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SEP/OCT 2017

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SEP/OCT 2017

GEAR EXPO GUIDE

features

technical

Vol. 34, No. 7 GEAR TECHNOLOGY, The Journal of Gear Manufacturing (ISSN 0743-6858) is published monthly, except in February, April, October and December by Randall Publications LLC, 1840 Jarvis Avenue, Elk Grove Village, IL 60007, (847) 437-6604. Cover price $7.00 U.S. Periodical postage paid at Arlington Heights, IL, and at additional mailing office (USPS No. 749-290). Randall Publications makes every effort to ensure that the processes described in GEAR TECHNOLOGY conform to sound engineering practice. Neither the authors nor the publisher can be held responsible for injuries sustained while following the procedures described. Postmaster: Send address changes to GEAR TECHNOLOGY, The Journal of Gear Manufacturing, 1840 Jarvis Avenue, Elk Grove Village, IL, 60007.


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NEW HMI
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Vol. 34, No. 7

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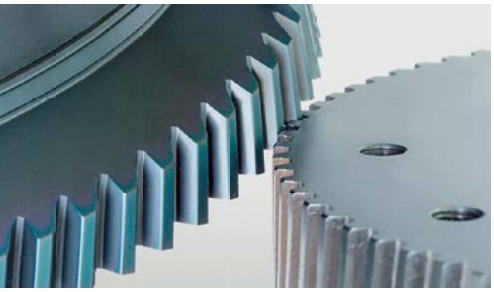

New gear skiving machine LK 300-500
Machine, tool and process from a single source

In the LK 300 and 500 gear skiving machines, process, tools and machine including tool changer and automation system come from a single source because in skiving^3 the delivery of an integrated solution for the customer is of primary interest. Skiving^3 is especially suited for internal gears of medium size and quantity, as it is much faster than shaping and more economical than broaching. The machine can be operated using the touch-based LHGe@rTec control system.

Machine
- Automation
- Deburring and tool changer
- Stiffness

Tool
- Design
- Manufacturing
- Reconditioning

Process
- Technology design
- Implementation
- Optimization

THE GEAR INDUSTRY'S INFORMATION SOURCE

www.geartechnology.com

Everything Gear Expo 2017

Stop by *geartechnology.com* for relevant updates, previews and product information on Gear Expo 2017 taking place in Columbus, Ohio from October 24-26. For three days, the full range of drive technology experts—design, manufacturing, application engineering, gear buyers and manufacturers—network and build relationships that benefit their respective companies.

Ask the Experts Live

Don't forget to stop by the Gear Technology booth (#1022) during the show to ask our live panel of experts your gear-related questions on topics like gear design, software, standards, grinding, inspection and more. And visit the website after the show for interviews and discussions related to Gear Expo.

Gear Talk

Catch up with our resident gear blogger Charles Schultz, who writes a bi-weekly column on his thoughts, musings and observations of the gear industry. (*www.geartechnology.com/blog/*)

GT Videos

Check out (*www.geartechnology.com/videos/*) for the latest videos relevant to gear manufacturing from companies like EMAG, KISSsoft and Sandvik.

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BPA WORLDWIDE℠ BUSINESS

Got Gear Questions? Get Gear Answers!

Publisher & Editor-in-Chief
Michael Goldstein

Gear Expo 2017 is your best opportunity to expand your knowledge, get answers to your technical questions and solve your toughest manufacturing challenges. The reason is quite simple. Gear Expo provides you with the greatest collection of gear expertise, know-how and experience you can find.

Whether you are making gears and gear drives, buying them, or doing some of each, you'll find solution providers at Gear Expo to help you better understand the choices that will work best for your operation. More than 240 exhibitors run the gamut of gears, with software providers and consultants to help you with the design; machinery and cutting tool suppliers to help you with the manufacturing processes and technology; and gear, reducer and components manufacturers to provide you with the finished product. If you make or buy gears or gear-related products, you can't help but find what you need at Gear Expo.

Most importantly, all those exhibitors know things—things you need. From the theorists who work largely in R&D to the practical, hands-on technicians who implement technology in the field, you'll find them all at the Greater Columbus Convention Center in Columbus, OH from October 24–26. They have the knowledge that will allow you to reduce costs, improve productivity, expand your product offerings, increase quality and otherwise improve your operations.

So if you have questions about gears, go to Gear Expo to get the answers.

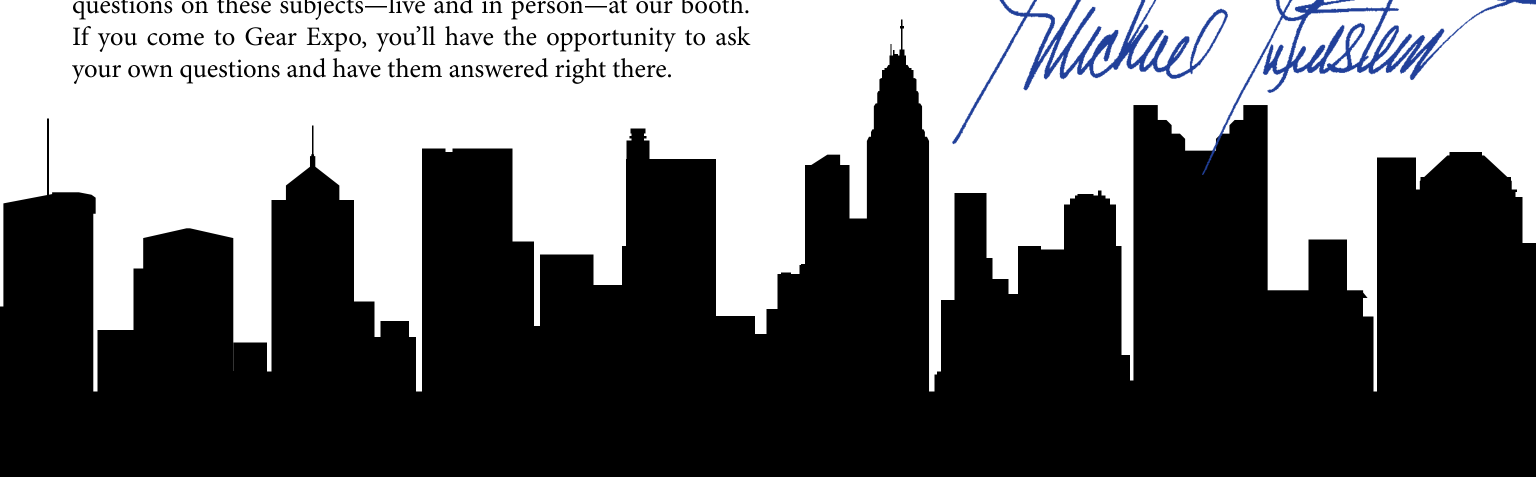
In fact, many of those answers can be found at our booth (***#1022***). As we did at Gear Expo 2015, we're offering four sessions of "Ask the Expert LIVE!" right in our booth. We've assembled four panels of experts to cover the following subject areas: Cylindrical Gear Cutting (Tuesday, Oct. 24 at 10:30 a.m.), Gear Design (Tuesday, Oct. 24 at 2:30 p.m.), Gear inspection (Wednesday, Oct. 25 at 10:30 a.m.) and "Ask Anything" (Wednesday, Oct. 25 at 2:30 p.m.). Our experts will answer your questions on these subjects—live and in person—at our booth. If you come to Gear Expo, you'll have the opportunity to ask your own questions and have them answered right there.

But you can also participate without being there. Send your questions today to Jack McGuinn, Senior Editor (jmcguinn@geartechnology.com), and we'll ask them for you. Questions can be about gear basics or advanced technical problems. Our experts will be able to handle them. Don't worry if you can't be there to hear the answer, either. We're video recording each session, and we'll make those recordings available on our website shortly after the show.

In addition, our editors will be conducting live interviews with many of the technical specialists from exhibitors throughout the show. We have scheduled more than 15 individual interviews to take place in our booth. We'll be asking them about the latest technology and solutions they have on display. We'll be recording these interviews as well, so that we can bring Gear Expo to you whether you were able to attend or not. But we hope you'll be there, because if you're in the audience, you'll have the opportunity to play editor and ask the questions we haven't thought of.

Here at *Gear Technology*, we consider ourselves to be "The Gear Industry's Information Source." Just like it does for you, Gear Expo gives *us* the opportunity to gather far more information, far more quickly and easily than is otherwise possible. We're doing everything we can to capture as much of that information as possible and make it available to you in the formats that are most useful. So stay tuned to our social media channels, our e-mail newsletters, and, of course, the magazine itself. We'll be bringing you lots of information over the coming months based on what we learn at Gear Expo.

We're looking forward to what promises to be one of the best Gear Expo shows in recent years. We hope to see you there.



Why Monitor My Power Consumption?

Joel D. Neidig, ITAMCO

At first, monitoring the energy I use at my plant or the energy for each individual machine seemed trivial. Isn't this just an overhead cost I have to pay? I'm certainly not going to turn off a machine that costs too much to run when I have to get a job out for that month. Then, I realized how much savings there was for monitoring power consumption and the ROI was timely.

Figure 1 Radioshack TSR80.

Most job shops don't run everything all the time. You probably turn off some of the equipment in your shop. Depending on how old it is, there's also the fear that you won't be able to turn it back on!

A device to connect your machines could cost around $500 and then a monitoring solution that can text, e-mail or even tweet machine updates and information directly to you is around $10,000 to $20,000. Let's examine the potential ROI for this scenario:

Let's say your company spent a total of $700,000 and you have two locations [$490,000 (Location A) and $210,000 (Location B)] on electricity in 2016. Out of the total charges, around $100,000 was spent on peak power consumption (also called demand charges).

Figure 2 Single-axis machine tools.

With the implementation of electricity notifications there can be a significant improvement in energy cost. Neglecting the improvement in base consumption—even if you concentrate purely on the peak — you get the following scenarios:

- **Worst case**—20% reduction in demand charge: Savings $20,000
- **Best case**—80% reduction demand charge: Savings $80,000
- **Most probable case**—50% reduction in demand charge: Savings $50,000

Note that the above ROI analysis concentrates only on the demand charge reduction. Strategies to improve the overall energy consumption can lead to five times the savings reported above.

If you're wondering what IoT is at all, let alone what it has to do with manufacturing, it's time to get acquainted. The IoT, or Internet of Things, is the next development of internet connectivity, in which everyday objects—devices, buildings, vehicles, etc.—send and receive data to other objects, and it's about to change everything.

The term IoT was first coined at MIT in 1999 by Kevin Ashton and Sanjay Sarma to describe the development of a global network of objects connected by RFID tags. At the time Ashton and Sarma were making IoT history, I was doing something that MIT and the history books would find much less significant. I was 16, and on the weekends, my friends and I would play strategy games like Warcraft (not WoW), Command & Conquer, Age of Empires and the occasional first-person shooter like Unreal Tournament—our FPS of choice.

Because it was 1999, we didn't have Wi-Fi, and PCs didn't seamlessly connect to the internet. We had a lot of latency or

Figure 3 Microsoft HoloLens.

"lag" back then, and we tried everything to improve our experience. To be honest, we spent most of our time arguing over how the network should be setup. We were geeks, and we knew a bad LAN setup meant the difference between ultimate victory and utter defeat. As teenagers trying to game back in 1999, we experienced issues similar to those the manufacturing industry is experiencing now in 2016.

How can I connect this to that?

Manufacturing has gone from a Radio Shack TSR80 (Fig. 1) and single-axis machine tools (Fig. 2) to a Microsoft HoloLens (Fig. 3) and multi-axis, multi-tasking and multi-channel machine tools (Fig. 4) in a relatively short period of time. It's an evolution that occurred without a standard way to communicate machine-to-machine. As a result, most manufacturers are like me and my friends when we were teens, cobbling devices together and settling for less.

Does it really have to be this hard?

No. MTConnect is a set of open, royalty-free standards that foster greater interoperability between controls, devices and software applications. By publishing data over networks via the internet that are XML-, human- and machine-readable, MTConnect connects manufacturing equipment and manufacturers more holistically. Most machine tools, including DMG MORI, Mazak, Okuma America, etc., now come with it pre-installed, which makes it easier for manufacturers to connect their machines to their machine monitoring software, whether ERP, MES, QMS or any other three-letter acronym business software system you're using.

I first "saw" MTConnect in 2008 at the Emerging Technology Center at IMTS in Chicago, IL. I knew immediately it was a technology our company desperately needed, and we have been involved as a member of MTConnect's Technical Advisory Group working to continue development of the standard ever since. While it's true that our people are our most valuable assets, as manufacturers, our machine tools run a close second. It only makes sense that we leverage the data they generate to make them even more efficient.

Manufacturing has changed. Today when we manufacture an item, we are simultaneously creating and improving technology to make that item better. When we harness the information generated in connected machines, we add value to ourselves and our customers. Just by connecting their factory's machines, most manufacturers increase utilization by 10 percent.

So the next time you're walking through your shop, don't think of your machines as things that just create physical objects; think of them as things that can also generate data to make your job a little easier.

For example, some of the IoT's greatest potential within machining is in third-party integrations. Once your machines' downtime is digitally tracked and automatically synced with, you'll be able to receive new job offers that are perfectly coordinated with machine availability. It's a future where your shop will more or less run itself.

Is your machine shop tapping into the Internet of Things? Learn more at *MTConnect.org*. You can also learn more about how to become involved in Digital Manufacturing at *http://uilabs.org*.

Figure 4 Multi-axis, multi-tasking, and multi-channel machine tools appeared in a relatively short period of time without a standard way to communicate machine-to-machine.

Joel Neidig is the director of reserach and development at ITAMCO. He has been a member of MTConnect since 2009. He has a bachelor's degree in operations management and has had 13 years of experience integrating manufacturing technology and software development. Neidig's experience includes motion control and PLC programming and integration with machine tools, as well as developer of MTConnect compatible mobile device apps for iOS and Android. Look for more articles on IoT topics from Neidig in future issues of *Gear Technology*.

Critical Cooling

TESTS PROVE PROPER COOLANT PRODUCES HIGHER GEAR GRINDING PRODUCTIVITY

DAVID GRAHAM AND PHILIP VARGHESE, NORTON|SAINT-GOBAIN

Selecting the correct coolant can provide numerous benefits. The purpose of using a grinding fluid is to provide lubrication and cooling that are critical to the economical production of precisely ground parts free of metallurgical defects. Additionally, it lowers abrasive cost by reducing wheel wear, aiding chip evacuation and protecting the machine from corrosion.

Inconel 718 (IN718) is the most frequently used nickel based superalloy. Some of the applications of nickel based superalloys are found in aircraft gas turbines, reciprocating engines, metal processing, space vehicles, heat treating equipment, nuclear power plants, chemical and petrochemical industries and heat exchangers (Ref. 1). Components made from this material are either ground using conventional aluminum oxide-based bonded abrasive grinding wheels or cBN superabrasives wheels. Grinding is usually performed with a grinding fluid or coolant. In order to provide the necessary lubrication and cooling capacity and achieve parts free of metallurgical defects while maintaining lower operating and abrasive costs, grinding fluids are developed with very complex formulations.

Figure 1 Norton TG grain.

How to Select the Right Grinding Fluid

When faced with the problem of selecting the optimal grinding fluid type for grinding a specific work material, it is often very difficult to find quantifiable data on wheel performance and wheel life as a function of type of grinding fluid used. There are many types of grinding fluids available for selection. Chief among these are straight oils and water soluble oils. Straight oils can be a blend of one or more of the different base oils (paraffinic, napthenic, synthetic and vegetable) and may contain boundary and/or extreme-pressure additives such as sulfur, phosphorous or chlorine compounds (Ref. 2). While these oils provide good lubricity and rust prevention and are easy to maintain, they are also combustible and components are left with an oily film that might need to be removed before use. In the case of water soluble oils, the concentrates sold by coolant suppliers contain 40 percent or more oil and are mixed with water at a ratio of about 5% to 15% to create the metalworking fluid (Ref. 2). These fluids provide good cooling but due to bacterial growth are not as easy to maintain as straight oils. The selection of an optimal grinding fluid type for any operation will vary based on a number of parameters, including the material to be ground, abrasive type used, wheel wear, maintenance, disposal and associated costs.

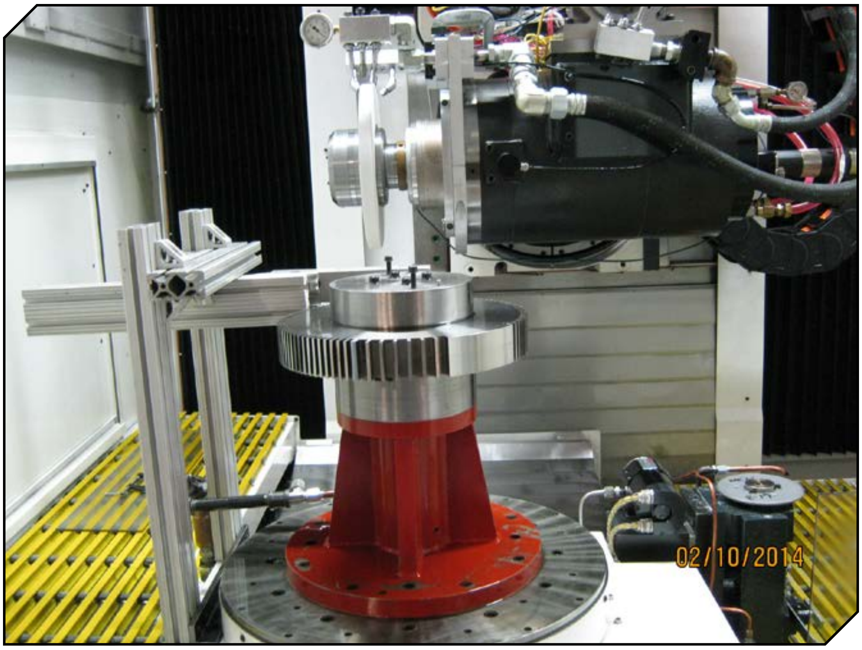


Figure 2 Test setup for grinding IN718 with oil coolant.

The Impact of Different Fluids on Wheel Life

In order to determine the quantifiable impact of the type of grinding fluid on grinding performance and wheel life, engineers from Norton|Saint-Gobain Abrasives did a comparative study at its Higgins Grinding Technology Center in Northborough, Massachusetts. The results of the study proved that grinding IN718 in straight oil gave a 9–10 times improvement in productivity and in wheel life over grinding in water-soluble oil.

Testing consisted of grinding slots in IN-718 parts with half-inch wide wheels. Two creepfeed grinding machines were used; one with a water-soluble oil coolant (Trim VHP E812) and the other with straight oil coolant (Castrol Variocut B27). Wheel speed was constant at 8,500 surface feet per minute and coolant pressure was 175 psi at a flow rate of 55 gallons per minute. An engineered, highly porous, ceramic aluminum-oxide-based grinding wheel specification, TG280-H20VTX2, from Norton Abrasives was tested and high-pressure scrubber nozzles were used to keep the wheel face clean. The TG2 grinding wheel used in this test consists of a shaped TG grain made by replacing post-sinter crushing with a pre-sinter extrusion process (see Figure 1). The resulting needle shaped grains, designated TG and TG2, have extreme aspect ratios (TG = 5:1, TG2 = 8:1). Not only do these grains maintain a high toughness, but they also have a very low packing density. Typical blocky grains will pack to about 50% by volume whereas the extruded grain with an aspect ratio of 8:1 has a packing density closer to 30%. Wheels made with this grain have a very high level of permeability/porosity and excellent coolant carrying capacity. In terms of chip modeling, the high aspect ratio presents a shape factor comparable to a much larger blocky grain, which in turn creates a much larger chip and lower specific cutting energy. The combination of all these factors makes the TG family of grains unusually suited to high stock removal rates when grinding superalloys (Ref. 3).

