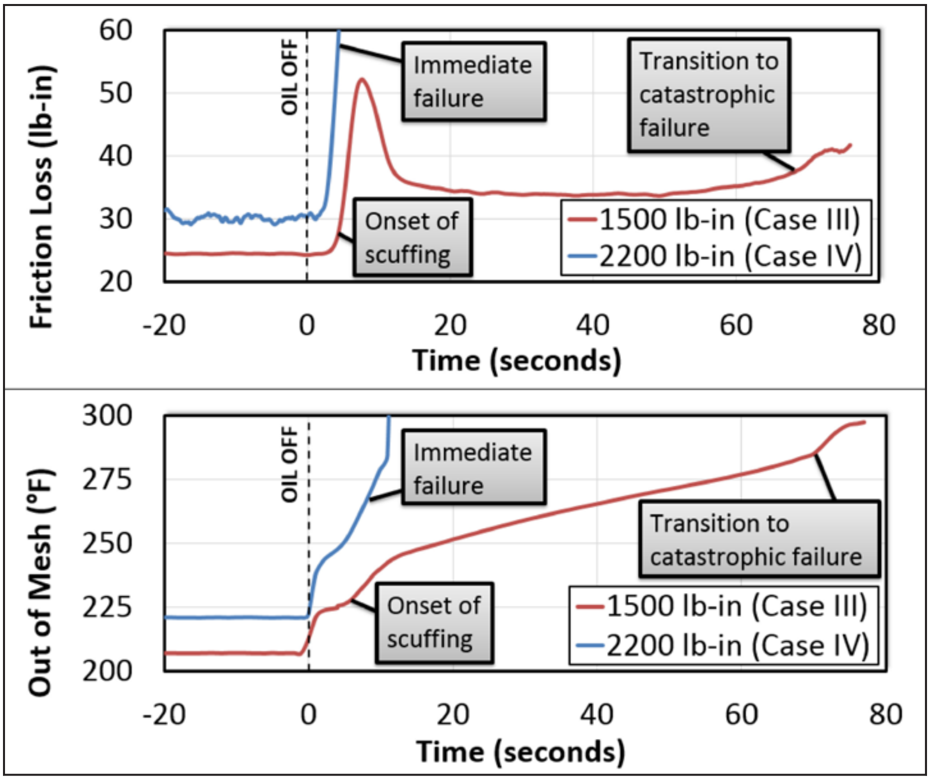

Figure 6 Case III vs. Case IV severity comparison.

Figure 7 Catastrophic failure, run to loss of power transmission.

enough to cause the test to progress to catastrophic failure.

A metastable thermal equilibrium is then reached where out-of-mesh temperature is asymptotic. The heat input to the mesh is being absorbed and removed from the system before runaway failure occurs. Although the tooth surfaces are scuffed, the gears still transmit torque and as such are not considered failures in the context of this test. Testing has shown that it is possible for gears to run in the scuffed oil-off state for several hours without progressing to catastrophic failure. If the run-out time limit is reached, the oil is turned back on and the torque is increased to prepare for the next oil-off step.

Case III: scuffing with progression to catastrophic failure. If test conditions are increased in severity further than in Case II, the test will eventually progress to catastrophic failure; a plot of the torque and temperature data for two different cases of catastrophic failure are shown (Fig. 6). With the failure progression of Case III, the initial friction peak from scuffing is followed by a period of stable operation. This period of stable operation that precedes the transition to catastrophic failure allows for the separation of performance of different test groups.

In Case III, friction then begins to increase again after the period of stable operation, which indicates the test is progressing to catastrophic failure. The out-of-mesh temperature rate of change also increases when catastrophic failure begins. Complete loss of power transmission typically occurs shortly after friction increases, and an example of a gear pair run to this extent is shown (Fig. 7). Testing to complete loss of power transmission can be damaging to the test rig, so tests are typically stopped once friction and out-of- mesh temperature trends suggest catastrophic failure is imminent. An example of a test stopped before loss of power transmission is shown (Fig. 8); note that there is significant plastic deformation present on the tooth.

Case IV: immediate catastrophic failure. If test conditions are increased in severity further than in Case III, catastrophic failure can occur immediately after oil-off, which is shown as Case IV in Figure 6. In this progression, the period of stable oil-off operation after initial scuffing from Case III is not present. Immediate catastrophic failure is not desirable since differentiating performance between test groups is difficult in this case.

Ideal Test Conditions

The ideal test conditions should produce a majority of Case III catastrophic failures at the established test torque. Per the test procedure, if a runout occurs (Case II) the torque is then increased, and the oil-off event is repeated. This will eventually lead to a catastrophic failure at a torque higher than the established test torque. It is desirable to select a test torque that is severe enough to minimize the number of runouts, since this requires multiple oil-off events to initiate a catastrophic failure. At the same time, the test torque must not be too high as to cause immediate catastrophic failures (Case IV) which do not produce useful performance data.

Load Step Searching Tests

The test torque which will produce a majority of Case III catastrophic failures will vary between test programs and is influenced by factors such as gear design, oil selection and surface finish. In order to establish an approximate value for the test torque using the minimum number of test gears, a load step approach is used. This is similar to the test procedure outlined previously, with the exception that a shorter time interval of 10 minutes oil-on and 10 minutes oil-off is used. A torque near the lower limit of the rig's capability is used as a starting torque, which is increased by 100 lb-in after 10 minutes of oil-off without catastrophic failure; a portion of a typical load step searching test is shown (Fig. 9).

Since a load step searching test typically subjects the test gears to multiple oil-off events before catastrophic failure occurs, the torque determined by this method may not be the final test torque that should be used. It will, however, establish a starting point for further testing to validate that new gears taken immediately to the test torque and subjected to oil-off will fail in the desired progression.

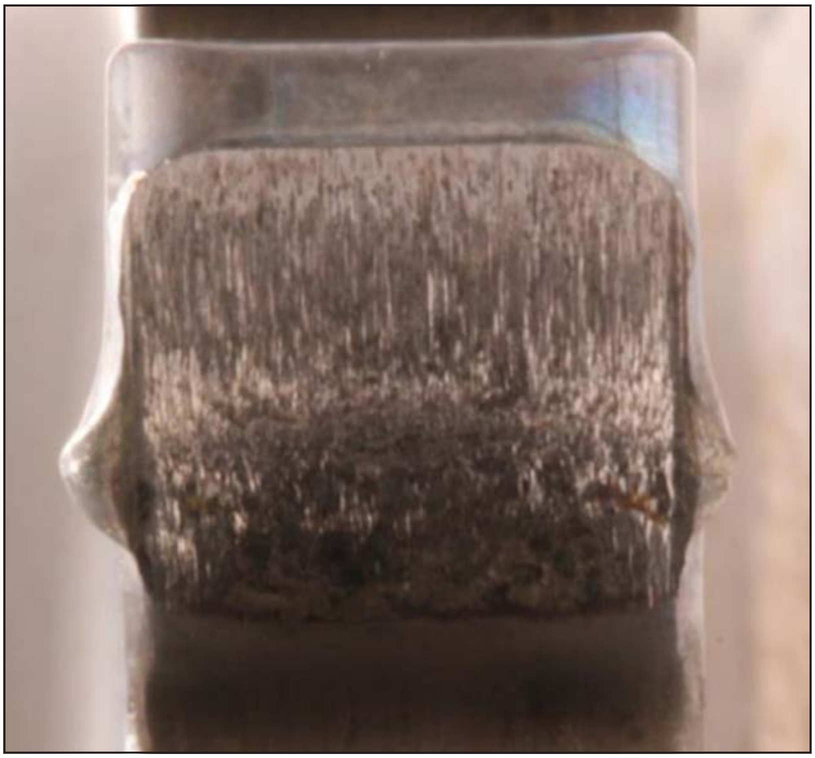

Figure 8 Catastrophic failure, stopped prior to loss of power transmission.

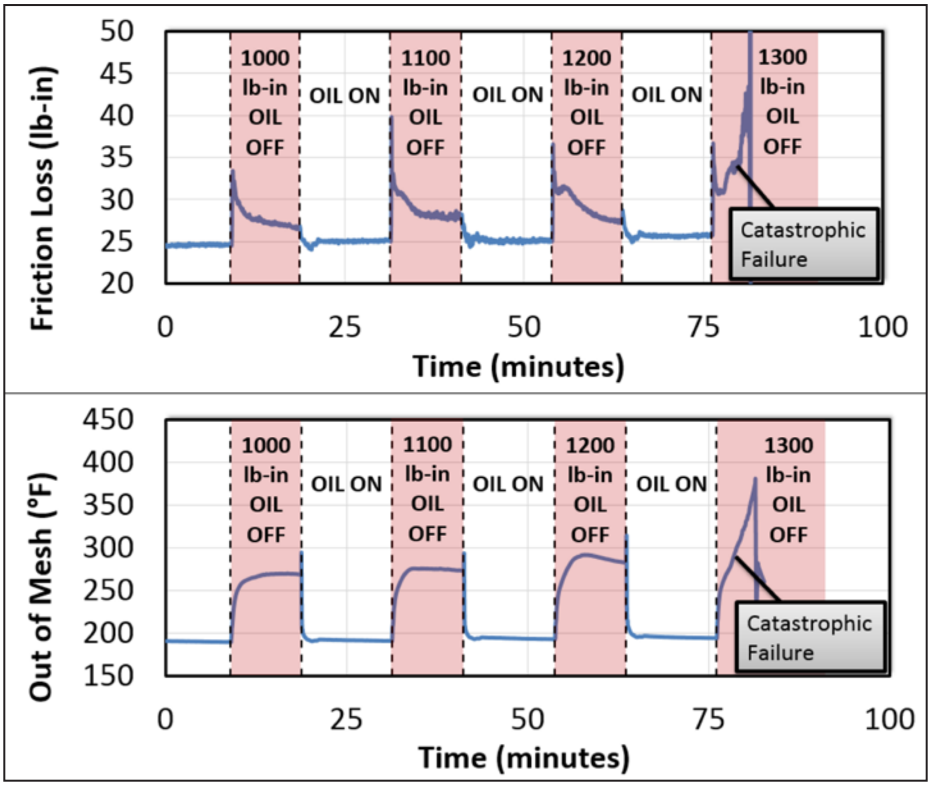

Figure 9 Load step searching test.

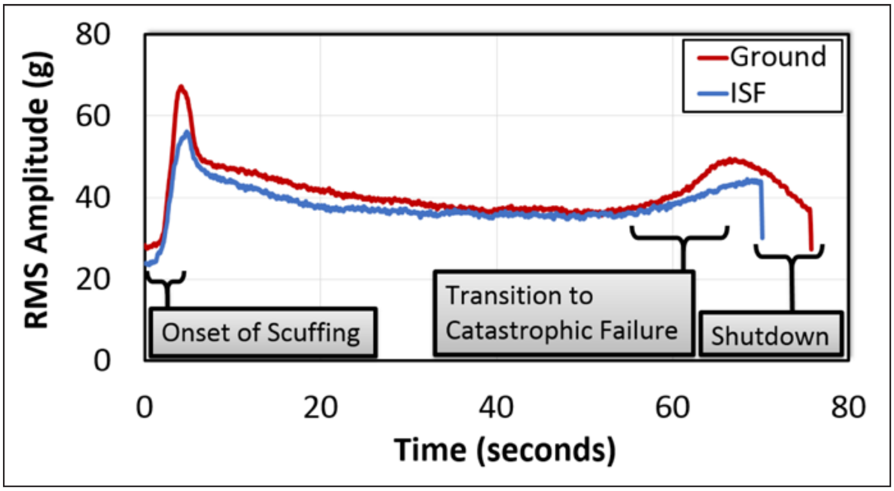

Figure 10 RMS accelerometer data.

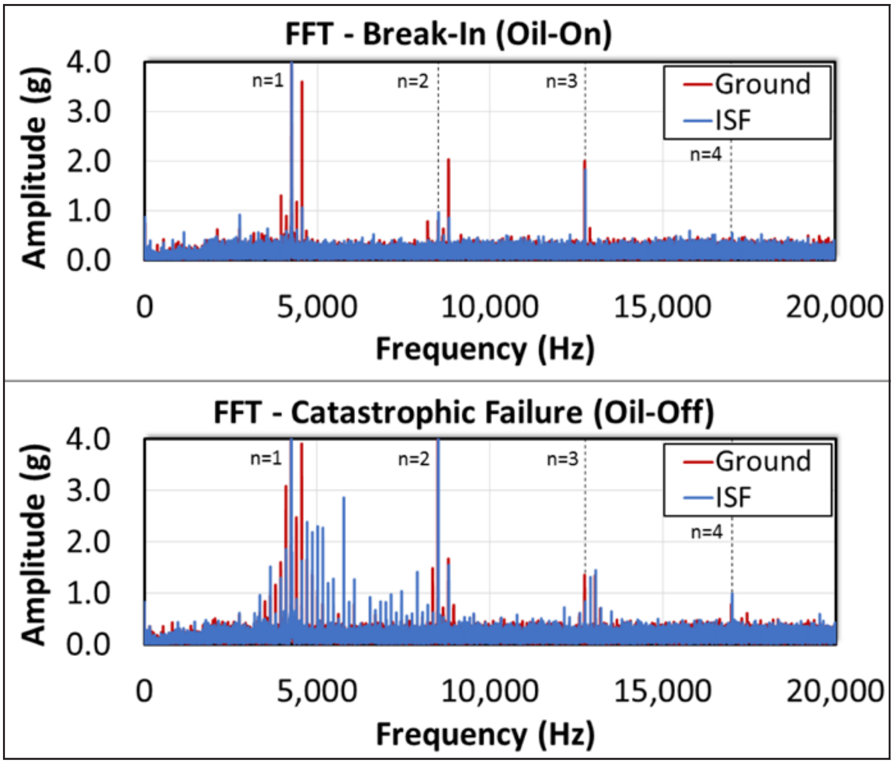

Figure 11 FFTs of accelerometer data (tooth mesh fundamental frequency and harmonics denoted by n = 1...4).

Figure 12 Thermocouple instrumented gear.

Additional Data Collected

Noise and vibration measurements. Noise and vibration data were also collected during testing. A sample rate of 51.2 kHz was used for the data presented (Figs. 10–11), which in this case captures up to the fourth harmonic of the tooth meshing fundamental frequency.