Figure 2 shows a picture of the test setup used for the grinding test in oil. All grinds were creepfeed in a non-continuous dress mode. Testing was stopped if visual burn was evident on the part. Testing began with straight oil coolant and depth of cut per pass was set at 0.100" (2.5 mm). Work speed began at 10 inches per minute and increased until it reached 180 inches per minute (254–4,572 mm/min). A minimum stock volume of 2 in³ was removed under each condition. With the oil coolant there was never any evidence of burn/thermal damage. Subsequent metallurgical analysis confirmed no burn, and bent grains on the part did not extend more than 0.001" (25 µm) below the surface. The test with WSO coolant began using the same 0.100" depth of cut used in the oil test. However, burn occurred at the first feed rate of 10 inches per minute (254 mm/min). Therefore, an alternate strategy was adopted in which a specific removal rate was set and work speeds were varied to determine when burn would occur. To keep the specific removal rate constant, the depth of cut was decreased as the work speed was increased. Specific removal rates of 1.0, 2.5 and 3.125 in³/

min/in (10, 25 and 31 mm³/sec/mm) were chosen and table speeds between 6.1 and 300 inches per minute (2.6 mm/sec –127 mm/sec) were tested.

Figures 3 and 4 show the graphs of specific power and grinding energy versus volumetric material removal rate. Specific grinding energy, which is defined as the energy required to remove a unit volume of material, is a measure of the efficiency of the grinding process. There is no difference observed in both these graphs when grinding IN718 with the TG2 wheel in oil vs. water soluble coolant.

Figure 5 shows a graph of G-Ratio vs. Volumetric Material Removal Rate. G-Ratio, which is an indicator of wheel life, was significantly higher when grind-

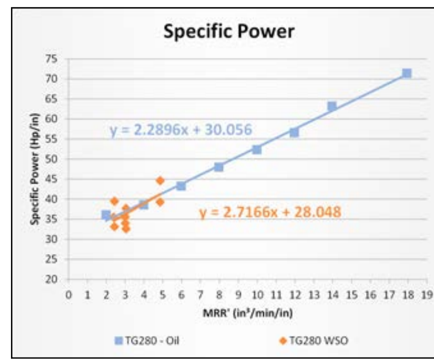


Figure 3 Variation of specific power vs. volumetric material removal rate.

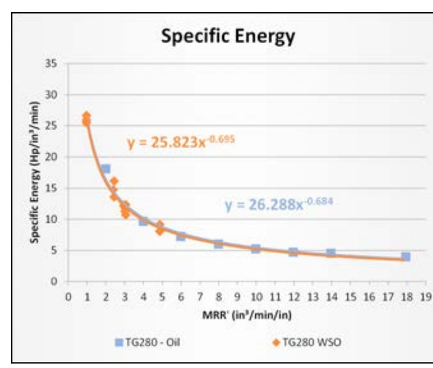


Figure 4 Variation of specific energy vs. volumetric material removal rate.

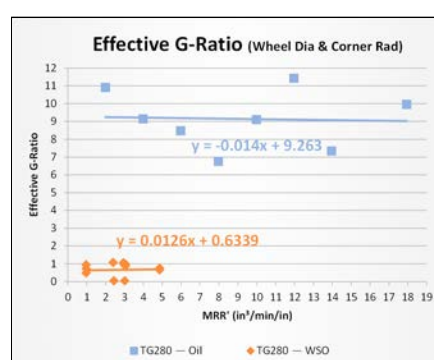


Figure 5 G-ratio vs. volumetric material removal rate.

ing in oil coolant. Because rapid wheel wear was observed, it wasn't practical to continue increasing removal rates when grinding in water soluble coolant beyond 5 in³/min/in (50 mm³/sec/mm). However when grinding with oil coolant, removal rates as high as 18 in³/min/in (180 mm³/sec/mm) with minimal impact on G-ratio are possible. This illustrates higher productivity, shorter cycle times and increased wheel life when grinding in oil.

When grinding with WSO, there were certain operating conditions which led to the occurrence of burn on the work pieces, and work speeds were varied to reduce or eliminate burn. As illustrated in Figure 6, at a constant volumetric stock removal rate, as the work speed was increased (and depth of cut decreased), the risk of burn diminished. We would therefore expect that for higher work speeds, the specific grinding energy would be lower. When thinking of the grinding zone as a moving heat source, as the rate increased, the time the source is in contact with any point on the part decreases, and thereby limits the amount of heat that is transferred to the part.

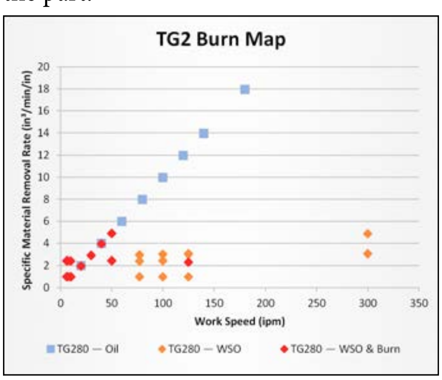


Figure 6 **At a constant volumetric stock removal rate, as the work speed was increased (and depth of cut decreased), the risk of burn diminished.**

Figure 7 shows a graph where the specific grinding energy for each removal rate is plotted with respect to the work speed, it is clear that the trend for increasing specific grinding energy with decreasing work speed holds true. This is due to the fact that, for a given removal rate, as work speed increases and the depth of cut gets smaller, the chip thickness increases. Whereas at lower work speeds, chip thickness is diminished and more energy is consumed in friction due

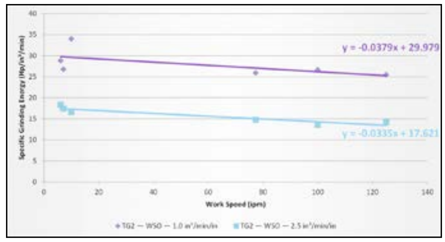


Figure 7 **Graph shows where the specific grinding energy for each removal rate is plotted with respect to the work speed.**

to plowing and sliding interactions in the grinding zone. It should be noted that this strategy for alleviating burn was only used in grinding with water-soluble coolant.

In summary, the results from the comparative test demonstrates the quantifiable impact of the type of grinding fluid (straight oil coolant, water soluble coolant) on the grinding performance and wheel life, when grinding IN718 alloy with a modern aluminum-oxide-based ceramic grinding wheel. Both in terms of achieving higher productivity and wheel life, straight oil coolant outperforms water soluble oil coolant. However, the actual performance and G-ratio values will be different for each grinding wheel and work material combination. Additionally, the reason for certain operating conditions causing the occurrence of burn on the components when grinding in water soluble coolant versus oil coolant needs to be investigated with additional testing and thermal modeling, taking into account the dissimilar properties of the two types of coolant.

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3. Hitchiner M., Besse J., Varghese P., "Grinding Innovation in a Growing Defense Market," MFG4The Future Conference, Hartford, 2012.

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DIGITAL MICROMETER INTEGRATES DATA TRANSMISSION

Mahr wireless data transmission capability is now integrated within its new digital micrometer Micromar 40 EWRi. The new 40 EWRi is the latest addition to Mahr's Integrated wireless family of products, including digital calipers, Indicators and depth gages, which allow users to measure faster, more easily and more reliably. Measurement data is transferred to an i-Stick on a computer without any interfering data cables, and MarCom software makes data acquisition simple: just take a measurement and transmit measuring data directly into MS Excel or via a keyboard code into any Windows program or existing SPC application.

Micromar 40 EWRi is the first digital micrometer with large 10 mm digits on a high contrast digital display, making for safe fatigue-free reading of the measured values. It offers an easy to understand tolerance display and additionally displays warning limits.

The reference system in the Micromar 40 EWRi makes handling the micrometer very simple since the zero position is set only once. This setting remains stored for all further measurements. Also, a new "Hold" function (digital lock) allows measured values to be "frozen" so they can be easily read.

Highly precise, the Micromar 40 EWRi micrometer is equipped with a state-of-the-art inductive measuring system that exceeds international standards. Class IP65 protection against dust, coolants and lubricants makes the Micromar 40 EWRi ideally suited for use in difficult environments in the manufacturing environment.

The MarConnect integrated wireless interface is active as soon as the i-stick is plugged in, and each micrometer/caliper/indicator is identified by signal coding in the *MarCom* software so there is no confusion as to signals. The micrometer confirms whether the transmitted data was transferred correctly, or whether the operator is in the receiving area of the i-Stick receiver.

Since the wireless data transmitters are built into the micrometer/caliper/indicator, no interface boxes or additional batteries are required. Plus, integrating the transmitters into the gage electronics makes the units extremely energy efficient and can extend battery life up to 50% longer than competitive systems.

For more information:
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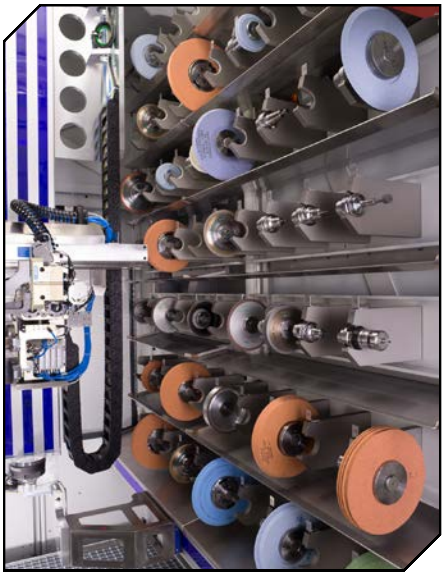
Haas Multigrind

CA AND CB MACHINES UTILIZE HIGH-CAPACITY GRINDING WHEEL SHELF MAGAZINES

All Haas Multigrind grinding centers are available with an automatic wheel changer. This feature enables Haas customers to combine multiple high-precision, complex grinding and milling operations into a single part clamping and single machine cycle. Users can realize significant improvements in overall part quality and significant reductions in overall throughput time and cost.



Now Haas customers can take another leap in productivity with the new high-capacity "shelf magazine." On the Multigrind CB grinding machine, the new Haas shelf magazine (2,000 × 2,400 × 3,200 mm, L × W × H) offers space for 65 grinding wheels of up to 300 mm diameter. On the Multigrind CA grinding machine, the shelf magazine can be equipped with up to 70 grinding wheels of up to 250 mm diameter. The magazine can also hold up to 20 coolant nozzles.

The new high capacity magazine enables customers to add more operations on a single part AND to dramatically reduce change-over time between different parts by loading wheels and tools for multiple part numbers in the magazine.

The Haas Horizon programming system maintains locations, dimensions and life information of all wheels and tools in the magazine in addition to programming the machine's grinding and automation functions.

Even with much more wheel capacity, tool change time on the new shelf magazine is only 10 seconds.

"We're not aware of any other tool magazine that offers as much space and flexibility." says Dirk Wember, Haas Multigrind's president.

The system was first unveiled to the general public in April 2017 at Haas's GrindDate, their in-house trade fair. In June is created strong interest when presented at the Paris Airshow.

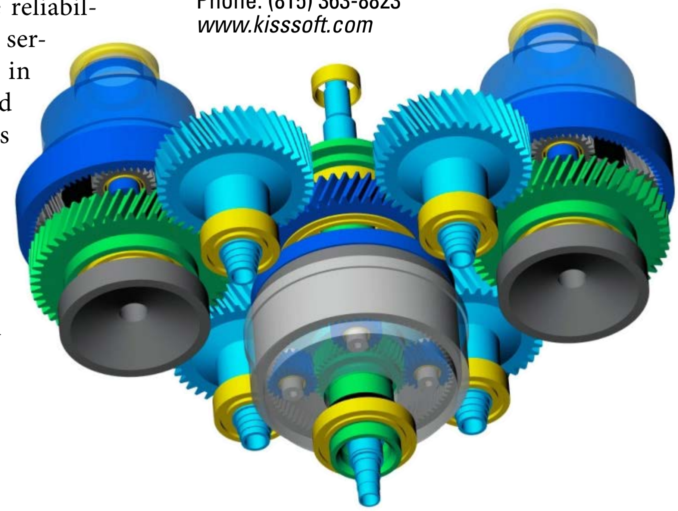
For more information:
Haas Multigrind LLC
Phone: (574) 268-0053
www.haas-schiefmaschinen.de/en

KISSsoft

UPDATES SYSTEM CALCULATION WITH KISSSYS

A function in *KISSsoft Release 03/2017* enables you to evaluate the reliability of gear units, individual gears and rolling bearings. (New KLR module)

For gears, the reliability is evaluated for tooth root fracture and pitting, whereas for rolling bearings, the reliability is determined using the service life method specified in ISO 281 or ISO 16281, and the results are displayed as a graphic. The calculation is performed according to Bernd Bertsche. The well-established 3-parameter Weibull distribution method is used as the statistical model.



The way in which the model tree structure is handled in *KISSsys* has also been improved. Elements can now be deleted, renamed, copied, cut out and pasted in. All the references involved in your model are also displayed clearly. All the paths in the structure can be updated as needed. This has the advantage that there are no limitations on the changes you can make to the model tree structure at a later date.

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The Valued Troublesome Employee

To Terminate or Not to Terminate

Joe Arvin

I'm sure it comes as no surprise that finding skilled people to work in your manufacturing facility is no simple task. But after finding them, and investing in the development of their abilities, what happens when one of them—an employee your company really needs—becomes a troublesome employee? This is among the trickiest situations a manager can face.

Early in my career, I was faced with this challenge. When I first became a supervisor at Indiana Gear Works, one of the people reporting to me was Max, the lead man for the department. Max was very talented at setting up the machines. In fact, he was the best we had…and he knew it. But there was a problem with Max. He was a troublesome employee. He was disruptive, disregarded work rules, showed no respect for management, and was a prime example of someone with a caustic bad attitude. He expressed his belligerent attitude for the workplace by frequently being late for work, taking extra time for lunch, and periodically he was even insubordinate. Any suggestion to Max that he was out of line was met with a look that conveyed, "Yeah, what are you gonna do about it?"

I learned that the previous supervisor had been reluctant to confront Max about his bad attitude because of his technical competency. And this led to another deeper problem: the other workers in the department saw how Max was able to get away with ignoring work rules, and more than a few had picked up bad behavior as well.

After a couple of days of this, my impulse was to march over to Max's work station and point to the door. But then again, what would happen to our productivity if our best lead man was shown the door? This really felt like a no-win scenario.

First of all, terminating any employee should never be taken lightly. And it is essential that you as a manager attempt to get to the heart of the matter and work through a carefully thought-out resolution strategy that takes emotion out of the formula.

A good first step is to ask yourself some questions:

- How much harm is the individual causing to the work environment?
- How difficult will it be to replace his or her expertise?
- Is the person genuinely trying to do a good job but his or her communication style is the problem?
- What is the likelihood of an intervention resolving the problem?

Most companies have disciplinary procedures in place, so I won't take the time to address policies, labor law, or best practices. However, here are a few ideas about how to systematically work through the problem.

The first step should include informal, friendly, and positive conversations with the individual. This process can provide some valuable insights as you size up the problem. Next, a private conversation with the individual that is still friendly, but direct, is a good step. Here you can explain the detrimental effects of their actions and what work rules have been violated and ask them for their assistance in resolving the problem.

Here is a potential approach for this conversation.

Bob, you are a valued employee and you have a great talent. We definitely need you and want you here. But the fact that you're not following the work rules is causing some problems. First, your behavior is negatively affecting the attitudes of the other workers, and this is bad for the company. And by not following the rules, you're putting me in a bad position. You see, the company's management is expecting me to do my job and ensure that all work rules are followed. If I don't take action about your behavior, I'm not doing my job. If things keep going as they are, you'll be giving me no other option than to administer the company's disciplinary procedures. So, it's really up to you, and I'm asking for you to help me and for you to do the right thing for the company.

If the employee's behavior shows no improvement, consider these next steps.

First, recruit someone in management who may have a good relationship with the person to talk to them about the problem. Also, a talk with your HR manager should be included.

So now you're thinking, "Come on Joe, how long do I have to tip-toe around this person?"

These friendly conversations are important initial steps to see if you can easily resolve the problem. Remember that your company really does need this person's contributions. But by this time, if your efforts have yielded no improvement, it's time to dial things up.

The next step now is the verbal warning—where the issues are clearly delineated. And make sure they know that this is an official verbal warning. The employee should also be informed of what is to follow if improvement does not take place. Be sure that a written note of this conversation is placed in their HR file.

If there is no improvement, then it's time for a formal written warning. You should ask the person to sign this, but it is not uncommon for someone to refuse to sign. If this is the case, make a note as such in their HR file.

If there is still no improvement, it's time for a three-day disciplinary lay off. And of course the last step is termination. But if termination is the outcome, this should come as absolutely no surprise to the person.

Again, one must look at the negative effects this person is having on the work environment. If this negative behavior outweighs the positive value of the individual's contributions, losing them may have a short term negative impact on your productivity, but you will most likely be better off in the long term.

But now back to the story about Max.

Being a new supervisor, I felt caught between a rock and a hard place. At first, I let the situation ride for a while, but eventually it became clear to me after discussions with my manager and HR that Max had to go. Finally when the deed was done, and Max was terminated, I thought those in management would welcome the fact that I had taken care of the dirty work. But on the very next day, the plant manager stopped me and said, "I hope you're not going to be sorry. Max was the only one who could set up the most difficult jobs and he had the highest efficiency in the department." Yes, I hoped I had not made a serious mistake.

Then an interesting thing happened. With Max gone, another operator named Dale asked for the opportunity to set up several of Max's difficult jobs. "Of course," I said, having nothing to lose. Wouldn't you know, after a couple of days, Dale was setting up the jobs as fast as Max. When I asked Dale about why he had not taken this initiative before, he said, "Max didn't want anyone setting up his jobs."

After Max's departure, there were other changes as well. I found that everyone was at their work stations even before the start of their shift and right after lunch. At first, there was a decline in the department's output, but in a short period of time, the department efficiency increased and started to surpass previous records.

This reminded me of what I had observed when I was in the military when I saw first hand the Army's no-nonsense approach to discipline. The Army's methods of discipline not only served as a swift way to bring an individual in line with the rules, but also showed others that the rules were to be taken seriously and rigorously adhered to. I'm certainly not suggesting managers should run their companies like an iron-fisted drill sergeant, but keep in mind the value of having others see the importance of the rules and your commitment to making sure they are followed.

But that's not the end of Max's story.

Max called me three weeks after his termination and said that after giving it some careful thought, he figured he had actually been at fault because he thought management would never let him go. So, with a "Last Chance Agreement" I had Max's employment reinstated. And while Max was never going to win a departmental award for congeniality, he did correct his errant ways and became a valued contributor to the department for many years.

I learned from this that there is nothing wrong with offering a person their job back after some time has passed. However, the ex-employee must know that their behavior must change if they elect to return. It has been proven, more often than not, if the person returns to work for one last chance, their attitude and behavior will indeed improve. Losing your job, especially if it was your fault, is one of the most stressful things a person can go through. In the case of Max, it was just what was needed for the message to get through.

Finally, it comes down to this. We may not always like the people we work with or have complete harmony, but it is essential that people work together and managers strive to promote a civil environment. This has long-reaching benefits for making your company productive and for being a positive place for people to work.