Figure 10 shows the RMS amplitude of the accelerometer data for two tests conducted with as-ground and isotropic superfinished (ISF) test surfaces. The accelerometer data is shown to have trends similar to the friction measurement data. An initial peak during the scuffing event is followed by a period of stable operation, leading to a second increase when the test transitions to catastrophic failure.

Data from the same tests are shown in the frequency domain in Figure 11 — both before and after oil-off.

As expected, peaks in the FFT (fast Fourier transform) data at the tooth meshing fundamental frequency and harmonics are visible during oil-on break-in. The progression to catastrophic failure shows the appearance of additional sidebands as the tooth profile degrades from severe scuffing.

Side-of-tooth thermocouple data. In an effort to correlate out-of-mesh entrained air temperatures to gear tooth surface working temperatures, gears were instrumented with a thermocouple on the side of one tooth using thermally conductive epoxy (Fig. 12). Figure 13 shows the friction loss result of an oil-off test, together with out-of-mesh and side-of-tooth thermocouple data. The side-of-tooth temperature shows an initial maximum followed by a gradual reduction to near steady state (thermal equilibrium). This validates the theory that the maximum heat generation at the mesh interface occurs during the initial scuffing event, indicated by the friction peak immediately after oil-off. This particular test did not catastrophically fail and ran for over 90 minutes without oil. A steady state temperature of approximately 440°F was measured on the side of the tooth when the test was terminated as a runout.

Figure 14 shows an example of side-of-tooth thermocouple data for a test which catastrophically failed. At the onset of catastrophic failure the rate of change of the side-of-tooth temperature increases, similar to the trends observed for out-of-mesh temperature. Side-of-tooth temperatures of over 700°F were measured before the test was terminated. This data is useful for validating computational models of the loss-of-lubrication event, examples of which can be found in (Figs. 13 and 14).

Application Example: Comparison of Experimental Group vs. Baseline.

An example of this test method's ability to differentiate performance between test groups is illustrated in Table 2 and Figure 15. The results of oil-off testing with a baseline test group and a second experimental test group with an advanced material, coating, and oil are shown. Multiple test repetitions were used, since scatter in oil-off performance test data is well documented (Refs. 1, 5, 10, 17 and 27). As shown in Table 2, although scatter is present in the experimental group data, a significant increase in performance is shown over the baseline group in all cases.

Figure 15 highlights the differences in friction and temperature trends between the two test groups. The experimental group shows a delayed scuffing onset and slower progression to catastrophic failure, along with reduced out-of-mesh temperatures in both oil-on and oil-off conditions.

Summary

The testing method and data presented show that the friction loss in the gear mesh and out-of-mesh temperature are effective means of evaluating the operation and performance of aerospace gears in loss-of- lubrication conditions. Specifically, gear mesh friction was shown to be a sensitive indicator of scuffing and the progression to catastrophic failure during oil-off events. The effort described in this paper provides an experimental methodology for evaluating oil-off performance of gears — a phenomenon that has been difficult to characterize in the past owing to its catastrophic and sudden nature. Typical failures were found to fall into one of four categories based on severity of the test conditions, and guidelines were proposed to establish the desired failure progression. Examples of data from baseline and experimental test groups demonstrate the ability of the test method to highlight performance improvements of advanced materials, coatings and lubricants in oil-off conditions.

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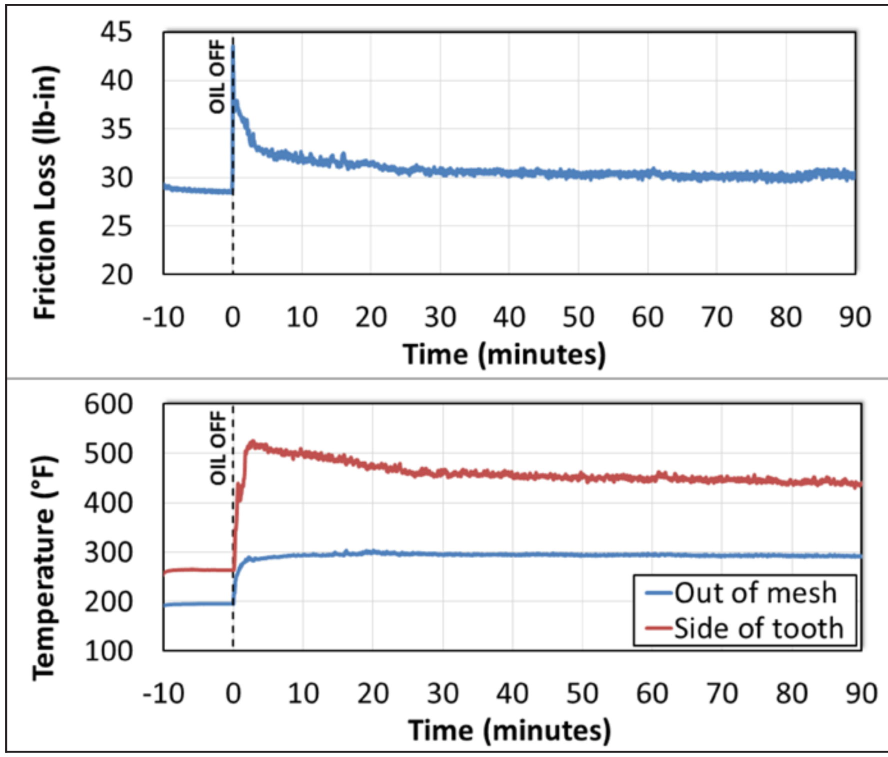

Figure 13 Oil-off results with side-of-tooth thermocouple data (runout).

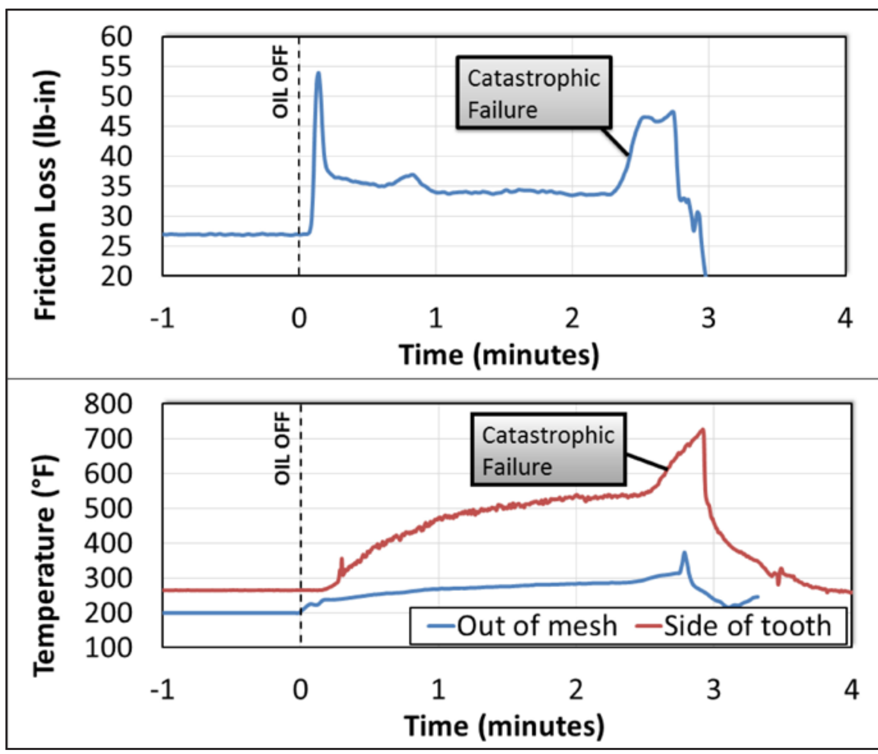

Figure 14 Oil-off results with side-of-tooth thermocouple data (catastrophic failure).

Table 2 Time to failure for baseline vs. experimental group

	Time to Catastrophic Failure (minutes)	
	Baseline Group	Experimental Group
Test #1	0.7	9.1
Test #2	0.7	12.5
Test #3	0.8	5.3

or financial contribution in support of this work.

For more information. Questions or comments regarding this paper? Contact Aaron Isaacson at *aci101@arl.psu.edu.*

References

1. Hudgins, W.A. and H. A. Schuetz. "Loss-of-Lubrication Operation of Helicopter Transmissions," in *34th Annual National Forum of the American Helicopter Society*, Washington, D.C., 1978.
2. Electronic Code of Federal Regulations. Title 14, Chapter I, Subchapter C, "Part 29 - Airworthiness Standards: Transport Category Rotorcraft," 2018.
3. Handschuh, R.F. and W. Morales, "Lubrication System Failure Baseline Testing on an Aerospace Quality Gear Mesh," in *Design Engineering Technical Conferences and Computers and Information in Engineering Conference (ASME)*, Baltimore, Maryland, 2000.
4. Abdelmaseh, M., C. Orkin and E. Sikorski. "Seasprite Oil Out Transmission Testing," in *American Helicopter Society 49th Annual Forum*, St. Louis, Missouri, 1993.
5. Gasparini, G., N. Motta, A. Gabriella and D. Colombo. "Gearbox Loss of Lubrication Performance: Myth, Art or Science?" in *European Rotorcraft Forum*, 2014.
6. Riley, W. and C. Kilmain. "Drive System Loss of Lubrication Operation,"in *American Helicopter Society 67th Annual Forum*, Virginia Beach, Virginia, 2011.
7. Chavez, A., T. Baker and J. Fetty. "Future Advanced Rotorcraft Drive System (FARDS) Full Scale Gearbox Demonstration," in *AHS International 73rd Annual Forum & Technology Display*, Fort Worth, Texas, 2017.
8. Usuki, K., H. Akahori, M. Nakagawa and T. Yamauchi. "Upgrade of Loss-of-Lubrication Operation Capability for EC145T2 (BK117 D-2) Main Gearbox," in *AHS 69th Annual Forum*, Phoenix, Arizona, 2013.
9. Handschuh, R.F. and L. J. Gargano. "Test Facility Simulation Results for Aerospace Loss-ofLubrication of Spur Gears," ***Gear Technology***, pp. 48–53, June 2015.
10. Handschuh, R.F., J. Polly and W. Morales. "Gear Mesh Loss-of-Lubrication Experiments and Analytical Simulation," in *American Helicopter Society 67th Annual Forum*, Virginia Beach, VA, 2011.
11. Acharya, R., H. Zhang, Z. Chaudhry, J. Maglieri and B. Thompson. "Experimental and Numerical Investigation of Lubricant Retention on a Rotating Disc and Gear Teeth," in *AHS International 73rd Annual Forum & Technology Display*, Fort Worth, Texas, 2017.
12. Mukherjee, S., R. Mueller and M. Chakram. "Flow and Heat Transfer Simulation in a Splash Lubricated Bell 525 Accessory Gearbox," in *AHS International 73rd Annual Forum & Technology Display*, Fort Worth, Texas, 2017.
13. Yu, Q., S. McIntyre, R. Kunz, L. Chang and R. Bill. "A Physics-Based Tribology Model and Parametric Assessments of Loss-of-Lubrication Using Reduced-Order System Level Analysis," in *AHS 72nd Annual Forum*, West Palm Beach, FL, 2016.
14. McIntyre, S., Q. Yu, R. Kunz, L. Chang and R. Bill. "A Computational System Model for Gearbox Loss-of-Lubrication," in *AHS 70th Annual Forum*, Montreal, Quebec, 2014.
15. Handschuh, R.F. "Thermal Behavior of Aerospace Spur Gears in Normal and Loss-of-Lubrication Conditions," in *AHS 71st Annual Forum*, Virginia Beach, Virginia, 2015.
16. R. F. Handschuh, R.F., G. Roberts, K. LaBerge and S. Thorp. "Update on Hybrid Gear Research at NASA GRC," in *AHS 71st Annual Forum*, Virginia Beach, Virginia, 2015.
17. Berkebile, S., N. Murthy, K. Radil, B. Dykas, R. Colon-Rivera and J. Fetty. "Experimental Evaluation of Transmission Loss-of-Lubrication Technologies," in *AHS International 74th Annual Forum*, Phoenix, AZ, USA, 2018.
18. Bartilotta, I., E. Ciulli, S. Manconi and E. Toson. "An Experimental Investigation of Aerospace-Quality Gears Operating in Loss-of-Lubrication Condition," ***Gear Technology***, pp. 72–77, August 2013.
19. Riggs, M.R., N. K. Murthy and S. P. Berkebile. "Scuffing Resistance and Starved Lubrication Behavior in Helicopter Gear Contacts: Dependence on Material, Surface Finish, and Novel Lubricants," *Tribology Transactions,* Vol. 16, No. 5, pp. 932–941, 2017.
20. Snidle, R.W., H. P. Evans, M. P. Alanou and M. J. A. Holmes. "Understanding Scuffing and Micropitting of Gears," in *The Control and Reduction of Wear in Military Platforms*, Williamsburg, VA, 2003.
21. LaBerge, K.E., S. P. Berkebile, R. F. Handschuh and G. D. Roberts. "Hybrid Gear Performance Under Loss-of-Lubrication Conditions," in *AHS International 73rd Annual Forum & Technology Display*, Fort Worth, Texas, 2017.
22. Yagi, K., S. Kajita, T. Izumi, J. Koyamachi, M. Tohyama, K. Saito and J. Sugimura. "Simultaneous Synchrotron X-ray Diffraction, Near-Infrared, and Visible In Situ Observation of Scuffing Process of Steel in Sliding Contact" *Tribology Letters,* Vol. 61, No. 2, 2016.
23. Berkebile, S. and K. Radil. "The Progression of Gear Tooth Damage in a Loss-of-Lubrication Event," in *STLE Annual Meeting*, 2016.
24. Berkebile, S.P. Interviewee, *Loss of Lubrication Testing Discussion* – Email Interview, August 31, 2016.
25. Kozachyn, M., M. Robuck, B. Black, S. McIntyre, A. Isaacson and V. Sahay. "Loss of Lubrication Testing," in *AHS 74th Annual Forum and Technology Display*, Phoenix, Arizona, 2018.
26. Isaacson, C., M. E. Wagner, S. B. Rao and G. Sroka. "Impact of Surface Condition and Lubricant on Effective Gear Tooth Friction Coefficient," in *AGMA Fall Technical Meeting Proceedings*, 2016.
27. Berkebile, S., J. Fetty, R. F. Handschuh and B. Dykas. "Finding Oil-Loss Solutions for Rotorcraft Drives," *Aircraft Survivability*, pp. 16–20, Fall 2016.
28. Zhang, H., F. Sun, H. Wu, Z. Chaudhry and J. Maglieri. "Temperature Rise and Tooth Surface Evolution of Gearbox under Loss of Lubrication: Experimental and Numerical Investigation," in *AHS International 74th Annual Forum*, Phoenix, AZ, USA, 2018.