Joe Arvin is a veteran of the gear manufacturing industry. After 40 years at Arrow Gear Company, Joe Arvin is now President of Arvin Global Solutions (AGS). AGS offers a full range of consulting services to the manufacturing industry. His website is *www.ArvinGlobalSolutions.com* and he can be reached by email at *ArvinGlobal@Gmail.com*.

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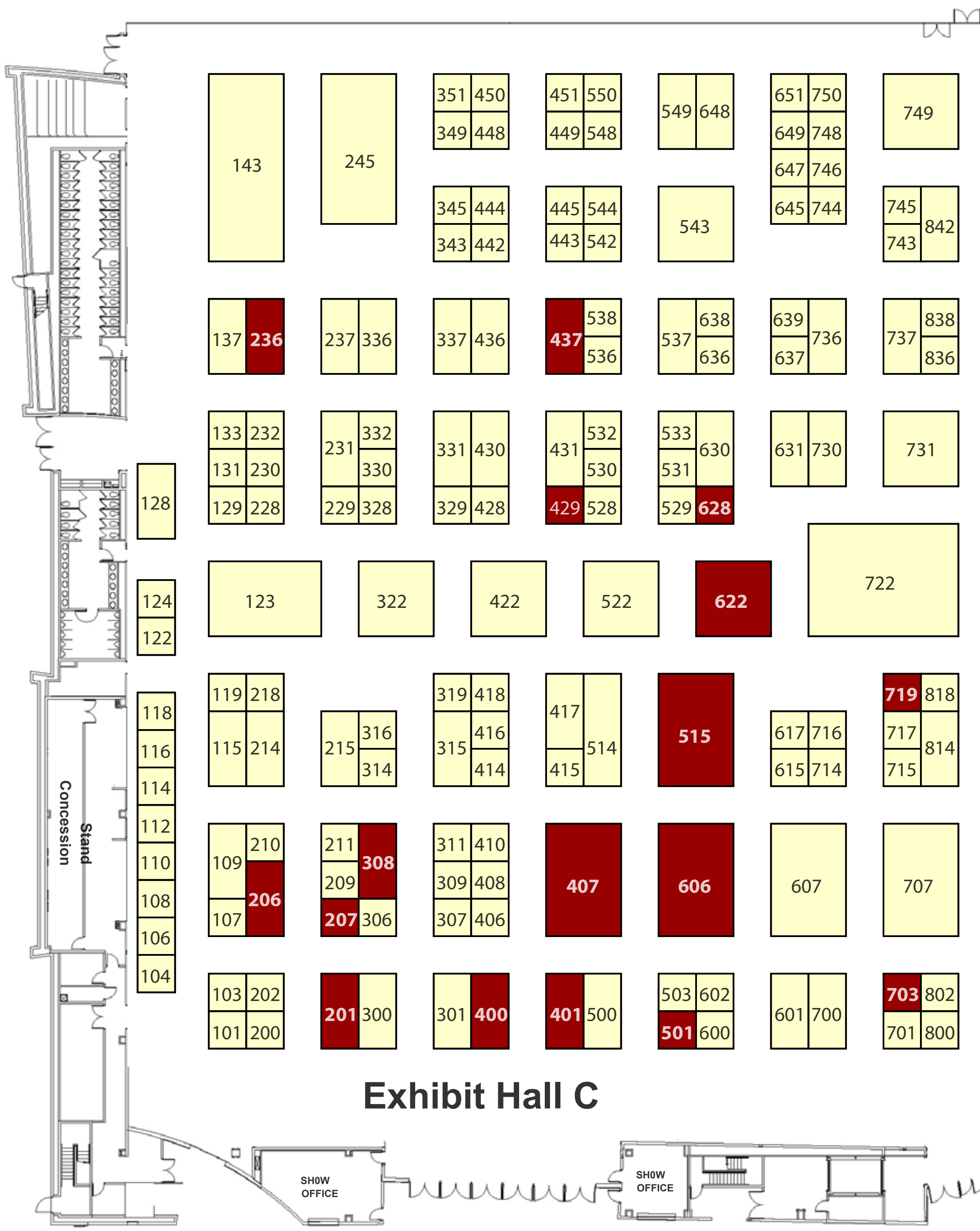

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The latest technology on display in Columbus, October 24–26

Alex Cannella, Associate Editor

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ACE will show off GIT Automation (Guaranteed Inspection and Traceability Automation), which is designed to eliminate uncertainty by incorporating inspection and traceability inside your automation cell. Parts are inspected and marked before they leave the cell, eliminating downstream in-process gauges and laser marking stations.

ACE's patented robotic material handling system will load/unload gears or shafts directly from trays with bore vertical or bore horizontal, then have gears washed, roll checked for runout/TCE and laser marked for traceability — all inside the automation cell.

ACE will also feature Slone Gear International's *GearVU* software on Non-Contact Laser Measurement and Contact Laser Measurement Systems. *GearVU* software is designed to accomplish 100 percent production volume tooth profile measurement in seconds and can accurately measure down to microns.

For more information:
Automation Controls & Engineering, LLC
Phone: (734) 424-5500
www.ace-automation.net

Affolter

Booth 537

Visitors will see the brand-new gear hobbing center Affolter AF110 Plus, the most advanced machine offered by Affolter Technologies.

The AF110 Plus has eight axes with a maximum DP17, minimum DP1270 and a spindle speed of up to 12,000 rpm. Different automation systems for part loading and unloading are available, such as universal grippers, drum loader or robot loading as well as options such as deburring, dry cutting, centering microscope and oil mist aspiration.

The new loader system AF71 with two grippers ensures 24 hours automatic production. While a gear is in the hobbing process, the other gripper reaches out for the next part to load. The AF110 Plus can cut spur, helical, frontal, bevel and crown gears. The machine is equipped with the in-house developed Affolter Leste CNC control, specifically designed for handling up to 12 axes. The newly designed worm screw power skiving (WSPS) technology is available as an option.

"It is an innovative machine concept: Power, rigidity, and precision combined with universal applicability provide a means of manufacturing complex parts at the cutting edge of technology. From standard products to custom-made developments, it encompasses the full range of expertise in very stringent fields," explains Mikael Affolter, head of sales at Affolter Technologies.

Affolter Technologies recently introduced the innovative WSPS process. Unlike in worm hobbing, where the hob turns much faster than the workpiece, the Affolter engineers inverted the process. "The workpiece turns extremely fast, with two new spindles up to 12,000 rpm, while the cutter turns much slower. Only technology advanced machines can reach such speeds and at the same time provide the necessary stiffness", says Managing Director Vincent Affolter.

The company sees a large demand for this WSPS technology in the automotive, aerospace and medical equipment industries. "WSPS allows us to finish a high-precision worm in only six seconds. If done by worm hobbing, every piece takes about 25 seconds," explains Affolter. In other words: WSPS reduces cycle time by up to four times. Manufacturers of high volume worms in these industries will greatly benefit from this new process. The WSPS technology focuses on small worms with a module up to 17 DP.

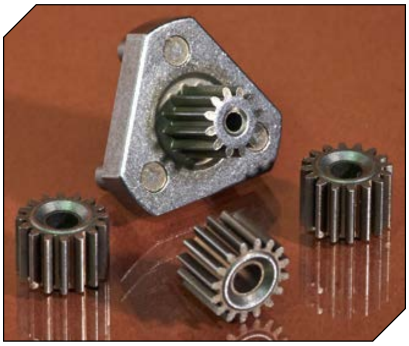
For more information:
Affolter Technologies
Phone: +41 32 491 70 00
www.affolter-applications.ch

Asco Sintering

Booth 207

ASCO Sintering Co. will exhibit its award-winning powder metallurgy gears.

"ASCO's participation in Gear Expo helps reinforce our position as an acknowledged industry leader in the manufacture of award-winning highly complex powdered metal gears and planetary gear carriers through the application of a six sigma zero-defect philosophy," stated the company.



ASCO received the MPIF Grand Prize Award in the Medical/Dental Category in 2015 for its sinter-hardened steel planetary gear system, featuring a carrier with an integrated sun gear and three planetary gears.

The company's latest PM gears will be on display with sales and engineering management staff in attendance to discuss their design and application.

For more information:
ASCO Sintering Co.
Phone: (323) 725-3550
www.ascosintering.com

Bourn & Koch
Booth 407

Bourn & Koch, Inc. will feature their re-engineered 100H horizontal gear hobber. Capable of producing gears up to AGMA Q-13 (Q-9 to Q10 typical) in a compact footprint, the 100H now features their brand new, Millennial-friendly BK-HMI conversational gear cutting software, which drastically reduces the time and specialized knowledge required to program a quality gear.

The new BK-HMI is displayed on a full 19.5" touchscreen monitor with an integrated cycle time calculator, error-proofing and numerous modular programming cycles, including Bourn & Koch's industry exclusive point-to-point array programming. The re-engineered 100H also features a more ergonomic machine tool enclosure, ready for integration with automation.

The Bourn & Koch 100H features standard single and double cut cycles, Fanuc 0i-F CNC control, a power-programmable CNC hob swivel, automatic hob shift, crown and taper hobbing cycles, constructed with hardened and ground precision linear ways, a 4.00" diameter hob slide and a standard high-intensity work light. The 100H can cut gears up to 127 mm in diameter and 2.54 module.

The 100H has the same spindle face as the Barber-Colman 6-10, allowing for all workholding and tooling to be directly interchangeable between the two machines. This makes the transition to CNC gear hobbing a less costly investment overall. In a head-to-head complete cycle time comparison, a newly trained machine operator can set-up, program and cut a gear on a 100H 25 percent faster than on a Barber-Colman 6-10. The 100H also produces superior quality.

For more information:
Bourn & Koch, Inc.
Phone: (815) 965-4013
www.bourn-koch.com

EMAG USA
Booth 1107

EMAG USA will feature manufacturing systems for precision metal components with a special focus on its solutions for gear manufacturing.

The modular VL Series for chucked components will be on display, with EMAG's VL 4 machine. With the goal of developing a system of modular machines for medium and large batch runs, EMAG offers flexible solutions on a standard machining platform. For example, the process of single spline hobbing can be performed on a VT vertical lathe for shafts. With the capability of offering gear cutting on a standard machine, EMAG modular machines offer flexibility over specialized and custom hobbing machines. Machining is performed on four axes at a maximum speed of 6,000 rpm. The process employs two turrets with twelve tool stations each equipped with turning tools or driven tools. One common feature of the VL and VT machine sizes is the shared modular design. Their small footprint reduces floor space costs and increases flexibility in floor layout options. Every VL and VT machine features an integrated automation system for transporting workpieces. When combined with the self-loading pick-up spindles, this automation concept ensures short cycle times and high productivity. To accommodate machine operators, all the service units are easily within reach, with the various units (electrics, hydraulics, cooling system, cooling lubricant and central lubrication system) accessible at any time so that the machines can be maintained with ease. While the standard lathes are commonly used for gear blanks, a wide range of technologies can be incorporated into the machines, including turning, grinding, hobbing, chamfering, induction hardening and laser welding. (More information at *vl-vt.emag.com*)

The technologies in the EMAG Group cover the entire spectrum of metalworking — including non-traditional processes. Laser welding is essential in the light weighting of automotive components while electro-chemical machining (ECM) is a broaching and deburring option. For more information on ECM Broaching, EMAG ECM experts will be giving a presentation on the topic in the Solutions Center at the show. In addition to the VL 4, EMAG will have an eldec induction hardening system with a modular induction (MIND) machine at the show. Featuring Simultaneous Dual Frequency (SDF) technology, where two different frequencies are applied to the workpiece, MIND machines can apply mid-frequencies to penetrate deeper and heat the root of the gear tooth simultaneous to high frequencies to accurately heat the tip of the tooth. eldec hardening systems complement the workpieces machined by EMAG lathes to create efficient, complete production lines. The flexible machine concepts and complete systems from EMAG offer modular and customized solutions for the production of workpieces in nearly every industry.

For more information:
EMAG USA
Phone: (248) 477-7440
www.emag.com

Emuge
Booth 1501

Emuge Corp. will showcase their comprehensive line of clamping solutions for applications from low volume job shops to high volume automotive production environments.

"Our workholding group stays close to our customers to learn about their unique challenges and production environments. Doing so helps us develop the best solutions for their applications," said David Jones, precision workholding manager at Emuge Corp. The precision workholding lineup on display will include:

Emuge's System SG features an expanding-bush design and is used in many machining operations such as hobbing, shaping and shaving for gear production, as well as milling and inspection. The System SG's large surface area contact with the workpiece provides a clamping solution which is very rigid, accurate and repeatable.

The high precision System SP, is used not only to clamp workpieces but also tools. By applying an axial force, the clamping sleeves move in the direction of the force and expand radially. This eliminates the clearance between clamping sleeve and body, and between clamping sleeve and workpiece. System SP achieves concentricity of < 0.002 mm (corresponding to < 0.0001 inch).

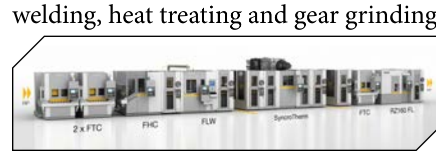
System SZ is designed for use on workpieces that have a short clamping base or for diameters with a very large tolerance. By applying an axial force, a slitted collet is radially expanded by a cone. Simultaneously an axial movement occurs, clamping the workpiece.

Diaphragm clamping System SM is ideal for when the eccentricity between pitch circle and seating bore is very small. It allows clamping of the gear wheel at the pitch circle for machining the seating bore. The gear wheel is clamped in both axial and radial directions.

For more information:
Emuge Corporation Precision Workholding Group
Phone: (800) 323-3013
www.emuge.com/products/precision-workholding

Felsomat
Booth 1135

Attendees will be able to review and discuss Felsomat's Flexline — the flexible manufacturing solution combining all aspects of gear production into a seamless automated cell. This unique concept incorporates turning, hobbing, laser welding, heat treating and gear grinding.



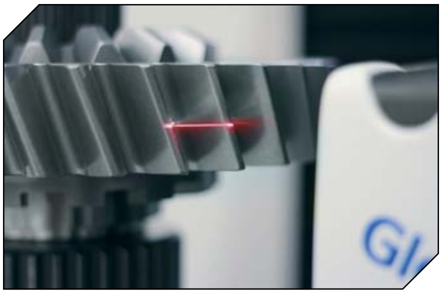
Felsomat has garnered a global reputation for precise, efficient and autonomous loading systems designed to enable all manufacturing processes to be completely decoupled. Felsomat solutions include gantry, single-arm robotic cells and automated storage/stacker cells.

For more information:
Felsomat USA
Phone: (847) 995-1086
www.felsomat.com

Gleason

Booths 1411 and 1628

Gleason will demonstrate a host of advanced machines, tooling, software and global customer support services.



Among the most noteworthy of the new technologies is the Gleason 300GMSL inspection system, which, in addition to conventional tactile probing, offers non-contact laser sensor scanning of tooth flanks to support gear development. Complete topography data can be recorded more rapidly than with conventional tactile probing, with comparable results.

The integration of laser scanning and associated 3D graphics with CAD interface considerably expands both functionality and range of applications for this machine platform, making the 300GMSL appropriate for research and development applications for prototype and production parts or when reverse engineering is required. It can accommodate spur and helical cylindrical gears as well as straight, spiral and hypoid bevel gears, with diameters of up to 300 mm. Its capabilities also include surface finish measurement and Barkhausen noise analysis to inspect for grind burn.

Another new Gleason technology at Gear Expo will be the Genesis 400HCD Hobbing Machine. For hobbing of larger cylindrical gears in small batches, Gleason's new continuous fly cutting process offers significant advantages for improving chamfering flexibility and reducing costs as compared to chamfering on a dedicated, standalone machine. This feature is available on the new Genesis 400HCD Hobbing Machine, designed for workpieces up to 400 mm outside diameter and module 8 mm. The 400HCD has the capability to chamfer/deburr in parallel with hobbing — eliminating the cycle times and cost per piece added when chamfering/deburring conventionally.

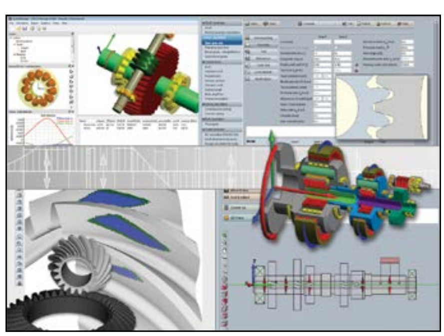
The 500CB Cutter Build Inspection Machine is for automatic, accurate and repeatable builds. The 500CB delivers more accurate and highly automated build, truing and inspection of all types of stick-blade bevel gear cutters with automated closed-loop blade positioning for better gear quality and maximum tool life.

For more information:
Gleason Corporation
Phone: (937) 859-8273
www.gleason.com

GWJ Technology

Booth 944

GWJ Technology provides professional software development for mechanical engineering to support engineers and designers in their daily work. The GWJ products range from standard software for classical machine elements with 3D CAD integration modules to the determination of whole systems up to a complex special software for 5-axis milling of gears. There are common features that all GWJ solutions share: intuitive design, sleek interface, ease of use and suitable applications for all users from beginner to very advanced. GWJ is constantly working on software enhancements and adding new features to the system in order to keep the applications up-to-date. They are also committed to providing high-quality customer services, including engineering services and workshops.



Several of GWJ's various software suites will be on display. *eAssistant* is a web-based calculation software for mechanical engineering. The software allows for professional calculation, design and optimization of machine elements including shafts, bearings, cylindrical gears, bevel gears, shaft-hub connections plus many more. The suitable 3D CAD plugins offer a great way to connect calculation and design. 3D CAD models can be automatically created with just a mouse click and the design table with all manufacturing details can be placed on the manufacturing drawing.

For more than 30 years, the *TBK* software has been a widely accepted calculation software and is being successfully used by many engineers worldwide in the widest range of sectors. Gear manufacturing is one of the key applications. The software is used in the steel and cement industry, open cast mining, wind turbines and even for Formula 1 engines. The high-quality calculations are based on generally accepted calculation methods (DIN, ISO, VDI, AGMA, ANSI, etc.).

SystemManager is a true software application for complete systems of machine elements. The software is a coupled FE calculation of multi-shaft systems with gears as non-linear coupling elements. *SystemManager* runs as a desktop application, making it possible to configure and calculate entire systems with just a few mouse clicks. The application ranges from simple to complex systems, e.g. multi-stage gearboxes, shift gear transmissions or different types of planetary gear trains. *SystemManager* allows the import of 3D housings as STEP files. The software meshes the parts automatically to consider deformation and stiffness of the housing throughout the system. A further extension of the 3D elastic parts function is the support of planet carriers and imported shafts. Planet carriers can be imported as CAD models or be defined parametrically; various basic designs are available for the parametric planet carriers.

The *TBK Manufacturing Suite* is a powerful software especially designed for calculating the real 3D geometry of gearings. This geometry provides the basis to manufacture cylindrical and bevel gears in conjunction with multi-axis machining centers. The software calculates the tooth form based on a mathematical simulation of the manufacturing process analogous to traditional manufacturing on gear cutting machines.

For more information:
GWJ Technology
Phone: +49 (0) 531 129 399 0
www.gwj.de

Hardinge
Booth 401

Hardinge will be on hand to discuss their line of products, most notably the all new Kellenberger 100 platform. Kellenberger's Vista and Vita machine model ranges, the Tschudin T25, and the Jones & Shipman Ultramat CNC and Ultragrind 1000 were integrated in the Kellenberger 100 platform concept.

In terms of functionality the new platform concept goes far beyond the possibilities of the machines named above and delivers the most diverse of configuration options for the widest range of grinding operations. Because of the modular solution on one common platform and the new assembly concept designed to reduce throughput time, it was possible to optimize production costs for the machine and ensure an excellent price/performance ratio. Numerous standard options put the finishing touch on the machine variety.

The user-friendly and ergonomic design of the Kellenberger 100 machines will feature a new, simple operator guidance system on an intuitive touchscreen panel. The machines are equipped with the latest Fanuc 31i CNC controls with 19" touchscreen, optionally also with newly designed cycle programming or workpiece-related graphic programming.

The Fanuc 31i controls replace Hardinge's Kel-Easy interface with intuitive touchscreen operation. They offer consistent support for the operator throughout, expanded range of functionality, integrated automated technology calculation, context-sensitive help images, online operation and maintenance instructions. No ISO programming skills are necessary to interact with the interface, which is also optionally available with familiar Fanuc 31i applications

Three important features distinguish the new Kellenberger 100 machine series. First is a new collision-free tandem wheelhead in compact construction with motor spindle which features reinforced casing for larger grinding wheel diameters for internal grinding. Customers can choose between 10 wheelhead variations for optimum layout of the machine based on the components to be processed. The Kellenberger 100 series also enhances several performance parameters: Higher grinding wheel drive power for increased productivity, a newly designed Z guideway for higher profile precision and a C axis with direct drive for higher precision for non-circular grinding. Lastly, the service department was involved in the optimization of the machine concept. This means that faster maintenance and service operations and optimum accessibility of maintenance-intensive components are assured.

For more information:
Hardinge Grinding Group
Phone: (607) 734-2281
www.hardinge.com

Hainbuch America
Booth 622

Hainbuch America Corp. announced a mandrel with hexagonal pyramid shape instead of a round taper, designed with stringent manufacturing requirements and process reliability in mind. Hainbuch has acted in response to demand from specific areas that has been growing year by year. Users are requesting mandrels that deliver higher performance as well as process reliability. The result is called Maxxos. It exceeds even the specified customer requirements, and more than this, offers all the advantages of a hexagonal clamping mechanism. The segmented clamping bushing with hexagon inside shape fits perfectly onto the clamping pyramid and enables maximum cutting performance. The lubrication, combined with its tightness ensures a very constant production flow and as a result, achieves maximum reliability. Customers that value process reliability and maximum torque transmission will be delighted with the Maxxos T211.

Thanks to the hexagonal pyramid clamp, maximum torque transmission can be achieved. Up to 155 percent more transmissible torque and up to 57 percent higher bending stiffness compared to the classic Mando T211 mandrel. This makes it possible to achieve higher process parameters and consequently improve the yield of finished parts. Greater process reliability is facilitated by the spacious layout between the clamping bushing and the clamping pyramid. Even during the clamping process, this design prevents virtually any dirt getting onto the surfaces. This significantly cuts down the frequency of maintenance times for cleaning and lubrication. Overall, the mandrel has a clamping diameter range of 18 to 100 mm. The clamping areas of each size are designed to overlap. This has the advantage that users can choose from up to three mandrel sizes depending on the clamping diameter. The aligned, segmented clamping bushings have a minimum concentricity of 0.01 mm and can even be supplied in a high precision version.

For more information:
Hainbuch America Corp.
Phone: (414) 358-9550
www.hainbuchamerica.com

HobSource
Booth 703

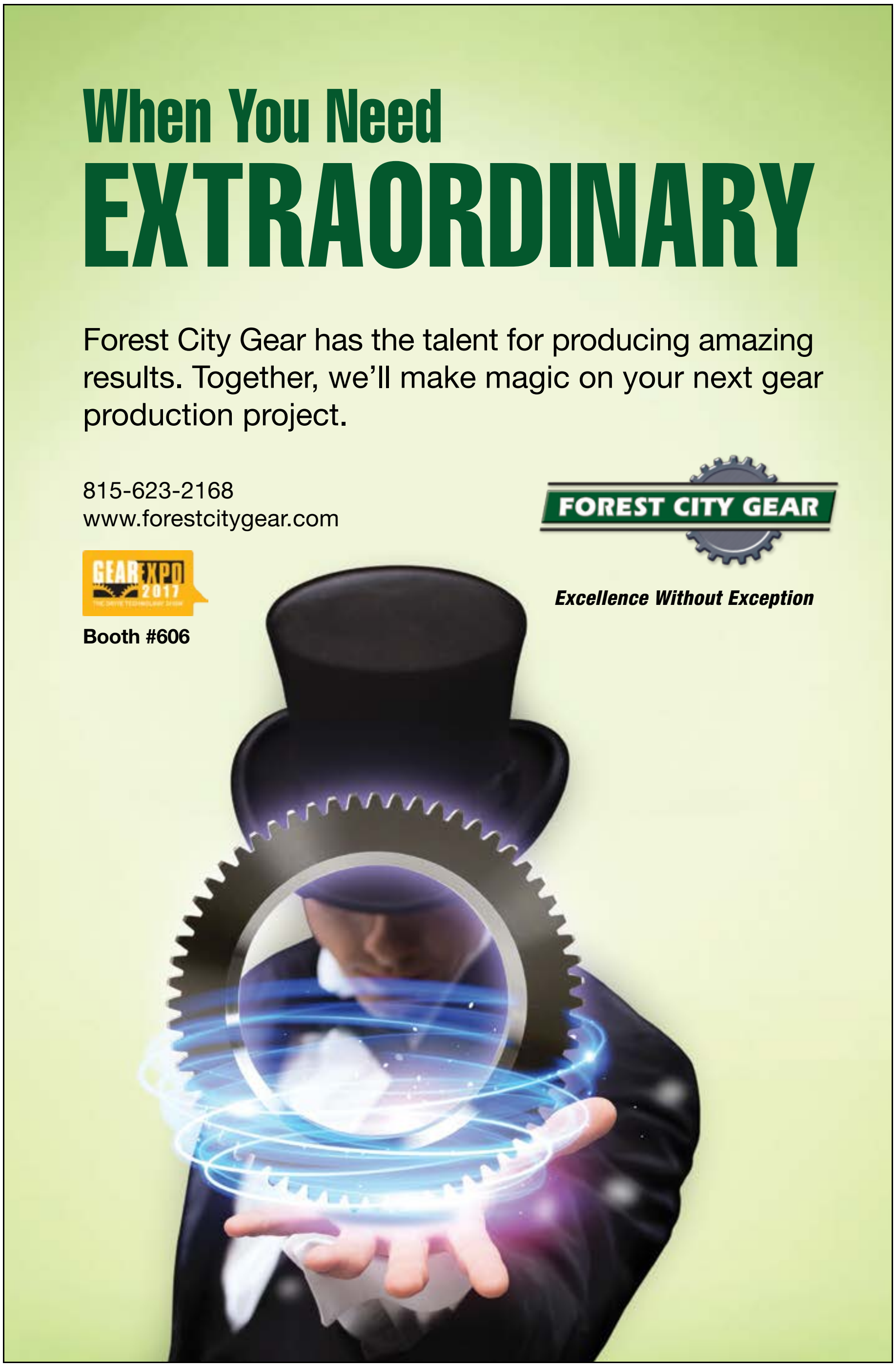
Whether you hob, shape, shave, broach or mill, HobSource delivers quality tools manufactured to exacting quality standards in ISO/QS facilities using the latest grades of high speed steels and carbide, CAD/CAM technology and state of the art CNC equipment.

For more information:
HobSource Inc.
Phone: (847) 398-8320
www.hobsource.com

Kapp Niles
Booth 1006

Kapp Niles will display their latest grinding machine generation — the KNe3G — together with the analytical gear inspection system PGM 400 and the ultra-precise measuring machine KNM 7C, both now part of the newly founded division Napp Niles Metrology.

Efficient, easy to use, ergonomic and effective — that's what the "e" is all about. The machine concept of the KNe3G comes with the new KNgrind software and HMI (Human Machine Interface) which means operator-friendly and machine-oriented parameterization of the generating grinding task. The latest control hardware and a multi-touch screen technology from Siemens (Sinumerik 840D) will interactively guide the user through the input of workpiece and technology data. The integrated measuring system of the KNe3G allows various alignments, analysis and correction possibilities.



The PGM 400 analytical gear inspection system for workpieces up to 450 mm in diameter is designed to maximize uptime and throughput. Its measuring ability in relation to functional datums eliminates the need for expensive tooling or fixtures. With its modular design approach to both hardware and software, the PGM400 allows easy system upgrades and expansions.

The KNM C series complements diameter requirements from 500 mm up to 1,600 mm. The KNM 7C with its highly accurate mechanics is the result of well-proven technology and innovations, adjusted to meet customer requirements specifically to determine form deviations of bearing rings, race rings and all kind of cylindrical workpieces.

For more information:
Kapp Niles
Phone: (303) 447-1130
www.kapp-niles.com

KISSsoft
Booths 1411 and 1628

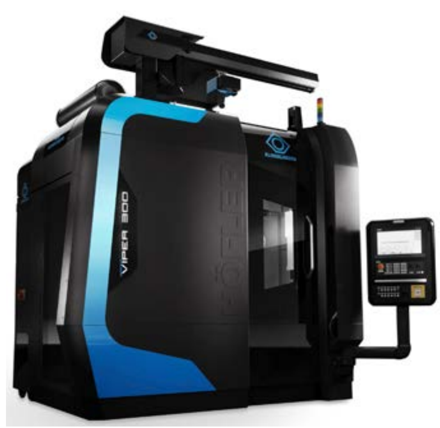
KISSsoft and Gleason invite you to visit them and find out about the highlights from *KISSsoft Release 03/2017*: transmission reliability calculation at system level, simplified modeling in *KISSsys* using predefined gear stages, verification of root stresses with FE for cylindrical gears and determination of balancing requirements when vibrations on a shaft have been calculated.

They also are taking this opportunity to present the first benefits resulting from the merger of KISSsoft AG and Gleason Corp.: *GEMS* and *KISSsys* programs are now linked by a direct interface to exchange gear tooth and system design data between the two software packages. *GEMS* supplies the values for the geometry data for the bevel gear pair, which is imported into *KISSsys*. KISSsoft determines EPG misalignments for specified load points, taking shaft bending values into account. Results are transferred to *GEMS* which carries out a comprehensive contact analysis. KISSsoft will be able to demonstrate the whole process in detail live at Gear Expo.

For more information:
KISSsoft
Phone: +41 55 254 20 50
www.kisssoft.ch

Klingelnberg
Booth 1123

Klingelnberg will display the Höfler Speed Viper generating grinding machine. With the Speed Viper platform, Klingelnberg is presenting itself as a pioneer of Industry 4.0 technology — and it will be demonstrating the cost savings and efficiency gains that are possible as soon as the potential of digitally-supported processes is fully exploited. With this new development, Klingelnberg is celebrating a market premiere: new construction, a completely revised, ergonomically optimized design and Gear Operator, a newly developed operating concept focusing on a simple, innovative operating philosophy.



Modifications and corrections no longer need to be entered manually, but are automatically loaded using Gear Operator. Klingelnberg is aiming to set a new standard regarding machine operation by presenting this operator guidance via a modern 19-inch touch screen display.

The all new Speed Viper is designed for high-productivity and robustness of the grinding process, and therefore meets any requirements of today's large-scale production: short set-up times, minimum cycle times, innovative software solutions and digital process control in a closed loop system.

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

Koepfer America
Booth 807

Koepfer America will show three important technologies for hobbing, shaping and deburring.

First, gear manufacturers will see the proven technology of the Koepfer Model 200 CNC gear hobbing machine with a completely redesigned control interface. This new Vektor control ushers in the latest generation of Koepfer's user-friendly control concept. It optimizes functionality by using a minimum number of control elements. Instead of a fixed menu structure, the Vektor control's adjustable apps make operation more intuitive. The control panel interface is 50 percent larger compared to the previous generation, and the panel has complete touch and swipe technology. The front panel is also flush and sealed, allowing for easier cleaning. Other updates with the Vektor control include a compact design, integrated NC and PLC, and a USB interface for data backup and easy updates.

The next feature will be a gear deburring machine that is brand new to the North American market: the Tecnomacchine ("TM") 200 R3, which uses five work stations that produce a fully deburred and brushed part in approximately 25 seconds. CNC work stations also allow automatic tool wear compensation. The TM 200 R3's CNC automatic loading and unloading system features two rotary magazines, each comprising 8 adjustable turrets, making this a versatile, flexible deburring solution for job shops with parts up to 200 mm (7.874").

Third, Koepfer America will show the CLC 200-SZC CNC gear shaping machine. As with all CLC machines, the 200-SZC features robust components, such as direct drive torque motors, for maximum quality and machine life. This show machine will feature CNC cutter relief, crowning and taper. Traditionally, these CNC features have limited stroking speeds; however, a new design concept from CLC provides both CNC cutter control as well as mechanical control. This allows up to 2,000 strokes per minute. This machine will also feature on-board robotic loading and unloading with Koepfer-style gravity and conveyor parts magazines.

Koepfer America will be celebrating 30 years of service to the industry in tandem with Koepfer Germany's 150th anniversary. All gear manufacturers are welcome to join Koepfer America in their booth to celebrate and see the new TM 200 R3 gear deburring machine, the new CLC 200-SZC CNC gear shaping machine, and the new Koepfer Model 200 Vektor control.

For more information:
Koepfer America
Phone: (847) 931-4121
www.koepferamerica.com

Liebherr
Booth 1015

Liebherr Gear Technology will introduce gear skiving machine series LK 300 and 500, which are based on the tried-and-tested components of the corresponding large hobbing machines but feature greater rigidity and more powerful spindles. A gear skiving machine requires a table with a direct drive, owing to the high workpiece speeds required. This drive works with an automatic control that constantly has the optimal parameters. The complex clamping fixture, which links the workpiece and the machine, is designed by Liebherr.

As skiving is a highly dynamic process, the machine is supplied on a "turnkey" basis with individual clamping fixtures for each workpiece, precise rigidity and contour accuracy. "This overall view is an important part for the production success," explains Siegfried Schmidt, team leader in development and design of skiving. "A complex process such as skiving has many specific obstacles, which we overcome with very specific mathematical solutions."

With its *Skiving³* program, Liebherr not only provides the LK 300 or 500 skiving machine, but a whole process, including machine, tools and technology for gear production. This integrated approach from Liebherr has already been tried and tested in practice. For many customers, the process of skiving is new, and therefore the operators of the machines need comprehensive training and assistance. On top of that, the tool design is a very complex issue.

Skiving[3] is popular especially for internal gearing with medium size and quantity as it is much faster than shaping and more economical than broaching. In situations where gear skiving is not possible or appropriate, owing to interfering contours or quantities that are too low, Liebherr still offers technological alternatives with gear shaping and gear hobbing.

The newly developed LHGe@rTec control system also contains the mathematical formulas for pressure angle corrections. This way, quality improvements can be easily achieved via the kinematics of the machine.

The optional tool changer, which can be used to change between roughing and finishing tools, for example, is new. Liebherr offers a ringloader as a standard option for the workpiece changing device; other automation solutions, such as belts and robots, can also be realized upon request.

The LK 300/500 has a maximum module of 5, can machine gears up to 300/500 mm in ID diameter, 500/600 OD diameter, has a maximum table speed of 3000/1500 1/min, maximum tool diameter of 250 mm, maximum tool speed of 2700 rpm and maximum spindle output of 32 kW.

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

Luren Precision
Booth 722

Luren Precision will present two new gear grinding machines. The newest is the LVG-100 CNC spiral bevel gear grinding machine. Luren's CNC spiral bevel gear grinder joins their generating gear grinding machines and profile gear grinding machines, offering value without compromising precision, reliability or versatility. The LVG-100 features an interactive and communicative Luren designed Windows 7 based software, reducing training time and increasing profits through increased up time. The LVG-100 also utilizes a Siemens 840D controller, dedicated cooling systems for the direct drive spindle and direct drive work head, separate dedicated cutting oil chiller system, air-conditioned electrical cabinet and rigid construction with robust components.

Luren Precision is also presenting the LFG-8040 CNC profile gear grinding machine. Engineered to be flexible, the LFG-8040 comes standard with an advanced on-board inspection system, giving the operator critical information needed to reach gear classes of AGMA class 14 and above. With Luren's proprietary, user friendly and communicative Windows 7 based software, combined with Fanuc's advanced 32i MB CNC controller and Fanuc ai series servo motors, a direct drive high torque spindle, automatic lubrication systems, dual chillers for cutting oil and the spindle motor, the LFG-8040 is equipped to handle the ever-changing and demanding needs of the gear industry.

For more information:
Luren Precision
Phone: (847) 882-1388
www.lurenusa.com

Machine Tool Builders
Booth 1401

MTB is launching their beta version of New Grinding Technology, which include form grinding conversational software, on-board inspection, wheel dressing and automatic setup adjustments. Yefim Kotlyar and Ken Flowers will be available for discussions at the booth.

D+P (Donner+Pfister), a company that continues Maag's tradition of manufacturing and servicing highly accurate gear measuring instruments and grinding machines, will be displaying its ultra-precision ES4100 pitch testing unit and featuring a truly portable ES4400 gear inspection measuring unit from Switzerland. Christoph Donner, owner of D+P, will be available for discussions.

Diablo Furnaces will be displaying four miniature size pieces of equipment to acquaint captive and commercial heat treaters of their capabilities: IQ, car bottom, temper and washer.

Burri GmbH, manufacturer of BZ generative gear grinders and PM — profile wheel dressing — machines from Germany, will have Mr. Dieter Burri, owner, at the booth for discussions regarding the Burri technology.

A technical expert, Kwanjoo Hong, from Yunil, manufacturer of Hera Gear Hobbers, will be present in the booth for questions.

MTB will display a recontrolled Pfauter P400G form grinder featuring numerous new technologies that can be added to an existing grinder. With a new controls system and these new technological features, customers can extend the life of their grinder very cost-effectively.

For more information:
Machine Tool Builders
Phone: (815) 636-7502
www.machinetoolbuilders.com

Marposs
Booth 400

Marposs Corp. will present its Artis process monitoring system for gear hobbing applications, which detects and tracks tool wear, provides a real tool life count according to the cutting conditions and instantly stops the process in case of chip welding, damaged or broken teeth or other conditions such as peeling coatings.

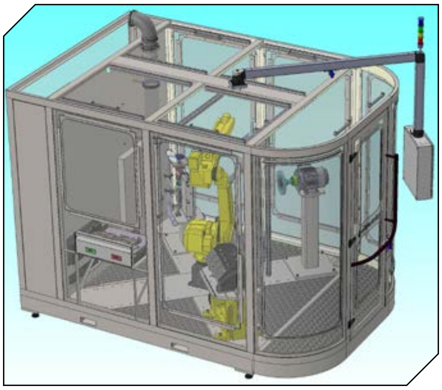
The Artis system utilizes an algorithm representing the life cycle of a hobbing tool to identify the optimum time to remove the tool for re-sharpening based on its actual condition. Additionally, a system of machine mounted sensors monitors spindle torque, spindle vibration, true power consumption and other parameters depending on the specific application. Using these inputs, the system then captures the exact signature of each operation in the process and automatically generates a "good" tolerance band for the process based on that signature.

While the concept of monitoring process inputs is not unique, the Artis system couples it with software specifically designed to detect the exact kinds of anomalies produced by worn and/or damaged hobs. The Artis software can identify and quantify each of these signatures to generate an approaching end-of-life warning for normal wear, or an automatic machine stop in case of actual tool damage. In the case of normal wear, the Artis system notifies with ample time to schedule the downtime required to minimize the impact on production.

Another unique aspect of the system is the ability to detect and automatically compensate for tool diameter changes after re-sharpening.