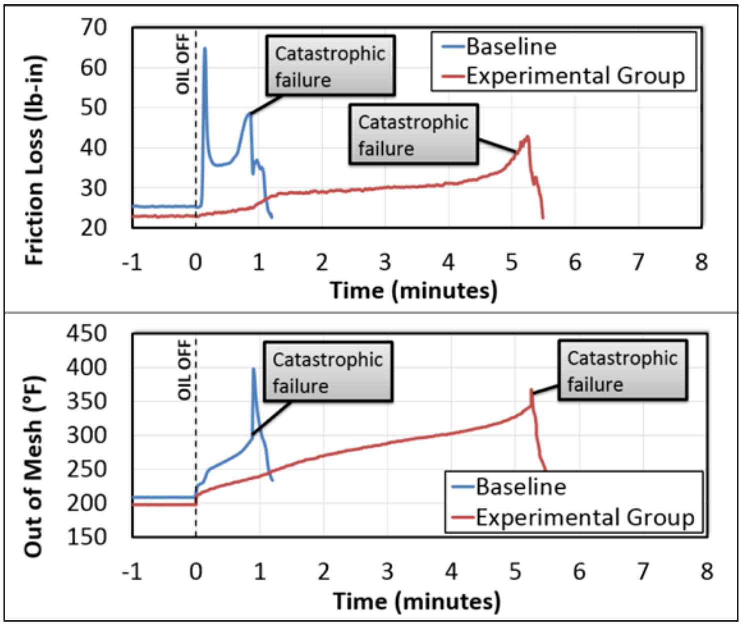

Figure 15 Experimental vs. baseline performance comparison.

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

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

July 10–11—Dritev 2019 Bonn, Germany. Increased CO_2 discussions, sustainable mobility and electrified drives: The automotive transmission world is changing. Why the understanding of the transmission changes, how it is to be understood as part of the overall powertrain and why cross-component know-how becomes more and more important are some of the subjects that will be discussed. Attendees can expect more than 1,500 developers, around 100 international exhibitors and 80 specialist lectures on one of the world's largest networking platforms for powertrain and transmission development. A special thematic focus of the Dritev 2019 is on the special topic Noise Vibration Harshness (NVH), which is both audible and tactile vibrations in motor vehicles in the range from 20 Hz to 100 Hz. Innovative analysis techniques identify these vibrations, reduce them and thus increase ride comfort for the passengers. Another special topic is the increase in powertrain power density. For more information, visit *www.dritev.com*.

July 10–12—AGMA Bevel Gear System Design Oak Lawn, Illinois. Learn how to design and apply bevel gears systems from the initial concept through manufacturing and quality control and on to assembly, installation and maintenance. Engage in a practical hands-on guide to the bevel gear design, manufacture, quality control, assembly, installation rating, lubrication and, most especially, application. Engineers, technicians, and others involved in the selection, application and/or design of bevel gear systems should attend. Ray Drago is the instructor. For more information, visit *www.agma.org/education/advanced-courses/2019-bevel-gear-system-design/*.

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

August 6–8—8th CAR Management Briefing Seminars Grand Traverse Resort, Traverse City, Michigan. The Center for Automotive Research (CAR) MBS leads the industry in providing a context for auto industry stakeholders to discuss critical issues and emerging trends while fostering new industry relationships in daily networking sessions. Seminars include targeted sessions on manufacturing strategy, vehicle lightweighting, connected and automated vehicles, advanced powertrain, supply chain, sales forecasting, purchasing, talent and designing for technology, future factories, design optimization, the mobility ecosystem and more. CAR MBS 2019 will focus on the auto industry's commitment to change, across the spectrum of technology, strategy, mobility, policy, and manufacturing issues. This August, join us to connect with more than 1,000 stakeholders, representing automakers, suppliers, startups, media, government, and academia. For more information, visit *www.cargroup.org*.

August 20–22—AGMA Detailed Gear Design Clearwater Beach, Florida. This class, taught by Raymond Drago of Drive System Technology, will provide gear engineers, gear designers and application engineers with: a basic introduction to gear theory and standardization; practical considerations and limitations associated with the application of standard AGMA/ISO durability rating analyses; investigation of the differences in stress states among the various surface durability failure modes, including pitting, spalling, case crushing and subcase fatigue; extended load capacity analysis techniques; consideration of friction in the calculation of surface compressive stresses; and much more. The course is designed for gear engineers, gear designers, application engineers, and others who are responsible for interpreting gear design or who want to better understand all aspects of gear design. AGMA members: $1,395 for first registrant from a company, $1,195 for additional registrants. Member rate is $1,895 for first registrant, $1,695 for additional registrants. Non-member rate is $2,395, $2,195 for additional registrants. Register at *www.agma.org*.

The Electric Evolution

CTI Symposium Presents Latest Automotive Transmission Developments and Applications

Matthew Jaster, Senior Editor

The challenges remain the same regarding the electrification of the automotive industry. A majority of the CTI Symposium USA event in Novi, Michigan focused on areas like battery life, battery range, cost issues, buyer needs, buyer incentives and charging stations. The focus in 2019 appears to be on bringing competitors and product families together in order to provide a connected eco-system for electrification.

While the industry continues to plan and prepare for major changes regarding e-mobility, ride-sharing, autonomous vehicles, electric commercial bus and freight fleets and the future of the transmission itself, the audience of this very magazine (the suppliers) will be thrilled to learn that almost every panel expert or market analyst at CTI shared a similar, unified voice regarding component suppliers. The word in question: Opportunity.

"The integration that is occurring in the automotive segment will create many new opportunities for suppliers," said Mayank Agochiya, managing director at FEV Consulting, Inc., USA. "These will include sensor integration, software packages and mobility as a service."

In the coming years, the automotive industry also will rely heavily on new product developments and technologies in areas like bearings, drives, motors, pumps, clutches, brakes, etc. Here's what we learned during the symposium:

NVH in Electric Drive Units

Thomas Wellerman, department manager, transmission and driveline systems at FEV, Inc., examined NVH issues in electric drive units during a presentation at CTI.