For more information:
Marposs Corporation
Phone: (888) 627-7677
www.artis-systems.de

Matrix Design
Booth 422



Matrix Design, LLC will feature their brand new Deburr Demo cell. Here, attendees will have the opportunity to see live advanced robotic deburring technologies. This modular-designed automation system includes four interchangeable stations arranged in a quadrant formation around a single M-20iA35M FANUC robot, each featuring various deburring solutions that address the unique challenges associated with deburring.

"We are very excited to unveil our new robotic deburring applications system," says Jeff Bennett, vice president of sales and marketing. "This new system will allow us to demonstrate our automated deburring technologies to manufacturers as well as qualify new potential deburring applications." Matrix's staff will be on hand to present, answer questions and help end users understand how manufacturers' operations can benefit from increased productivity, improved safety and work environment, decreased costs and consolidation of processes.

For more information:
Matrix Design, LLC
Phone: (847) 841-8260
www.matrixdesignllc.com

Mazak

Booth 123

Mazak will demonstrate recent advances in manufacturing systems for gears. Visitors will discover how Mazak's Multi-Tasking Machines, when equipped with the latest Mazatrol Smooth CNC and Mazak Smooth Gear Cutting Solutions, can serve as adaptive machining solutions for precision gears of all shapes and sizes.

More than 90 model configurations of Mazak Multi-Tasking Machines can be paired with the right software and CAD/CAM system to perform a wide variety of operations that include hobbing, forming, surfacing and skiving in a single setup. Shops with occasional gear work, for example, can use a Mazak Multi-Tasking Machine to turn a part's I.D. and O.D., process its mating features, then power skive its gear tooth pattern. Such capability on one machine improves overall accuracy because every part feature runs true to the gear teeth. Plus, when the machine is not busy with gear work, it can be used to process a broad range of complex, non-gear components.

At the Expo, Mazak will highlight its new closed-loop gear machining strategy, developed in conjunction with software developer Dontyne Systems, which simplifies the measurement and validation of the accuracy of virtually any gear tooth profile. Through this process, shops with full, 5-axis multi-tasking capabilities can productively and profitably produce tight-tolerance gears in small and medium volumes. The process also makes it possible to generate more complex and specialty forms for better overall gear performance.

Attendees will also experience how Mazak's Mazatrol SmoothX CNC operates four times faster than the company's previous-generation controls. Gear makers, especially, will benefit from faster rotary axis speeds, which allow the machine tool to quickly perform gear hobbing and skiving operations.

For more information:
Mazak Corporation
Phone: (859) 342-1700
www.mazakusa.com

McInnes Rolled Rings
Booth 1248

McInnes Rolled Rings specializes in seamless rolled rings from 4"-144" diameter and forged discs up to 54" diameter in carbon, alloy and stainless steel. Their ISO 9001, AS9100 and ABS certified plant in Erie, Pa. combines the latest in ring rolling technology with experienced professionals, resulting in the best value and the fastest deliveries in the industry.

For more information:
McInnes Rolled Rings
Phone: (800) 569-1420
www.mcinnesrolledrings.com

Oelheld
Booth 901

The multifunctional DiaGrind 535/15 HSG grinding oil has been used successfully on gear hobbing, gear grinding and even for gear shaping applications. DiaGrind 535/15 contains a blend of high quality additives and superior base oils and does not require regeneration or complete exchange for many years. Its high performance characteristics are coveted by a number of transmission manufacturing companies in this country, while its environmentally friendly composition keeps their operators safe and their equipment in top shape.

DiaGrind 535 was especially developed for doing high speed grinding operations like gear or groove grinding. Further it can be used for gear hobbing or thread cutting. The materials normally used are cast iron, steel and highly alloyed chrome-nickel-steels.

Benefits include very low oil misting, excellent temperature-viscosity behavior, very good aging stability, low foaming, extremely good flushing and cooling capacity due to low viscosity and physiologically safe materials.

With another product, the fully synthetic SintoGrind 353 high-speed grinding fluid, Oelheld is offering a product formulated from synthetically produced poly-alpha-olefin based fluid, which provides unlimited life span if properly filtered. It handles hardened steels in excess of 65 Rockwell with ease. Its lubricity lends to extended wheel life and minimal heat build-up in work pieces. This results in higher production rates and elimination of surface cracks and burns. The product has no hazardous components, is physiologically safe and exhibits stable viscosity at different temperatures.

SintoGrind 353 was specially developed for profile grinding of gear teeth on Reishauer machines but can also be used for grinding and honing and is the ideal fluid for metallic and electro-plated CBN grinding wheels.

Additional benefits and features include reduced wear on the grinding wheels, extreme aging stability, reduced temperature on workpiece surfaces, a high flash point, very little foam and oil mist, viscosity that fluctuates very little at various temperatures, extremely low vaporization tendency, high pressure absorption, extreme flushing and cooling ability and positively no shearing. SintoGrind 353 is an extremely thin-bodied, chlorine and heavy metals-free material.

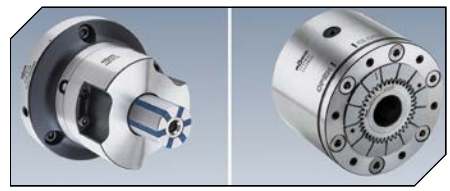
DiaMill HEF 1100 high-performance cutting fluid is the ideal alternative to water soluble cooling lubricants for turning, milling, drilling and cutting operations in modern CNC-controlled machining centers. DiaMill HEF 1100 is especially designed for the work on high alloyed steel, cast iron or non-ferrous metals. DiaMill HEF 1100 is a high performance product based on hydro-cracked oils. It is nearly odorless, has high shearing stability and ages extremely well. It displays outstanding viscosity properties over a wide range of temperatures, thus guaranteeing maximum flushing and cooling at all times. The use of high performance pressure additives and cleaning agents contribute to high cutting speeds and excellent surface finish, while being at the same time 100 percent physiologically safe.

DiaMill HEF 1100 is best suited for materials such as steel, aluminum and all non-ferrous materials. Additional benefits and features include increased productivity, better lifetime of your cutting tools, improved surface finish, extremely low foaming and best possible air release properties and the best possible value for your money as no oil change is required.

For more information:
Oelheld U.S., Inc.
Phone: (847) 531-8501
www.oelheld.com

Röhm
Booth 1000

Röhm Products of America will showcase its industry-leading workholding innovations. The highlight of Röhm's exhibit will be its KZF-S gear chuck shown side-by-side with its Agilis segment clamping mandrel to demonstrate a complete solution for gear manufacturers. Röhm will also display its drill chucks, live and dead centers, its RZM 125 5-axis vise, the RKE 90 intensified vise and the Duro-T manual chuck, as well as the F-senso clamping force measuring system, robotic end-of-arm grippers, Duro-NCSE power chuck and Captis modular workpiece clamping system.



The KZF-S is a powerful external clamping chuck specifically made for gear surface face grinding. It is well-suited for clamping gears/workpieces that have an external plane or gear teeth geometries accessible from the outside. Additionally, the chuck allows face and

ID diameters to be turned or ground concentric to outer gear pitch diameters. The chuck maintains its centrifugal force for extremely smooth rotation of less than 0.01 mm.

Röhm's Agilis segment clamping mandrel will be shown as the perfect partner to the KZF-S. Agilis holds the part on their inside diameters and KZF-S holds them on their pitch diameters.

The compact Agilis is built specifically for automatic changeover and small diameter clamping. The system draws in workpieces against a rigid work stop — an operation that happens independently thanks to incorporated pull-back action of the quick-change taper sleeves. The power-operated Agilis offers concentricity tolerances within 0.01 mm, as well as repeatable high clamping accuracy.

Röhm application specialists will also be on hand to discuss specific workholding challenges as well as show how the company's workholding and automation technologies can help increase productivity through lights-out and just-in-time manufacturing.

For more information:
Röhm Products of America
Phone: (770) 963-8440
www.rohm-products.com

Sinto Surface Treatment
Booth 201

Sinto Surface Treatment is a global market leader in the development and implementation of world-class, machine tool quality surface finishing systems. They will be showcasing their next advancement in shot peening technology by introducing their Sightia series of products.

The Sightia series offers surface evaluation where strength is required by using Sinto's non-destructive X-ray defraction residual stress measurement device to ensure your parts stand up to the highest quality. Sightia ensures the traceability of individual parts with features such as a laser marker and checking quality before and after peening. This series can be built into or embedded in-line with your peening machine. The non-destructive peening inspection is safe, easy and fast measuring, taking just three seconds. Sightia's X-ray residual stress measurement is the world's fastest measurement at only 10 seconds.

Sinto Surface Treatment will also be presenting their line of shot peening equipment to provide a solution for all aspects of the peening process. Their two peening systems, air blast and wheel type shot peening machines, can be used for a wide range of applications from general purpose to critical peening processes. The air blast type peening machines is best suited for piece-by-piece peening treatments and gives the best possible focus on the shot intensity and volume. The wheel type shot peening machines are capable of projecting large quantities of abrasive to cover large work areas and is versatile enough to use on small or large parts.

For more information:
Roberts Sinto Corporation
Phone: (517) 371-2460
www.robertssinto.com

Star SU
Booth 1306

Star SU will feature a complete library of product overviews, video displays and a new interactive customer application solutions tool. Gear Expo visitors can explore the Star SU Solutions Kiosk independently or have a Star SU representative guided tour through its complete machine tool, cutting tool and tool services offerings from the brands they represent, including Star Cutter Company, Samputensili, Bourn & Koch, Profilator/GMTA, FFG Werke (Hessapp, Modul) and H.B. Carbide.

The booth will also showcase the FFG Werke Modul H200 vertical hobbing machine and the latest in gear cutting tool technology on display.

The H80/100/160/200 series is the latest version of Star SU's hobbing machine line for small applications, specially engineered for the automotive industry. These machines have been designed for dry cutting operations in particular, although using oil or emulsion is not a problem. They are also available with the option of enlarged radial travel. This option allows users to cover the working range of H80 up to H200. The new CNC tailstock, driven by a servomotor, is standard now and allows the easy setup and monitoring of clamping force and position. The closed "O-frame" structure with cross beam allows the ideal integration of this tailstock.

These new features, combined with the user-friendly Modul operating interface, provide the optimal base for Job Shop applications. Request a budget quote and plan to see it at Gear Expo or by visiting Star SU's H 80-200 vertical gear hobbing webpage.

Star SU also carries a wide variety of gear cutting tools and offer precision tool re-sharpening services and advanced coatings, including Oerlikon Balzer's new Balanit Altensa, the high-speed coating solution that realizes productivity gains and efficiency.

Need more help managing your tool room? Let Star SU monitor the life cycle of your tools and re-sharpen, re-coat and replace them as needed. Visit *www.star-su.com/cutting-tools/gear-cutting-tools* and request a meeting with a representative to discuss how Star SU can help you with your gear cutting operation.

Star SU will also feature Scudding cutters in conjunction with GMTA and Profilator manufactured to produce gear and spline teeth for reduced cycle times and tool costs. Learn more by visiting at Gear Expo or going directly to Star SU's Scudding page.

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

Stresstech

Booth 1602

For more than 30 years Stresstech has been providing nondestructive evaluation instrumentation for the automotive, aircraft, machine and energy industries as well as universities and research institutes. Today their instruments are used daily in many of the world's motor component manufacturing facilities. There, they monitor the quality of gears, camshafts, crankshafts, bearings, valves, landing gear units and other important engine and aircraft components. In addition to quality control, the instruments have proven their worth of investment by helping to adjust in line processes before major losses of material, time and capital occurs.

Barkhausen noise analyzers offer a nondestructive evaluation method to identify issues such as grinding burn detection, case depth measurement, heat treat defect detection and residual stress measurement. For measuring residual stresses and retained austenite contents, Stresstech offers a product line of X-ray diffraction equipment. For measuring stresses, instrumentation based on hole-drilling by electronic speckle pattern interferometry technology is also offered.

One of Stresstech's Barkhausen noise analyzers will be available for demonstrations at Gear Expo 2017.

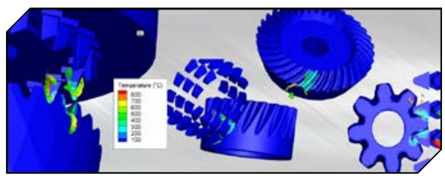
Unlike the traditional testing method, Nital etch, which relies on a subjective examination of a component surface, Barkhausen noise analysis provides a more sensitive, objective test and repeatable real-time grinding burn inspection without requiring chemicals or consumables. It is completely non-destructive and results in substantial cost savings by reducing scrap and eliminating the need for chemical disposal and personal protective equipment. Often compared to Barkhausen noise, eddy current is a traditional NDT method which is optimized for detection of physical flaws such as cracks. It lacks the sensitivity to stress and microstructure, the very properties most influenced by grind and heat treatment, to which Barkhausen noise is specifically tailored.

For more information:
American Stress Technologies, Inc.
Phone: (412) 784-8400
www.stresstech.com/GearExpo

Third Wave Systems

Booth 538

Third Wave Systems will showcase the latest advancements in new gear machining capabilities for its finite element software AdvantEdge. Stop by the booth for a demonstration or to determine if AdvantEdge Gear Machining is a fit for your machining processes.



Third Wave Systems will also be giving a presentation at 4:00pm, Oct. 24 on the Solutions Center stage. The presentation will show AdvantEdge Gear Machining demonstrations and examples.

For more information:
Third Wave Systems
Phone: (952) 832-5515
www.thirdwavesys.com

TimkenSteel

Booth 916

For 100 years, TimkenSteel has been creating some of the cleanest and best-performing special bar quality (SBQ) steel in the industry. Today, TimkenSteel offers its customers more than 500 grades of steel, including the company's new TimkenSteel Endurance steels, which is a specialized group of high-strength, high toughness products designed for extremely demanding applications that require a precise blend of steel toughness and strength.

"We've always been a leader in developing high performance steels with some of the greatest degrees of strength and toughness, and now we're making them better," said Ray Fryan, TimkenSteel's vice president of technology and quality. "TimkenSteel's Endurance steels combine strength and toughness for longer life, more power and/or lighter weight, depending on the application's unique requirements. Our technology allows us to develop an exact blend of strength and toughness that's needed based on the application. Better yet, customers don't have to wait for a redesign to reap the benefits that our Endurance steels offer."

By offering gear manufacturers the ability to create better gears from TimkenSteel Endurance steels that meet their customers' existing designs and grade specifications — not just during a major redesign — TimkenSteel's clean steel offerings can help gear manufacturers achieve a range of improvements that may ultimately translate into savings and performance advantages for their customers. Potential benefits, depending on specific application needs, can include increased power transmission, light-weighting, extended product life and reduced component failure, which can reduce downtime and warranty program costs.

"These steels serve demanding environments where things are moving at a high rate of motion and are very energy intensive," said Fryan. "They offer an incredible amount of strength and toughness in a small envelope."

Fryan says he envisions TimkenSteel's ultra-high strength and high toughness grades to benefit premium gear manufactures in a variety of market segments, including oil and gas, mining, marine, construction and more.

"One of the core benefits you get from TimkenSteel's family of Endurance steels is multiple options within existing grades, as well as new grades that can satisfy a range of performance objectives," said Fryan. "Our technology team is constantly working to push the envelope on what's possible in order to meet not only today's needs, but what our customers are looking for five, 10 and even 100 years from now."

For more information:
TimkenSteel
Phone: (330) 471-7000
www.timkensteel.com

Trojon Gear
Booth 1148

Trojon Gear specializes in under 24" diameter gears, shafts, pins, splines, sprockets and more. They can help you source gears, shafts and services like broaching, grinding and CNC machining are part of our expertise. Trojon works to make life easy for purchasers from small to large companies; for many industries within the agriculture, aerospace, packaging, mining, oil/gas and other markets. Since 1957 Trojon's gears have been found in everything from the iRobot to F16s. Their flexibility and broad range of capabilities make them a perfect supplier to get things done quickly for low to medium volume batches.

ISO 9001:2015 is process-based certification that recognizes organizations that can link business objectives with operating effectiveness. We recently achieved this new standard and have demonstrated effective implementation of documentation and records management, top management's commitment to their customers, establishment of clear policy, good planning and implementation, good resource management, efficient process control, measurement and analysis. Continual improvement has been institutionalized.

For more information:
Trojon Gear, Inc.
Phone: (937) 254-1737
www.trojon-gear.com

Wenzel
Booth 206

Wenzel will be showing off their GearTec WGT series, a range of 4-axis gear inspection machines which are designed to represent the ultimate in high accuracy, high speed analytical gear testing. We produce the WGT 280 (gears up to 280 mm in diameter), WGT400, WGT600, WGT850/1000 and WGT1200/1600. We also provide CMM-based solutions that allow customers to inspect gears up to 4m in diameter.

Both styles of solutions have the ability to inspect helical, spur, bevel, worm, worm wheel and synchronization gears as well as cams, racks, rotors, hobs, shapers, shavers and broaches. Wenzel is also able to reverse scan spur gears to obtain their nominal data and can inspect all of the above to the most common industry standards including AGMA, DIN, ISO, ANSI and JIS, as well as many company specific standards. All of this is performed through an intuitive and logical user interface. For Wenzel's scanning technology, they used trusted, reliable and ubiquitous Renishaw products in the form of the SP600M and SP80H scanning heads.

Other features and highlights of Wenzel's GMM solutions include: Uniquely designed WMC controller for 4-axis motion; all axes made from natural South African Black Impala granite, guaranteeing excellent thermal behavior; air bearings on all linear axes ensure smooth operation and high accuracy performance with no mechanical wear over the long life of the machine; fully counterbalanced tailstock, to support longer gears, tools, and shafts with parts easily loaded due to its ergonomic design; all WGT systems measure gears to VDI/VDE 2612/2613 Group I accuracy levels; and all system components and software are developed, produced and maintained by Wenzel.

As a family-owned company, Wenzel has a more personal relationship with their customers which makes them effective and flexible when it comes to solving problems. However, they still serve almost all manufacturing industries including automotive, aerospace, energy, construction, defense, transportation and agriculture. They are a global company with a local feel, large enough to support customers around the world while providing a unique and personal level of service.

For more information:
Wenzel America, Ltd.
Phone: (248) 295-4300
www.wenzelamerica.com

ASM Exhibitors

AFC-Holcroft/Aichelin
Booth 2047

AFC-Holcroft will feature their UBQ – Universal Batch Quench line of equipment, recognized as an industry leader by manufacturers, including the gear market, where heat treatment processes require precise metallurgical outcomes.

The UBQ uses both gas and electric heating with patented upflow quench agitation to assure uniform metallurgy. UBQ equipment is built with the highest level of maintainability with modular mounted equipment, standard access ladder and catwalk and an available jib hoist capable of removing fans, tubes, quench heaters and quench agitators without requiring an overhead crane.

The Universal Batch Furnace uses integral batch oil quench technology for carburizing, carbonitriding, neutral hardening, ferritic nitrocarburizing, normalizing, annealing, spheroidize annealing and stress relieving.

Additionally, the concept of "Lightweighting" is the latest practice prompting manufacturers to turn to AFC-Holcroft. The Universal Batch Quench Austemper Furnace (UBQA) – is another featured product at ASM Heat

Treat 2017.

AFC-Holcroft is at the forefront of the austempering process, having pioneered both continuous and batch furnace systems for this process decades ago. Austempering has been gaining momentum in the heat treatment of metals, and it is expected that many more companies will be looking to this process as part of their own environmental and energy-saving initiatives. AFC-Holcroft's global installed base for continuous and batch austempering equipment remains one of the largest.