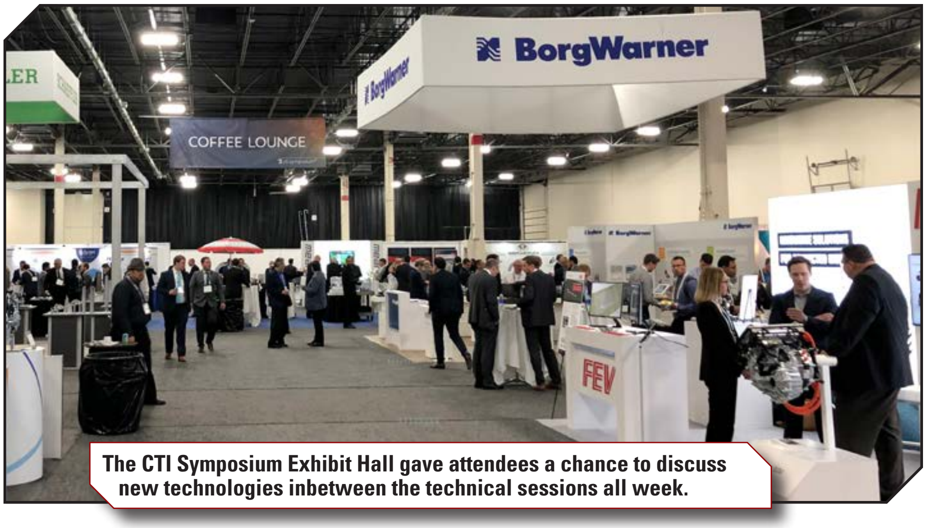
Wellerman said that with powertrain electrification as one of the megatrends in the automotive industry, corresponding market forecasts expect significant increase of shares of electrified powertrains. Pure electric vehicles (EV) and hybrid electric vehicles (HEV) are the most popular types of vehicles utilizing electrified powertrains. For achieving CO_2 fleet targets for passenger vehicles, high growth rates for both EV and HEV are expected, resulting in a strong demand for electric drive units (EDUs).

"The transition from combustion engines towards electric propulsion systems is accompanied by a reduction in vehicle exterior and interior noise levels, in particular during low vehicle speed operation. Without masking effects, objectionable sound content from EDUs in the vehicle interior can become crucial for customer acceptance. Further, electric drive units usually have a very tonal and high frequency content, which often result in an unpleasant sound quality. Therefore, it is important to include NVH considerations throughout the entire EDU development phase," Wellerman said.

An important aspect of electric vehicle development is the change in the vehicle's interior noise behavior. Noise components in the internal combustion engine such as combustion noise, induction and exhaust are no longer present. While these noise levels are reduced, wind and road induced noise become the main contributors to electric vehicle interior noise levels. The noise contribution of an electric drive unit is much lower from a sound pressure level perspective, and has a different noise and frequency content compared to the noise of an internal combustion engine. The tonal noise and high frequency noise character of an EDU is related to both the gear train and the electric motor. This is often subjectively rated as annoying which reduces vehicle pleasantness and ultimately impacts customer satisfaction.

To refine the electric vehicle interior noise level and character, continuous NVH support is needed during the development of the EDU system and its vehicle integration throughout the development process. This includes optimization of the overall EDU system, its individual subcomponents such as the gear drive, electric motor, inverter, and EDU mounting, and their corresponding noise transfer paths into the vehicle. The following areas need to be addressed during the NVH development process for an EDU: Gear train geometry, dynamic gear forces related to EDU drivetrain torsionals, electromagnetic excitation at the rotor/stator interface, stator stiffness, EDU housing stiffness, and power electronics (inverter).

(*www.fev.com*)



The CTI Symposium Exhibit Hall gave attendees a chance to discuss new technologies inbetween the technical sessions all week.

A roundtable discussion on electrification took place during the CTI Symposium USA 2019.

From Industrial to Automotive Applications

A prime example of taking knowledge from one industry and transferring that knowledge to another occurred in the case of Marzocchi Pompe S.P.A. The Italian company produced a gear pump specifically for automotive applications based on their expertise in the industrial segment.

North American Product Engineer, Dr. Andrea Rimondi, spoke about how company used its knowledge and engineering expertise from industrial pumps to build one from the ground up for high-volume automotive applications.

"Today, Marzocchi Pompe supplies the automotive market not only with pumps, but also integrated solutions, complete with motor and manifold with valves, actuator systems, and complete power units with reservoir," Rimondi said. "On one side, a range of products with very high performances and on the other side an enviable product know how that allows our engineers to develop new products in smaller sizes, at reliable and affordable cost as well as micro systems integrated into the gear pump."

Marzocchi Pompe consolidated the production of pumps for the automotive industry in a new plant built in 2016 in Zola Predosa, Bologna. It is divided into two divisions: one takes care of the manufacturing of all the gears for the entire Marzocchi's pump and motor range; the other takes care of the assembly and testing of pumps for automotive applications, on specifically designed lines.

These gear pumps have been specifically designed in order to be integrated into assemblies of automatic transmissions, semi-automatic clutches, electro-hydraulics power steering, AWD systems, assistance in hybrid-type of propulsion, etc. (*www.marzocchipompe.com*)

Deep Groove Ball Bearings for EV Motor Support

Motors used in hybrid electric vehicles (HEV), electric vehicles (EV), and similar drives are required to be small and have high-output. The downsizing of the motor brings demands for higher motor speeds to maintain power output. This in turn requires higher bearing performance. Standard steel and polymer cage designs have limiting speeds below what is needed for the faster drives.

Standard steel and polymer cage designs ring have limiting speeds below what is expected to become common for the electric motors driving vehicles of the future. A presentation by Mike Johns, consultant, advanced engineering, at JTEKT, reviewed the development of a two piece symmetrical dual support cage which increases the limiting speed to about 2 million dmn bearing pitch diameter (mm) x rotational speed (rpm) without the aid of more expensive bearing features like ceramic balls.

When using a steel cage, the contact between the ball and cage pocket intensifies with high shaft speeds due to the eccentric motion of the cage and marginal lubrication at the points of contact between each ball and its cage pocket. This can lead to seizure between the balls and cage.

The more standard crown type polymer cage has pocket claws. These asymmetrical claws deform unevenly when subject to high speed centrifugal loads. A more rigid reinforced crown type cage has excellent high speed performance, but also deforms unevenly at high speeds potentially compromising the ball cage contact. These two types of single piece cages generate more heat at higher speeds and are more prone to lubrication failure and seizure.

It was confirmed during the analysis that the developed cage has a high speed performance over 1.3 times that of existing cages (standard and highly rigid cage). Even after heat shock and durability tests, it was confirmed that the developed cage was free of abnormalities and displayed satisfactory durability. In line with the future growth of the HEV and EV markets, it is predicted that motors will have increasingly higher speeds. It is expected that specialized features like this dual support two piece cage will become more common as the electric motor supports the bearings. (*jtekt-na.com*)

Electric Opportunity

In summary, the panel discussions and Q&A sessions during CTI Symposium USA covered everything from sensors and simulation software to hybrid vehicle analysis and the electrification of trucks here in the United States. Experts debated these subjects as they attempted to look into the crystal ball and determine what the automotive industry will really look like 20 years down the road.

For component suppliers, the opportunity is going to be there no matter how the electrification of the industry pans out. Mechatronic systems, component upgrades and more powerful software tools will play a vital role in the coming years in automotive applications in all formats, ICE, EVs, BEVS, hybrids and more. Working closely with your partners and suppliers today will no doubt benefit product innovation and advancement in the future (win-win no matter what the inside of an automotive vehicle looks like).

For more information:
Car Training Institute (CTI)
Phone: +49 211 88743-3333
www.car-training-institute.com

AGMA and Richard J. Daley College

PARTNER ON NATIONAL TRAINING CENTER IN CHICAGO

The American Gear Manufacturers Association (AGMA) signed a partnership agreement with Richard J. Daley College, one of the City Colleges of Chicago yesterday, officially establishing the first AGMA National Training Center at Daley College in Chicago, IL. The AGMA National Training Center will be the center of engineering and operator level continuing education for all aspects of gear manufacturing.

The 10,000 sq ft. facility will train more than 600 students per year on all facets of gear manufacturing. From hosting the Basic Training for Gear Manufacturing to Gear Failure Analysis, students will be introduced to everything including machine set up basics to complex manufacturing procedures. In addition to the current gear industry and AGMA members, students enrolled in the Richard J. Daley College manufacturing or engineering programs will have the opportunity to participate in the program being offered by AGMA.

Photos courtesy of Richard J. Daley College.

"The National Training Center and the partnership with Daley College will allow us to achieve a significant education milestone for AGMA," said AGMA President Matthew E. Croson. "The education of our workforce has been a primary mission of AGMA for decades, and we are recognized for our efforts on a global scale. The AGMA National Training Center at Daley College will enhance our reputation while delivering a world-class facility, with the equipment, tools and knowledge transfer that will be required to ensure the gear manufacturing industry has its fair share of skilled labor."

Several people from AGMA and the Richard J. Daley College worked diligently together to make the training center a reality. The AGMA Board of Directors, the AGMA Education Committee, spearheaded by Vice President of Education Services Casandra Blassingame, the leadership at Richard J. Daley College including President Dr. Eduardo Garza and the Dean of Engineering and Advanced Manufacturing David Girzadas, have spent months strategically planning how the facility would unfold.

"AGMA has been in partnership with the Richard J. Daley campus for the past 26 years," said Blassingame. "Given the resurgence of the need to educate and train talent for the manufacturing industry, advancing the partnership to establish the AGMA National Training Center in collaboration is a creative and innovative way for industry to connect with education. We are excited about our presence in the backyard of many of our members and we are equally excited about the growth of this partnership under the amazing leadership of Dr. Eduardo Garza and Dean David Girzadas."

By 2020, the AGMA National Training Center will host the majority of AGMA engineering and operator-level courses from April until November. The remainder of the year, AGMA will rotate courses in other parts of the country to offer a variety of locations to those not centered in the Chicago-area. Due to 38% of the gear industry supplier base being in the Chicago backyard, the training center will significantly reduce travel costs for companies in the local area.

"We really cannot thank our partners at Daley College enough for the work that they put into this along with our own members who helped Casandra shape the training center," Croson added. "We hope that this facility will serve not only as an educational resource but will be a platform to introduced skilled workers to the industry and will be a primary tactic AGMA deploys to attract new employees to this dynamic and rewarding career path." (*www.agma.org*)

Seco Tools

NAMES DIRECTOR OF CUSTOMER EXPERIENCE

To maximize customer engagement and satisfaction, Seco Tools has named **Bill Barcelona** as director of customer experience. In this new role, Barcelona and his team will address rapidly evolving customer needs to enhance sales and service responsiveness further throughout the company.

At Seco, Barcelona's responsibilities will include automating and streamlining processes and procedures to provide all customers with the most up-to-date, comprehensive data about their interactions with the company. He will promote effectiveness in foreseeing customer needs and focus on providing ease of use throughout distributor and end-user relationships with the company.

"I'm delighted to welcome Bill to my management team and look forward to his impact on our customer-facing efforts and plans," said Rob Keenan, president of Seco Tools, LLC. "He will be instrumental in our continued emphasis on forging enduring relationships with our customers."

With a background in capital markets and technology, Barcelona joins Seco from Kasasa, Ltd., a Texas-based financial technology and marketing services company, where he served as Senior Vice President, Client Success & Strategy. In that role, he developed a client success team that enhanced customer service and support, yielding significant sales growth by enabling customers to take full advantage of the company's products and services.

"I relish the opportunity to help make the Seco name synonymous with the highest quality of customer support and success as defined by our channel partners and end users," Barcelona said.

Barcelona holds a bachelor's degree in Management Information Systems from the University of Dayton and is pursuing an MBA at the University of Michigan. He lives in Royal Oak with his wife, a research professor in Kinesiology and Health Sciences at Wayne State University, and their three children. The family pursues a love of the outdoors through recreational activities including golf. (*www.secotools.com*)

Forest City Gear

LAUNCHES ADVANCED TURNING AND MILLING FACILITY FOR GEAR BLANK PRODUCTION

Forest City Gear has expanded its turning and milling operations with a state-of-the-art facility designed to greatly improve lead times and quality for the production of precision gear blanks.

This highly productive 8,500 sq. ft. facility is in close proximity to Forest City Gear's main facility in Roscoe, IL, and now dedicated almost solely to the precision turning and milling operations needed to produce precision gear blanks. That's very good news for Forest City Gear customers, says Forest City Gear Turning and Milling Supervisor Mike Miller.

"This gives us complete control over the quality and delivery of the blanks (and slugs) that are the 'near net shape' starting point for many of the gears we produce," Miller said. "The types of projects we take on here at Forest City Gear for customers around the world have never been more demanding from a quality and delivery standpoint. If we start off a project with turned blanks out of tolerance, or waiting for blanks from a supplier, this can ultimately create a devastating production bottleneck when operations upstream are sitting idle waiting for product to arrive."

According to Miller, the facility, with its four late-model CNC lathes, three CNC machining centers, and dedicated Zeiss CMM, easily meets current capacity requirements, and gives the company much additional room to grow. Two Mazak Quick Turn 250 Turning Centers will arrive later this year to further expand capacity, and future plans call for the addition of a 5-axis machining capability for the production of small planetary housings and carriers. (*www.forestcitygear.com*)

Helios Gear Products

ANNOUNCES NEW TECHNICAL LEADERSHIP

Helios Gear Products has announced that **Dennis Hillary** has taken the new leadership position of senior service engineer for the company's technical service group. In response to growing demand for gear machine tool solutions, this team's size has doubled over the past two years. Consequently, Hillary now provides team leadership and mentorship in addition to continued technical service for Helios's North American gear manufacturing customers.

Hillary began his career as a tool maker for a small manufacturer in the Rockford, Illinois area. To grow his career, he moved to Ingersoll Machine Tools after a few years to take a position as a machine assembler. His 15 years' experience with Ingersoll grew to include general machine building, troubleshooting, and technical service. Before finally joining Koepfer America, he worked for a small machine tool rebuilder and retrofitter in the 1990s where he honed his experience and acumen for mechanical machine tool work.

In 1998, Hillary moved to Koepfer America, LLC to take a position as a dedicated service engineer for the fine-pitch gear manufacturing industry. As Koepfer America evolved its solutions, such as introducing the KFS series gear tool sharpening machines in 1999, he became a critical member of the technical team. Today, Helios Gear Products (formerly Koepfer America) recognizes Hillary as the senior leader for mechanical technical challenges, which include continued production of KFS gear tool sharpening machines, rebuilding and re-controlling of Koepfer models 160 and 200 CNC gear hobbing machines, supporting Helios's existing North American machine installations, and training the next generation of Helios personnel.