The UBQA is a leader in atmosphere to salt quench for batch furnace designs, and the UBQA design is unique to AFC-Holcroft. The UBQA offers extreme flexibility in processing various part sizes and features an easy-to-maintain, modular design for rapid and accurate assembly, installation, maintenance and serviceability. The system can be provided as a stand-alone unit, or with a full range of companion equipment to create an entire system. The installation can be expanded incrementally as production increases, optimizing the investment. A fully automated system is available, with process and control management provided by a fully computerized BatchMaster system.

A patented water injection system provides quench severity, and patented "upflow" quench agitation provides more uniform hardness. In addition, improved atmosphere circulation under the load provides for a more uniform case depth for carbo austempering. The UBQA design has an intermediate transfer chamber between the furnace and the salt quench tank. This transfer chamber allows work to be transferred under atmosphere to the salt quench tank as well as prevent salt fumes from entering the furnace chamber.

Other benefits include greater than 97 percent reclamation of quench salts; modern air-cooled furnace fan design which requires no water and is less expensive to maintain; and large diameter radiant tubes which effectively and uniformly heat work for faster recovery rates. The use of high efficiency, spark-ignited sealed burners assures extremely uniform tube temperature and longer tube life.

Product experts from both AFC-Holcroft and Aichelin Heat Treatment Systems will be on hand to discuss your heat treatment requirements.

For more information:
AFC-Holcroft
Phone: (248) 624-8191
www.afc-holcroft.com

Ajax Tocco Magnethermic

Booth 1823, 2821

Ajax Tocco Magnethermic/Saet Emmedi/GH Induction/Pillar Induction all provide innovative solutions for induction heat treating, heating and melting applications. A dual spindle compact scanner complete with a power supply, water system, quench system and control will be featured. The booth will include a computer presentation of Ajax Tocco/Saet Emmedi/GH Induction/Pillar Induction heating and heat treat products and the latest scanner controls with coil monitoring. Process development capabilities and regional service/repair facilities will be represented. Ajax Tocco's engineers will be available to review and discuss specific applications and equipment. Bring your toughest application problem.

For more information:
Ajax Tocco Magnethermic
Phone: (800) 547-1527
www.ajaxtocco.com

Seco/Vacuum Technologies

Booth 1813

Seco/Vacuum Technologies (SVT) will be participating alongside its sister company, Seco/Warwick, and will showcase its line of vacuum heat treating furnaces via multiple interactive displays at the ASM Heat Treat Show and Gear Expo. Using a giant iTab screen, staff at the show will walk visitors through the company's portfolio of products, including Vector, SVT's benchmark high pressure quench vacuum furnace; the Case Master Evolution (CMe), a unique multi-chamber vacuum furnace incorporating either oil or air for quenching; the Unicase Master (UCM), SVT's proprietary single-piece flow continuous vacuum furnace, designed for uniform high-volume heat treating of gears; and ZeroFlow, a patented gas nitriding furnace using uniform high convection heating, precision nitriding potential and ammonia control, all designed to reduce gas usage and minimize emissions.

Other interactive features will include a live connection to "Seco 4.0," offering visitors a real-time look into exclusive new developments in controls HMI and other proprietary tools, plus videos of manufacturing, a process description of the UCM single-piece flow vacuum furnace, customer interviews on UCM and ZeroFlow, as well as partner videos featuring Seco technologies.

For more information:
Seco/Vacuum Technologies LLC
Phone: (814) 332-8520
www.secovacusa.com

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ASK-THE-EXPERT LIVE!

ASK the EXPERT LIVE is coming to Gear Expo 2017 in Columbus, OH. This is your chance to have your questions answered in person by our live panel of experts.

See our expert at:
Gear Expo Booth #1022.
October 24–26

Tuesday, October 24

- 10:30 a.m. – Cylindrical Gear Cutting: Hobbing, Shaping and Skiving
- 2:30 p.m. – Gear Design, Standards and Software

Wednesday, October 25

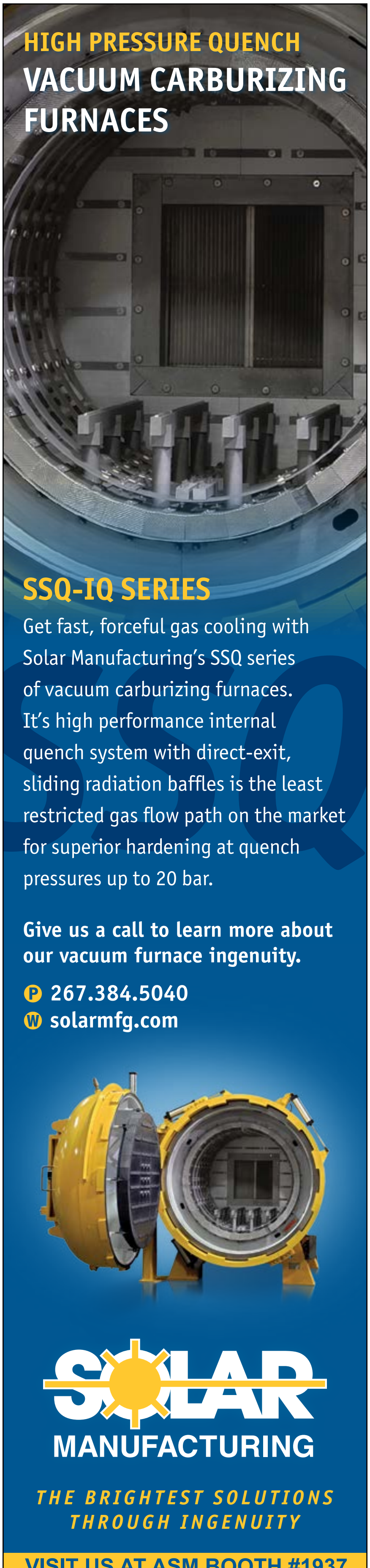
- 10:30 a.m. – Gear Inspection
- 2:30 p.m. – Ask Anything

Can't wait? Submit your question now!

Send it by e-mail to Senior Editor Jack McGuinn (*jmcguinn@geartechnology.com*) and we'll submit it to our experts.

www.geartechnology.com

VISIT US AT BOOTH #1022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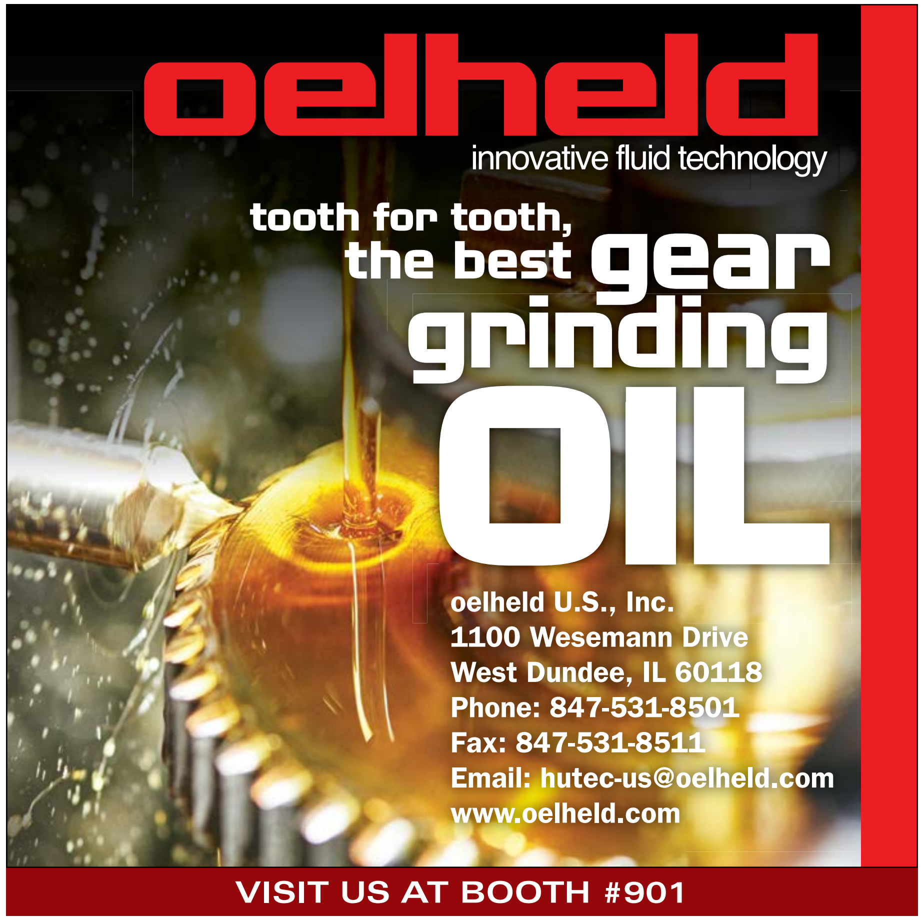
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West Dundee, IL 60118
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Fax: 847-531-8511
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www.oelheld.com
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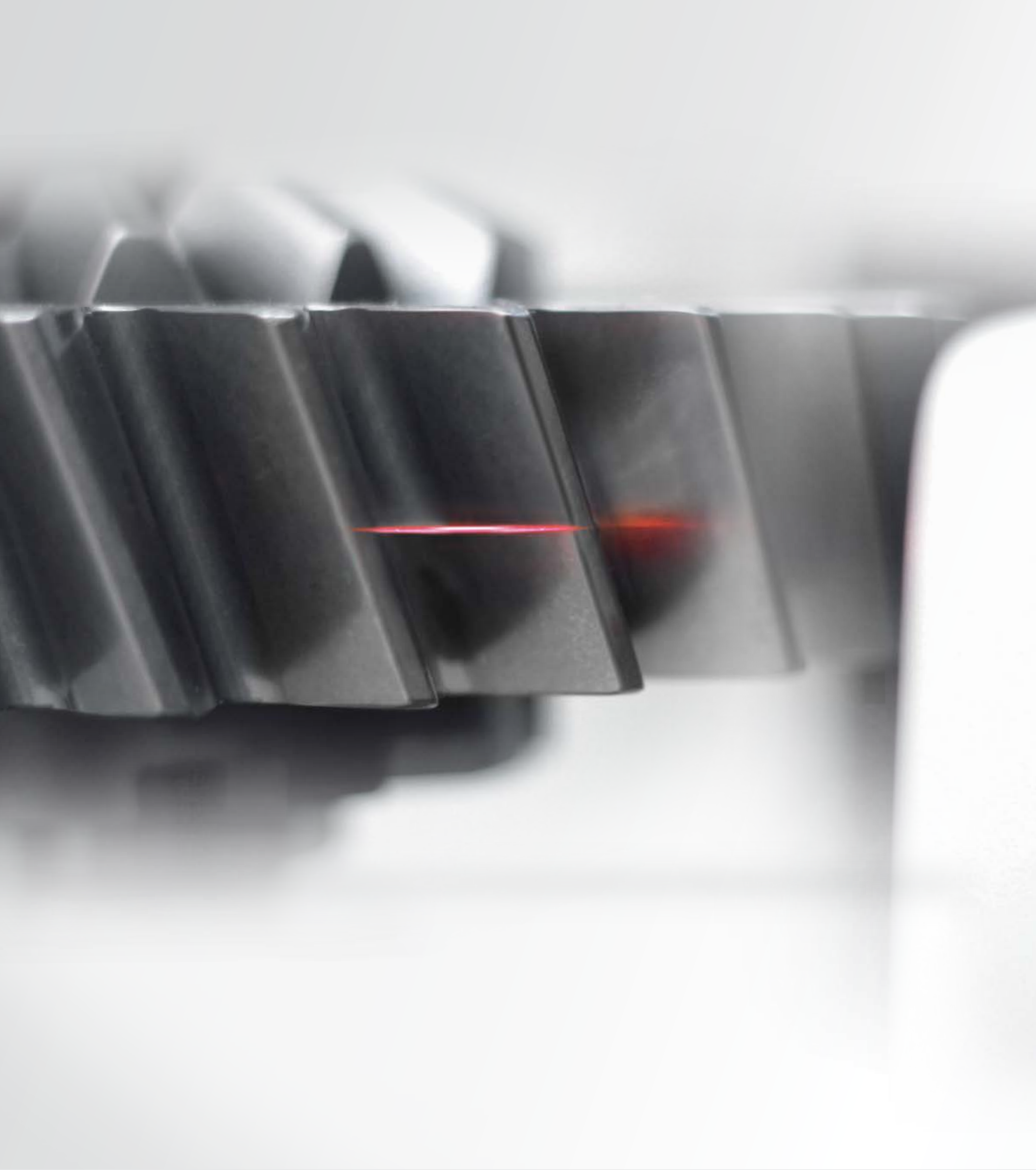
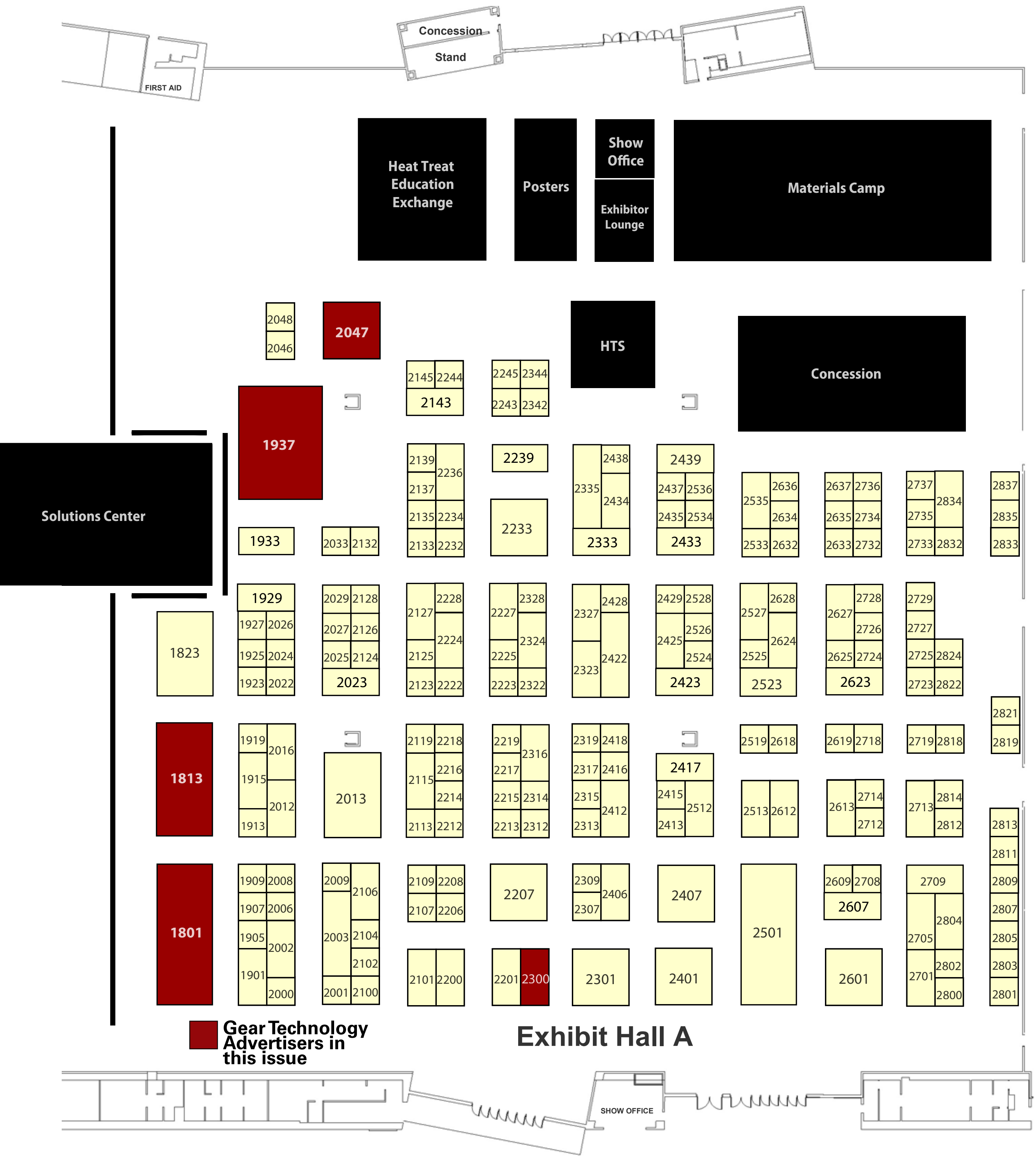


ASM Heat Treat 2017

Don't miss these exhibitors co-located with Gear Expo



Company	Website	Booth #	Ad
A.L.M.T. Corp.	www.allied-material.co.jp	1909	
Abbott Furnace Company	www.abbottfurncace.com	2000	
Across USA	www.acrosscc.com	2309	
Advanced Corporation for Materials & Equipments (ACME)	www.acmefurnace.net	2803	
Advanced Energy	www.advanced-energy.com	2627	
AFC Holcroft	www.afc-holcroft.com	2047	62
AFFRI, Inc.	www.affri.com	2225	
Air Products and Chemicals, Inc.	www.airproducts.com	2513	
Airflow Sciences Corporation	www.airflowsciences.com	2618	
Airgas	www.airgas.com	1905	
AJAX TOCCO	www.ajaxtocco.com	1823, 2821	
Allegheny Alloys		2214	
Allied High Tech Products	www.alliedhightech.com	2327	
Allied Mineral Products	www.alliedmineral.com	2709	
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AMECO USA	www.ameco-usa.com	2438	
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Andritz Metals Inc	www.andritz.com	2317	
Ariane Group	www.sps-industry.com	2714	
Astral Material Industrial Co.,Ltd.	www.amic.biz	2208	
Atmosphere Engineering Company	www.atmoseng.com	2207	
Avion Manufacturing Company	www.avionmfg.com	2323	
Beijing Huaxiang Electrical Furnace Technology Co., Ltd	www.hxzkl.com	2732	
Bloom Engineering	www.bloomeng.com	2125	
Bodycote	www.bodycote.com	2434	
BTU International, Inc.	www.btu.com	2524	
Buehler An ITW Company	www.buehler.com	2002	
C.C. Jensen Inc.	www.ccjensen.com	2628	
C.I. Hayes	www.cihayes.com	2102	
C3 Data	www.c3data.com	2528	
Can-Eng Furnaces International Ltd.	www.can-eng.com	2701	
CEIA USA Induction Heating Systems	www.ceia-power.com	2222	
CENOS LLC	www.cenos-platform.com	2312	
CeramSource, Inc.	www.ceramsource.com	2725	
Clemex Technologies Inc.	www.clemex.com	2001	
Cleveland Electric Labs	www.clevelandelectriclabs.com	2023	
CMI Industry Metals	www.cmigroupe.com	2139	
Contour Hardening	www.contourhardening.com	2800	
Control Concepts Inc.	www.ccipower.com	2416	
Cooley Wire Products	www.cooleywire.com	2113	
CoorsTek Technical Ceramics	www.coorstek.com	2319	
Custom Electric Mfg.	www.custom-electric.com	2218	
Daniels Fans North America	www.danielsfans.com	2328	
DANTE Solutions Inc.	www.deformationcontrol.com	2009	
DELTA H TECHNOLOGIES	delta-h.com	2029	
DF Fan Services Inc.	www.dffan.com	2216	
DixiTech CNC	dixitechcnc.com	2342	
DOWA THT AMERICA, INC.	www.dowa-tht.com	2239	
Dry Coolers	www.drycoolers.com	2406	
Duraloy Technologies, Inc	www.duraloy.com	2219	
Dynamic Software Solutions	www.getdwos.com	2109	
ECM USA Inc.	www.ecm-usa.com	2300	61
Edwards Vacuum	www.edwardsvacuum.com	2527	
EFD Induction	www.efd-induction.com	2433	
Eurotherm by Schneider Electric	www.eurotherm.com	2127	
Flame Treating Systems, Inc.	www.flametreatingsystems.com	1923	
Flowserve	www.flowserve.com	2026	
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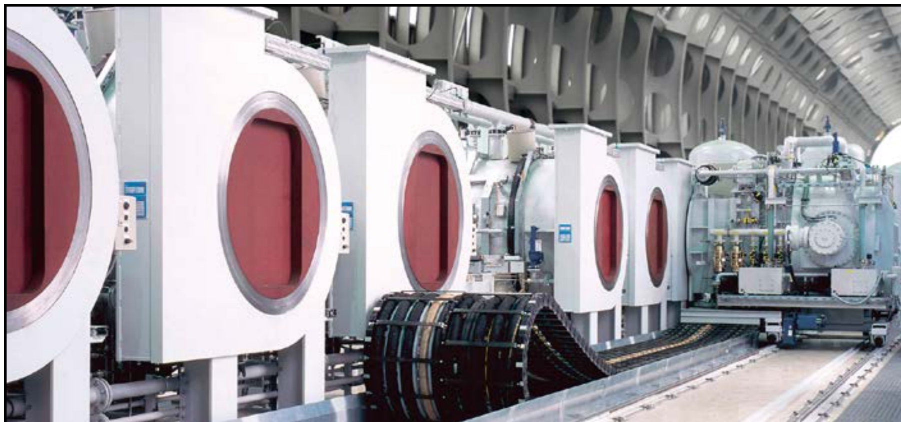

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Coming Clean on Gearbox Lubrication

Some Dos, Don'ts and Maybes

Jack McGuinn, Senior Editor

It is widely accepted common wisdom that the design and manufacture of gears is among the most complex and difficult disciplines of the industrial arts. From initial conception to machining and finishing, making gears ain't bean-bag. And guess what? Once those gears roll off the assembly line, it doesn't get any simpler. That's because gears—the metal ones at least—require the correct lubrication in order to prevent—or delay as long as possible—such things as wear, scuffing and Hertzian fatigue. (See pg. 73 sidebar, *"Basic Factors to Consider for Gearbox Lubrication*," from **Bob Errichello**, gear industry consultant (*rlegears@mt.net*) and longtime ***Gear Technology*** technical editor. In a sense, one can say first the gears are manufactured, and specifying the proper lubrication—grease or oil—helps make them work. With that in mind, the following will provide in greater detail information on what makes proper lubrication such an integral part of successful gearbox operation.