Hillary has always enjoyed the unique technical challenges associated with gear manufacturing. Considered by many as a "master mechanic," he provides unmatched solutions for customers in the industry. Gear manufacturers know that his mechanical expertise means fast troubleshooting, accurate solutions, and effective training. Said Adam Gimpert, business manager for Helios Gear Products, "Our company's accolades for gear manufacturing machine tool solutions simply would not be without Dennis's ongoing mechanical leadership." (*www.heliosgearproducts.com*)

Weiler Abrasives

RECOGNIZED FOR "LEADING A WARRIORS CHARGE" CAMPAIGN

Weiler Abrasives, a provider of abrasives, power brushes and maintenance products for surface conditioning received the People's Choice Innovation Impact Award at the 2019 Industrial Supply Association Convention on April 8. The award, which honors manufacturers who bring innovative products or services to the industrial MROP channel, is in recognition of the "Leading a Warriors Charge" Campaign the company launched in May 2018. The campaign supports Workshops for Warriors, a nonprofit school providing machining and welding training to veterans, wounded warriors and transitioning service members with the mission to "Rebuild American Manufacturing One Veteran at a Time."

"We are excited to be recognized by our peers in our efforts to bring awareness about Workshops for Warriors," says Nate Schmid, director of marketing – Americas, Weiler Abrasives. "It's taken a lot of hard work to bring the campaign to life, but we are proud to be able to support our veterans as they train to have successful careers in the advanced manufacturing sector. We hope that other manufacturers and industrial distributors will follow in our footsteps."

The "Leading a Warriors Charge" brand awareness and fundraising campaign includes print and digital advertising, video, distributor showroom displays and promotions, tradeshow signage, and a website where visitors can donate and read about success stories from Workshops for Warriors' graduates. To date, the campaign has helped raise over $77,000 for Workshops for Warriors. (*www.weilerabrasives.com*)

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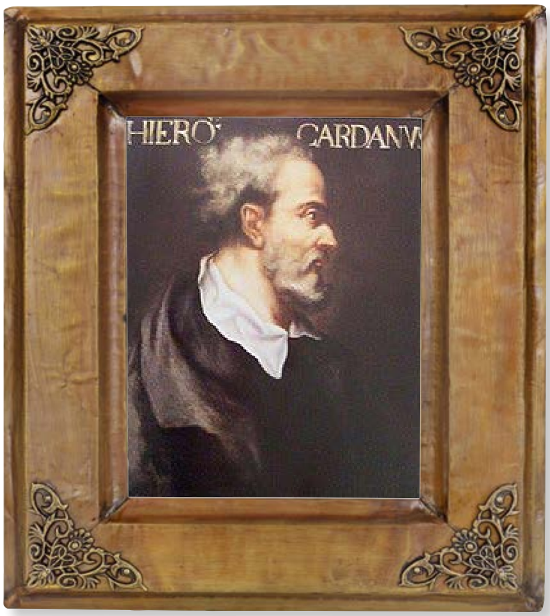
Gerolamo Cardano

A GENIUS BORN TO BE BAD?

Jack McGuinn, Senior Editor



Portrait of Cardano on display at the School of Mathematics and Statistics, University of St Andrews.

Gerolamo Cardano — where to begin? He was an Italian polymath of mystery, mischief and mayhem who also managed to make significant contributions to gear technology and games of chance along the way. Born in Pavia, Lombardy in 1501, history is unsure of his correct first name. He was known as Gerolama, Girolama and Geronimo — so take your pick.

What *is* known is that he was a mathematician, physician, biologist, physicist, chemist, astrologer, astronomer, philosopher, writer — and gambler. He was credited as one of the most influential mathematicians of the Renaissance, as well as a central player in the "foundation of probability," and was the first to introduce binomial coefficients and the binomial theorem to the western world. He wrote more than 200 works on science.

As for gear science, Cardano "partially invented and described" such mechanical devices as the combination lock, the gimbal, and the "Cardan shaft" with universal joints that allow the transmission of rotary motion at various angles. It is still used today. He is also cited for his revolutionary work with hypocycloids, published in *De Proportionibus* (1570). The generating circles of these hypocycloids were later named Cardano circles and were used for the construction of the first high-speed printing presses. What's more, he is recognized for his breakthroughs in algebra; he made the first systematic use of negative numbers in Europe; and published with attribution the solutions of other mathematicians for the cubic and quartic equations; and acknowledged the existence of imaginary numbers — a pretty significant biography for any scientist/inventor/writer.

But check this out.

Cardano was born illegitimately — the son of Fazio Cardano — himself a noted jurist and lawyer and a close paisan of one Leonardo da Vinci. In his autobiography, Cardano revealed that his mother — Chiara Micheri — had resorted to "various abortive medicines" to terminate the pregnancy. Upon birth, Cardano was taken from his mother. In labor for *three days*, just before his birth Mom had moved from Milan to Pavia to escape the Plague; her three other children died from the disease. Which, trying to cut her some slack, raises the question — is it possible Chiara wanted no part of another child lost to the Plague?

It gets worse. Despite enduring a depressing childhood — with frequent illnesses and a rough upbringing by his overbearing father — Cardano in 1520 entered the University of Pavia, studying philosophy and science. His bad luck continuing, war in Italy in forced the closing of the university in 1524. But Cardano continued his studies at the University of Padua, graduating with a doctorate in medicine in 1525.

However, Cardano apparently was possessed with an "eccentric and confrontational style" that did little to endear him with people. After his graduation in 1525, Cardano applied to the College of Physicians in Milan but was denied for reasons including his reputation and — his illegitimate birth. Nevertheless, apparently giving the devil his due, he was often consulted by members of the College of Physicians due to his uncommon intelligence. Cardano wanted to practice medicine where the money was — Milan, for example — but he was (of course) denied a license to practice. That led him to the town of Saccolongo, where he simply practiced without a license. It was there that in 1531 he married Lucia Banderini. Before her death in 1546, they had three children — Giovanni Battista (1534), Chiara (1537) and Aldo (1543). Cardano later wrote that those were the happiest days of his life.

Winning over the help of a few noblemen, Cardano taught mathematics in Milan. After finally receiving his medical license he practiced mathematics and medicine simultaneously. He ironically became one of the most sought-after doctors in Milan, and by 1536 he was able to quit his teaching gig. With his newly won celebrity in medicine, Cardano later wrote that he turned down offers from the kings of Denmark and France, and the Queen of Scotland.

As for his gearing contributions, Cardano's work with hypocycloids led him to what is known today as the "Cardan joint" — or gear mechanism — in which a pair of gears with the smaller being one-half the size of the larger gear is used converting rotational motion to linear motion with enhanced efficiency and precision; he is also credited with the invention of the Cardan suspension or gimbal.

Cardano was always short of money. What to do? He became a skillful gambler and chess player. His success led to his 1564 book about games of chance — *Liber de Ludo Aleae* (*Book on Games of Chance*) — which remained unpublished until 1663. It contains the first systematic treatment of probability — *as well as a section on effective cheating methods.* He rolled dice to understand the basic concepts of probability. Cardano also managed to publish two encyclopedias of natural science.

In 1570, Cardano was arrested by the Inquisition and lost his professorship. Upon his release he moved to Rome and received a lifetime annuity from Pope Gregory XIII.

Cardano was said to correctly predict the exact date of his own death. But, hedging his bets, he was ensured of being correct by — you got it — committing suicide.