Premature, lubrication-related gearbox failure is a painful experience for end-users. And, of course, those end-users are looking for answers to their cause-and-effect questions. Keep in mind, however, that premature gearbox failure can of course be attributed to at least several types of non-lubrication breakdowns.

Gearbox and lubricant failure

"The different major gear failure modes show very different time performance," say Dr. Thomas Tobie and Dr. Klaus Michaelis of the FZG Research Center. (*Ed.'s note: Tobie and Michaelis collaborated on the responses for this article and therefore from this point on will be collectively referred to as FZG.*) "Normal sliding or slow speed wear is a typical continuous failure mode with loss of material during every revolution. For critical operating conditions already after few cycles material loss from the flanks can be found. Before critical conditions of the gear pair are reached some time is required. Pitting, tooth root breakage and flank fracture are failure modes with a distinct range of finite life fatigue strength with failure accumulation in every load cycle and damage after the material strength potential is expired. Micropitting is somewhere in between as a fatigue failure mode, with more or less continuous material loss. Scuffing has no range of time strength; one single critical load cycle can lead to a catastrophic failure within milliseconds. Combined with a very large influence of run-in on scuffing, this failure mode typically occurs, if at all, at the very beginning of the gear life."

Errichello explains that "Time to failure depends on many things, but the most important parameter is the specific failure mode. For example, scuffing is instantaneous, and the most likely time for the initiation of scuffing is the initial start-up when gear tooth surfaces have not yet been smoothed by run-in. On the other hand, fatigue failure modes such as micropitting, macropitting, sub-case fatigue and bending fatigue require time to develop."

As for specific lubricant failure, Errichello lists the following typical causes:

"Selecting the wrong lubricant type, viscosity, or additive package for the gearbox application; oxidation due to too high operating temperature for the base oil type; contamination with solids, water, gases, or other lubricants; and starvation due to inadequate supply."

So how does one go about avoiding such pitfalls that Errichello mentions? What are the central considerations for choosing the correct gearbox lubricant? Who decides which lubricant to use? The following should go a considerable way in answering those questions.

Correct thickness and viscosity are critical

Film thickness is a key consideration in lubrication—both EHL film thickness and specific film thickness.

"EHL film thickness is the thickness of the oil film between Hertzian contacts, such as gear teeth and rolling element bearings," Errichello explains, adding, "Specific film thickness is the ratio of the EHL film thickness to the composite surface roughness of the two contacting surfaces (*see AGMA 925 for definitions and equations*).

(FZG) "EHL film thickness is the distance in micrometers separating the contacting, theoretically smooth surfaces with a lubricant. Specific film thickness is the relation between the EHL film thickness and a relevant value of surface roughness of the mating surfaces, and thus a characteristic value of the lubrication regime from boundary and mixed to full film EHL lubrication."

And what/who dictates which lubricant to use, such as—will it be oil or grease? Are OEMs involved? Designers?

(FZG) "The major tasks of a lubricant in a gear contact are EHL film formation and heat removal. Typically less than 5% of the available lubricant quantity is required for lubricant film formation; more than 95% is required for heat removal. Due to much better heat removal properties of oil compared to grease, the best lubricant for the gear contact would be oil. However, there are many environmental conditions where oil may be not the best choice. These are, e.g.—a missing gear case in open gear drives, difficult and expensive sealing conditions in do-it-yourself machines, or household appliances, etc. The lubricant selection is therefore typically negotiated between manufacturer and user."

"Many applications have specifications that are derived by experience," says Errichello. "Gearbox OEMs usually follow industry standards such as ANSI/AGMA 9005. Ultimately, the gear designer is responsible for ensuring the lubricant selection is appropriate for the gearbox application."

While another issue—viscosity—can be tricky, it is also among the most important considerations regarding lubrication.

"Yes," Errichello confirms regarding 'the V word'; "Firstly, the EHL film thickness must be adequate, and it depends strongly on the base oil viscosity. Secondly, the viscosity must be appropriate for the gear pitch line velocity, which strongly influences the EHL film thickness. Too low viscosity results in inadequate EHL film thickness, whereas too high viscosity results in overheating and low efficiency."

(FZG) "Lubricant viscosity is one important consideration. However, today often a compromise between highest gear load capacity and lowest no-load losses is required. Important considerations are also the base oil type and the additive system. Base oil type strongly influences contact friction losses and oil ageing properties. Additive type and concentration have different but significant influence on the failure modes — especially in the range of boundary and mixed lubrication where many gears operate."

Lubrication and high-tech manufacturing

Given gear lubrication's importance and complexity in any number of ways (not to mention *bearing* lubrication — but we're not going there this trip), might mechatronics play an expanding role in removing some of the guesswork attendant to lubricant maintenance and replacement issues?

Errichello: "Yes. Current technology provides all that is needed to maintain lubrication quality. Mechatronics allows gearbox designers to integrate the mechanical design of the gearbox with electronics to achieve effective condition monitoring."

(FZG) "Online vibration-based condition monitoring systems are (already) used in wind turbine applications and (have externally monitored them for quite a long time.) There are also quite a few lubricant condition monitoring systems on the market which can externally be supervised. Lubricant monitoring systems are based on, e.g. — electric conductivity change; viscosity measurements; acidity measurements; parts of infrared spectrum changes; particle measurements, etc.

Can mechatronics/condition monitoring assist in determining a gearbox lubricant's life?

"Currently," Errichello states, "on-line sensors are available

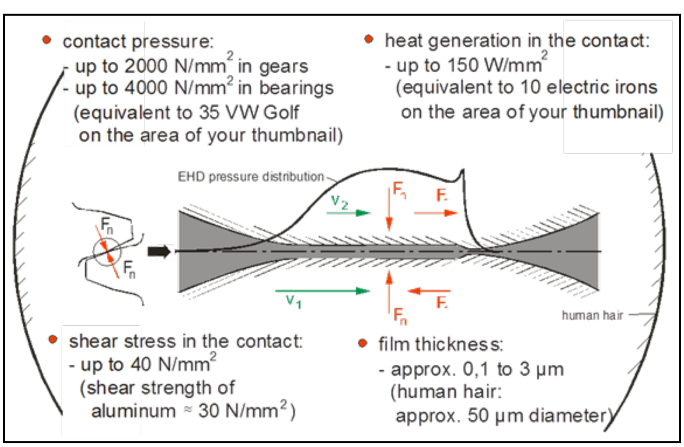

Figure 1 EHL Contact Parameters (acc. FZG/Kopatsch). The very challenging demands on a lubricant in an EHL contact. The contact pressure between the gear flanks is some 15,000 to 20,000 bar, corresponding to the pressure of 35 VW Golf on the area of a thumb nail. At the same time, in the same location heat is generated at a level of 150 W/mm², corresponding to 10 electric irons on the area of the same thumb nail. Shear stress in a fully lubricated contact without metal-to-metal touch is up to 40 N/mm² — or equivalent to the static shear strength of pure aluminum. The EHL film thickness is in the range of 0.1 to over 3 µm on a nanoscale, compared to the thickness of a human hair of 50 µm. (All graphics courtesy FZG.)

for real-time monitoring of both lubricant health and gearbox health. The sensors include particle counters; ferrous debris detectors; viscometers; thermocouples; water detectors (relative humidity); acidity monitors; and oxidation detectors." These sensors provide important information on contamination, oil aging, and wear debris that give significant improvement in condition-based maintenance."

FZG's response is that, "In principle, yes; however, there is only limited experience available today. Further testing is necessary."

Back to the here-and-now, do gear designers typically spec a lubricant type? It appears to be a question that conjures grey-area territory.

"Not often enough," Errichello believes. "Many times, the gearbox is the bastard child and other system priorities pre-empt gearbox considerations. Ideally, the lubricant and lubrication system are designed with the help of all stakeholders — including the gearbox (manufacturer) OEM, lubricant OEM, and end user."

"There is a discussion over many years that lubricants are calculable design elements and have to be considered in the early design process," (FZG). "Sufficient tribological knowledge of the design team is required. From tribological considerations of the lubrication regime and the expected gear efficiency and load capacity calculations, the gear designer can specify a lubricant that meets the requirements. The lubricant manufacturer confirms the specified lubricant properties with measurements of physical-chemical properties like viscosity at different temperatures, density, flashpoint, pour point, etc., as well as mechanical and technological properties using relevant methods such as scuffing test, wear test, micropitting test, pitting test, efficiency test, etc.

And if you are wondering whether some gearbox applications are more problematic than others, "For sure!" (FZG). "The latest challenges come from automotive applications in double-clutch automatic transmissions (DCTs) with low viscosity requirements; this is due to minimization of no-load losses, together with adverse frictional requirements in the gear and bearing, as compared to the clutch contact and high requirements for scuffing capacity. A simpler example is high-speed turbine gears with high demands on scuffing capacity of the oil, which can be realized with EP additives, whereas additives have detrimental influence on the required air release properties of the lubricant. Wind turbine gearboxes with high gear ratios require good wear performance in the slow-speed stage and high scuffing and micropitting performance in the medium- and high-speed stage."

And standards — are AGMA and ISO lubrication standards reliable guides for determining lubrication choice?

"Recommendations in AGMA and ISO lubrication standards are typically conservative and safe guidelines," (FZG). "With profound tribological knowledge and courage to embrace new ideas, still further improvements are possible. The balance between economic and ecological advantages has to be drawn."

"ANSI/AGMA 9005 and ISO/TR 18792 are very helpful guidelines," Errichello offers. "Gear designers should ensure conformance with these standards."

Load-carrying capability is something you often see mentioned in various places. As to its importance in lubrication choice, it apparently depends upon who you ask.

"Extremely important!" — according to FZG. "In comparing the load carrying capacity in terms of transmittable torque between an optimized and a poor lubricant, there is an estimated factor of over 10 for scuffing capacity, 3 for micropitting capacity, and 1.5 for pitting capacity."

For Errichello — not so much. "Lubricant nomenclature such as "load-carrying capacity" and "film strength" are misleading

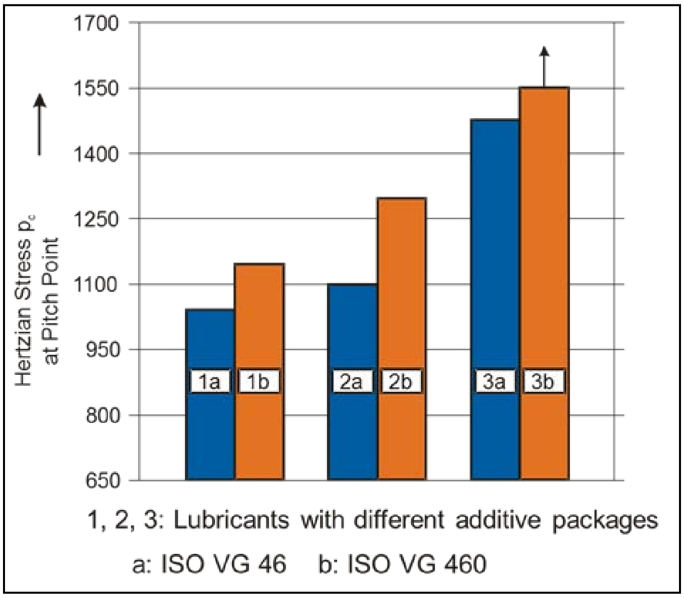

Figure 2 **Influence of base oil, additive package and viscosity on micropitting capacity (acc. FZG/Emmert). Shown is the allowable Hertzian stress in a gear contact without risk of micropitting for three different lubricants with different base oils and additive packages — each blended in ISO VG 46 and ISO VG 460. The figure shows clearly the important influence of the lubricant on micropitting failure. It also shows that higher viscosity is always better than lower viscosity for prevention of micropitting. And it shows that if using an inadequate oil, even high viscosity cannot prevent micropitting failures.**

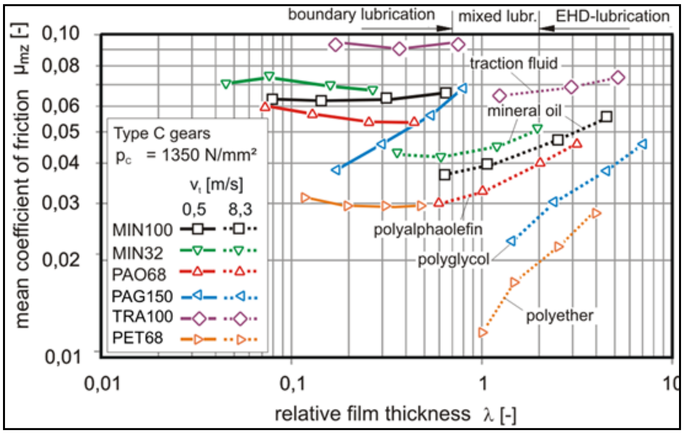

Figure 3 **Influence of base oil on coefficient of friction in a gear contact (acc. FZG/Doleschel). A look at measured friction coefficients in a gear contact as a function of the lubrication regime. Investigated were very different base oil types (MIN mineral, PAO polyalphaolefin, PAG polyglycol, TRA traction fluid, PET polyether) at different viscosity grades, including extreme oils from the marketplace with highest friction for a traction drive on the upper scale, and lowest friction for gear applications on the lower scale. Also shown is the very wide range of possibilities to reduce gear contact friction by choosing the adequate oil. For = 2 e.g. the relation between the mineral oil and the polyether is 5.1.**

terms. Gear designers should acquire the requisite knowledge of gear tribology so that they can competently specify the lubricant and lubrication system that is appropriate for the gearbox application."

Synthetic lubricants

We can't get away with at least a brief discussion of synthetic lubricants. They of course cost more, just like the synthetic oil on offer at your local auto repair shop. Is it money well spent?

"Synthetic lubricants are becoming more prevalent — especially for applications that involve wide-ranging temperatures or applications requiring high efficiency," Errichello says, but cautions, "However, synthetics are not a panacea, and they may not be appropriate for some applications. In some applications they are necessary, whereas in other applications the costs are prohibitive."

By way of elucidation, FZG offers, "First, a definition of 'synthetic lubricants' is necessary. SAE group I lubricants are purely mineral oil based. If group II and III oils, which are modified mineral oils, cracked and hydrogenated, reducing and eliminating double bonds in their molecules are regarded as semi-synthetic they are already most commonly used in many applications.

Gas-to-liquid (GTL) base stocks are also entering the market. Only polyalphaolefins (PAOs), polyglycols (PAGs), and polyesters (Pes) are regarded as fully synthetic (and are) entering the market gradually. Taking the potential of these synthetic lubricants on friction reduction and lubricant life extension into account, there are quite a few applications where the extra costs pay off! Individual analysis of the specific situation and application is required."

Is correct gearbox lubrication an energy saver?

"Absolutely," says Errichello. "Both lubricant type and lubricant viscosity influence efficiency. Generally, mineral oils are the least efficient. In order of increasing efficiency, lubricant base oils rank as mineral, PAO, PAG, and esters. Generally, the lower the viscosity, the higher the efficiency."

"'Correct'" is probably not the right (word)," (FZG). "Any lubricant choice is a compromise between different requirements and typically not in a win-win situation. Energy saving is possible with synthetic lubricants having longer thermal oxidative life, but higher material costs."

Is gearbox lubrication still an evolving process? Is the arrow pointing up regarding future advances?

FZG: "Base oil technologies of mineral group II and III oils as well as PAOs, PAGs, and PEs as well as traditional additive technologies of organic sulfur-phosphorus and metal containing sulfur-phosphorus are probably on a degressive innovation course with only minor improvements possible. However, very new approaches with e.g. water-based lubricants with a friction reduction potential of 1/50 compared to mineral oils using alternative gear materials are highly innovative.

Errichello: "Depending on one's point of view, lubrication technology has advanced to the point where the information can be overwhelming, or to the point where it offers many opportunities for improving gearbox lubrication. Gear designers should take advantage of the technology advances."

Table 1 Required oil cleanliness for wind turbine gearboxes

Source of oil sample	Required cleanliness per ISO 4406:99
From new oil before adding to gearbox	16/14/11
From gearbox after factory load testing	17/15/12
From gearbox during service	18/16/13

Final Comments

FZG: "Since the introduction of the term 'tribology' by Peter Jost in the UK in the 1960s, in the last century lots of investigations were supported and a lot of knowledge was gathered in research institutes around the world. Our impression, however, is that in daily use there yet remain fundamental knowledge gaps among engineers that have to be faced, and substantial improvements are still possible."

Errichello: "To maximize gearbox life, it is imperative that gearboxes be assembled in a clean room that is separated and insulated from any contamination from manufacturing or environmental debris. For critical applications such as wind turbines, the gearbox should be run-in under a carefully controlled load spectrum at the gearbox OEM. Oil cleanliness should meet the specifications shown in Table 1."

For more information

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Bob Errichello's Basic Factors to Consider for Gearbox Lubrication

- Lubrication-related failure modes, including wear, scuffing, and Hertzian fatigue (macropitting and micropitting)
- Elastohydrodynamic lubrication (EHL) film thickness, surface roughness, and specific film thickness
- Lubricant selection including types: oil, grease, open-gear, or solid
- Selecting lubricant viscosity
- Lubricant application including splash or pressure fed
- Lubricant quantity
- Lubricant heating and cooling including temperature limits, pour point, and oxidation
- Lubricant cleanliness including particle counts, filtration, change interval
- Lubricant contamination with water, wear debris, other lubricants, and gases
- Lubricant compatibility with seals, paint, and other lubricants
- Gear materials and heat treatment
- Condition monitoring including on-site, online, and laboratory analyses
- Lubricant laboratory tests
- Lubricant maintenance and troubleshooting

ExxonMobil on Benefits of Synthetic Gear Oils

David A. Blain, PhD

Base oils play an important role in determining the performance of an industrial gear oil. They influence characteristics such as low temperature performance, biodegradability, energy efficiency and high temperature thermal and oxidative stability.

When considering base oil options for a formulation, it's important to consider the common operating conditions that the equipment will be subjected to. Each base oil type has its own distinct characteristics, so you must select one that will meet the needs of the specific applications. For example, some base oils perform better in high or low temperatures, while others are geared more toward delivering energy efficiency benefits.

In most cases, synthetic base oils—such as polyalfaolefins and a Group V base oil or a blend of the two—will be most ideally suited for a high performance lubricant. Synthetics typically offer better performance at extreme high and low temperatures and longer oil life, resulting in lower maintenance and operating costs, less used oil disposal, improved equipment durability and enhanced energy efficiency.

Potential Energy Efficiency Savings from Using Synthetics

In fact, in-service and field testing has proven that synthetic gear oils—such as Mobil SHC 600 series and Mobil SHC gear series oils—can help deliver up to a 3.6% improvement in energy efficiency as compared to conventional mineral gear oils.

One of the many companies that have seen success with Mobil SHC gear oils is Chinese-based Xinyu Iron & Steel Co. The company was experiencing abnormal wearing of the gear and short oil drain intervals for gearboxes in 16 sets of conveyors, so they converted from a mineral-based oil to Mobil SHC 630.

After the conversion, the average operating temperature of the gearboxes decreased by 6.7 degrees Celsius and the electric motor current decreased by about 3.3%—yielding an annual savings of more than $1,800—as well as important safety benefits from less-frequent equipment interactions.

Note that these results are based on the experience of a single customer; actual results can vary, depending upon the type of equipment used and its maintenance, operating conditions and environment, and any prior lubricant used.

While synthetic base oils are a preferred option most of the time, there are select situations where it makes sense to use a mineral-based gear oil, such as if there are extreme levels of contamination due to specific equipment operating conditions that result in the need for frequent oil changes. In these cases, it might be more practical to use a mineral oil.

Operating Temperature Benefits of Synthetics

High operating temperatures can quickly degrade the gear oil, resulting in the need for frequent oil changes. Extreme low operating temperatures can also impact an oil's flow characteristics.

A high-quality, synthetic oil formulated with the right basestocks and additives can help to deliver enhanced low- and high-temperature performance, as well as help deliver low-temperature pumpability to ensure proper flow properties in extreme cold climates as well as improved thermal stability to mitigate lubricant degradation at high temperatures.

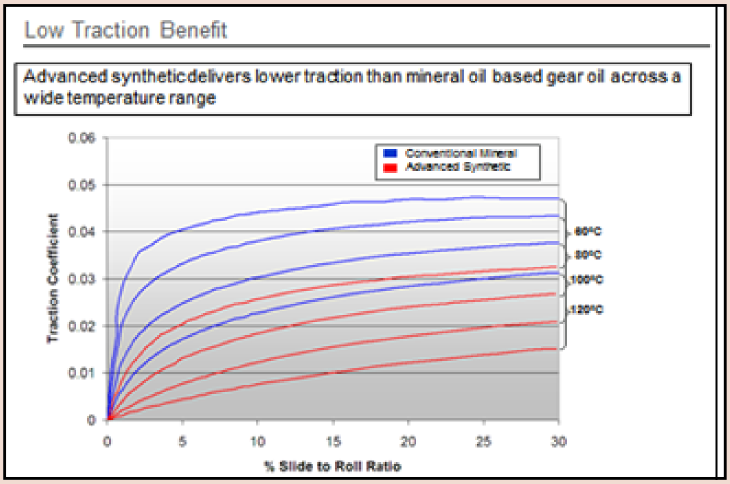

Figure 1 Actual traction coefficient measurement over range of slide to roll ratios and temperatures shows that synthetics have much lower traction coefficient than typical mineral oils. This leads to a more energy efficient operation, reduced heat generation, and lower overall system operating temperatures.

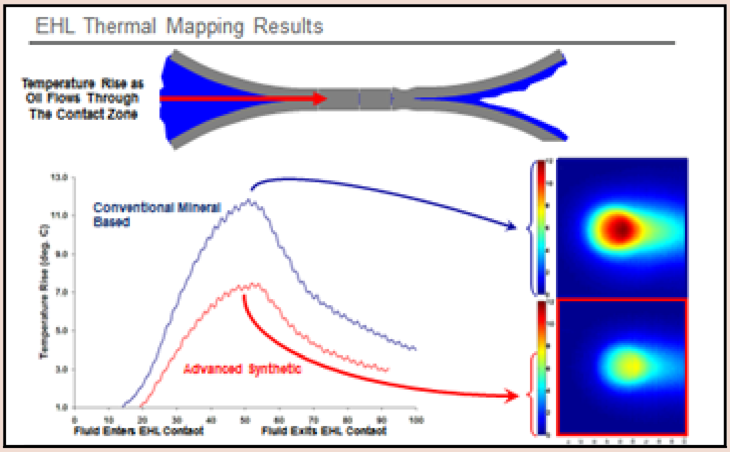

Figure 2 MTM thermal mapping shows that synthetics operate at lower temperatures in the contact zone, leading to longer oil and equipment life.

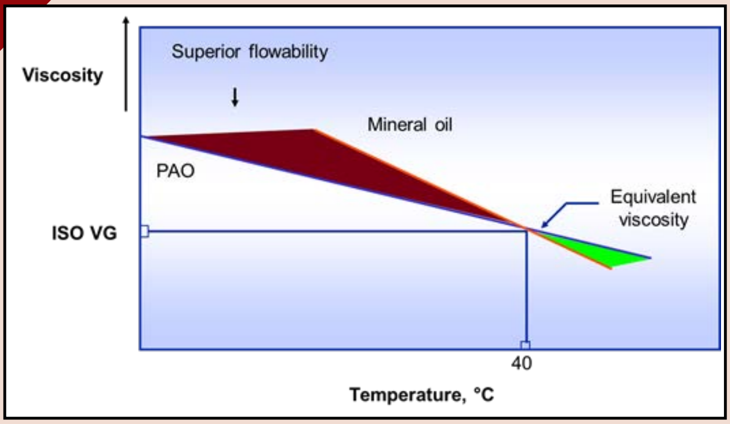

Figure 3 Synthetic oils (PAO) deliver improved flow at low temperatures.

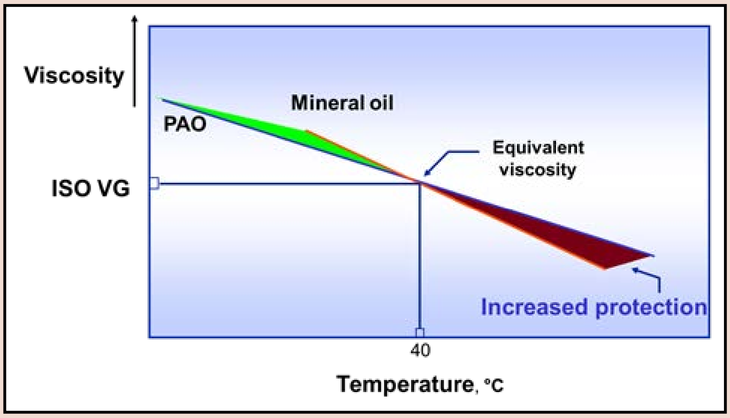

Figure 4 Synthetic oils (PAO) deliver improved viscosity control and equipment protection at higher temperatures.

Formulating Gear Oils

Most lubricants today are formulated using traditional lubricant development processes, which rely on blending a conventional base stock with an off-the-shelf additive package to create a product that meets basic industry specifications.

However, due in part to today's competitive marketing environment, traditional formulations often focus on delivering exceptional results solely based on one or two criteria — such as energy efficiency — which may negatively impact other critical performance areas.

ExxonMobil devotes significant resources to product research and development, using an advanced, scientifically engineered formulation approach that leverages our leading technology and application expertise to deliver lubricants such as gear oils that are optimized for their intended applications.

We call this our balanced formulation approach, which relies on the use of the right base stocks and carefully designed additive systems that complement the properties of the base fluids to deliver exceptional performance across all critical areas for each application.

That's why the first step in our approach is to define the application's operating conditions. We consider the temperature operating range, types of seals used, load, and specific original equipment manufacturer (OEM) requirements, among other items.

Once we understand all of the performance benefits the oil will need to deliver, we then formulate the oil using the right advanced base stocks and additive components before putting the lubricant candidate through a range of industry-standard laboratory tests.

We also supplement this testing with our own dynamic testing using industrial equipment and field trials. Our proprietary rig tests are designed to stress the lubricant under conditions even more demanding than it is likely to experience in severe operating conditions, and in combination with field trials results, they help give us an accurate indication of real-world performance.

Strong OEM relationships are an important part of this development process. ExxonMobil's Equipment Builder Group has been working for many years with leading OEMs from around the world to help develop advanced lubricants. These relationships help provide unique insights into advanced equipment and allow us to better understand and address specific operating conditions.

Final Comments

In addition to baseline gear performance demands, gear oils must meet a wide variety of OEM and industry requirements that are constantly evolving, such as material compatibility with seals, paints and other materials.

Formulators are regularly revising formulation chemistry to ensure compatibility, which can sometimes lead to tests that are run under accelerated conditions to simulate equipment/oil life.

However, these tests do not necessarily correlate with real-world conditions, so extensive field service trials are often required to ensure that the oils will perform as needed. That's why, as mentioned previously, we always put our lubricants through our proprietary rig tests, which simulate real-world conditions.

The company's commitment to extensive product research and development expertise ensures that we are at the forefront of lubricant innovation and able to stay ahead of these trends.

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What's New and Noteworthy in Powder Metal?

Industry Focuses on Strength, NVH and Heat Treatment in 2017

Matthew Jaster, Senior Editor

First, the facts: powder metallurgy is a cost-effective method of forming precision net-shape metal components that allows for more efficiently designed products. It saves valuable raw materials through recycling and the elimination of costly secondary-machining. PM competes with wrought steel gears as the technology continues to advance. You'll find PM components in everything from automobile transmissions to aircraft turbine engines, surgical equipment and power tools.

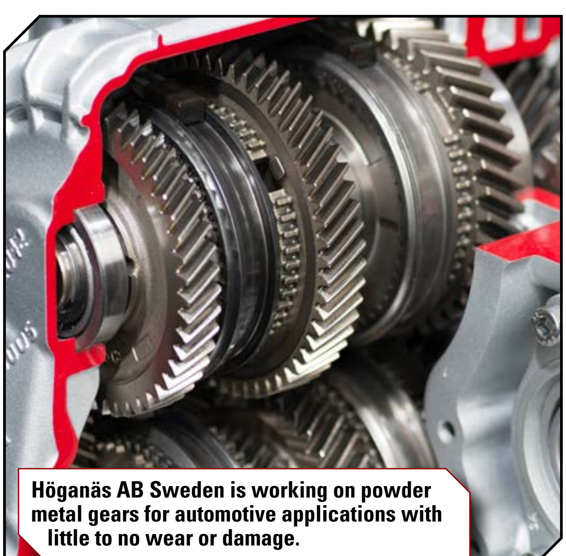
In 2017, strength and safety are two areas of focus in PM gears, particularly in highly-critical applications. The following short articles will address risks, benefits and advancements to PM technology and examine where the industry is today and where it's heading in the future.

Höganäs Improves Rolling Simulation Technology

Höganäs is a key supplier of powder metals, developing new products and technologies in areas like additive manufacturing, brazing, electromagnetic applications, filters, metal injection molding, sintered components and surface coatings. Anders Flodin, business development manager, Eckart Schneider, director of PM components and Thomas Schmidtseifer, manager, market development and customer projects at Höganäs, recently discussed some of the latest PM technology.

Flodin believes that much of the research currently being conducted in PM involves data collection. "A lot of research has been done at the big suppliers. One of the more important factors for the designers is the availability of coherent solid fatigue data," Flodin said. "KISSsoft has this data in its material database and we are working with others to incorporate our material there. Press and tooling has been developed too, helical gear drive systems and faster electromechanical presses."

One feature that is being heavily investigated by the major players is the NVH aspects of PM gears. "Some of the PM houses are generating data and exploring E-vehicle NVH advantages using PM gears. Also for high-strength gears, there is powder forging for helical gears that has been developed by GKN. Höganäs has developed the HIP process to obtain similar strength levels," Flodin said.



Höganäs AB Sweden is working on powder metal gears for automotive applications with little to no wear or damage.

The "green" or eco-friendly benefits of PM remain one of its greatest strengths according to Schneider. "With 5-8 times increase in manufacturing speed, and 95% (or higher) material utilization with no cutting fluids and chip disposal; machine inventory can be reduced and shop floor size cut by 50%. This all helps in reducing the CO_2 footprint and keeps competitiveness and cost efficiency at par or better than current cutting technologies," Schneider said.

Flodin believes the greatest challenge in powder metal is the inertia in the industry. "There are many non-technical barriers that have to be overcome. The growth will probably be exponential, but we are at the beginning of that curve where it is still near horizontal. From a technical aspect Höganäs is working on improving the rolling simulation technology since the OEMs that are working with PM gears are choosing this technology for extra safety and strength. We are also supporting with proof of concept of different technical systems in test vehicles, PM gear design and awareness seminars all over the world, lecturing at expert conferences, bundling tech partner competencies in the POP center," Flodin added.

In the heavyweight battle to compete with steel, PM continues to make significant progress. "We have learned a lot on how to improve heat treatment results as well as distortions so we can match solid steel micro hardness. Regarding strength we are anywhere from 75 to 110% of normal gear steels. It depends on the manufacturing path. PM can be tailored for the strength needed. It is coming to the point where purity of the material is becoming influential," Schneider said.

The automotive industry is one area that continues to reap the benefits of PM advancements. "This industry sees the opportunity as long as there are cost benefits and minimal risk. For example, a few big OEMs have recently announced they will use PM gears in their transmissions," added Schneider.

While the PM industry is growing, Schmidtseifer said the major activity is taking place in China. "Although internal combustion engines will be the dominant power source until 2030, there will continue to be faster implementation of hybrid and electrification strategies," he said.

For pure electrification, the drives become significantly simpler. New players will enter the arena since less value will be in the transmission and entry barriers will be lowered. "Developing and making a 7-speed dual clutch transmission, however, requires a lot of special know-how and deep pockets, something only a few have," Schmidtseifer said.

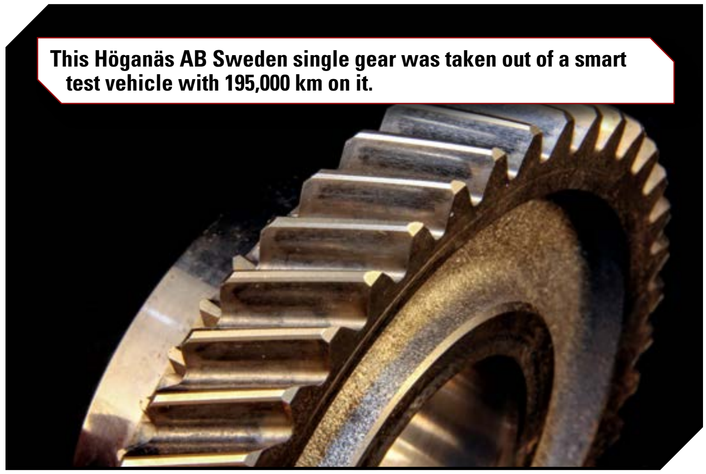
Höganäs AB has a track record of having implemented and tested PM gears in multiple demo car transmissions. This includes PM gears in a SMART car, a high-performance rally car, an electric vehicle and a 320 Nm popular European 6-speed manual transmission passenger car. The company has hands-on experience and supporting data for several successful applications of PM gear technology.

By understanding modern transmission designs and their application performance requirements, the Höganäs team can help clients analyze specific gear load scenarios. They can assist in optimizing the component's macro and micro design modification needs. They can also help choose the best suitable manufacturing processes and material solutions and ensure a proper heat treatment result.

They encourage industry professionals to utilize the extensive tech partner network in their application- and process development center where they can support everything from technical feasibility analysis, to design optimization, prototyping and off-tool sampling for PM gear testing and validation purposes.

Capstan Atlantic Examines PM Evolution

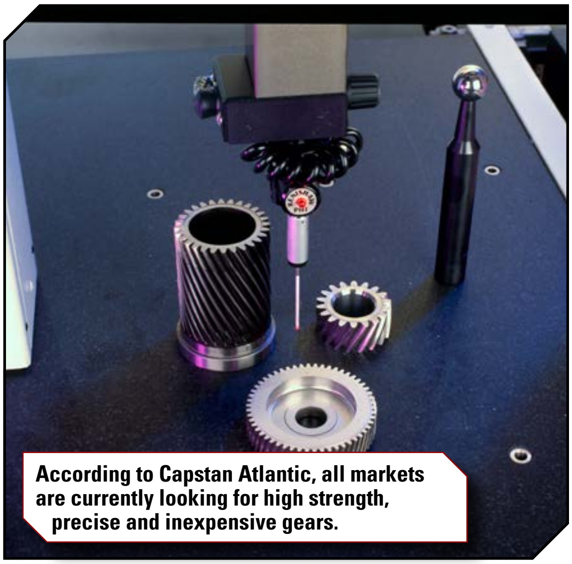
Capstan Atlantic is a producer of precision powdered metal gears, sprockets and complex structural components. The company combines advanced gear engineering with proprietary processing techniques to meet the most demanding applications. Capstan's roll densification process and high density single press technology (HD4) allows Capstan to achieve original gear design tolerances, reduced wear and noise characteristics while maintaining a competitive cost advantage. *Gear Technology* recently caught up with said Richard Slattery, vice president, engineering at Capstan, to dis-


This Höganäs AB Sweden single gear was taken out of a smart test vehicle with 195,000 km on it.

cuss trends, technologies and future considerations in the powder metal (PM) industry.

"PM has evolved on a technical level to rival the precision and strength of wrought steel gears at a fraction of the price. Material systems, process methods and innovative metrology enable this advancement," said Slattery.

According to Slattery, gear tooth qualification achieved via pressurized gear rolling (in oil) against specifically engineered roll dies enable custom involute forms for noise reduction, precise gear crowning, combined with selective densification to improve fatigue properties. PM is also a "green" technology using >90% recycled raw materials. Additionally PM is a net shape process with near zero scrap.



According to Capstan Atlantic, all markets are currently looking for high strength, precise and inexpensive gears.

Similar to other manufacturing processes, cost is the biggest challenge in the PM industry despite being an economically attractive process against most other manufacturing methods.

"An additional focus has been on maintaining dimensional precision on hardened gears, without the need for a post hardening grind operation. This is achieved through the development of low, or no, distortion hardening methods," Slattery added.

Slattery has witnessed the strength and hardness of PM gears improving in recent years.

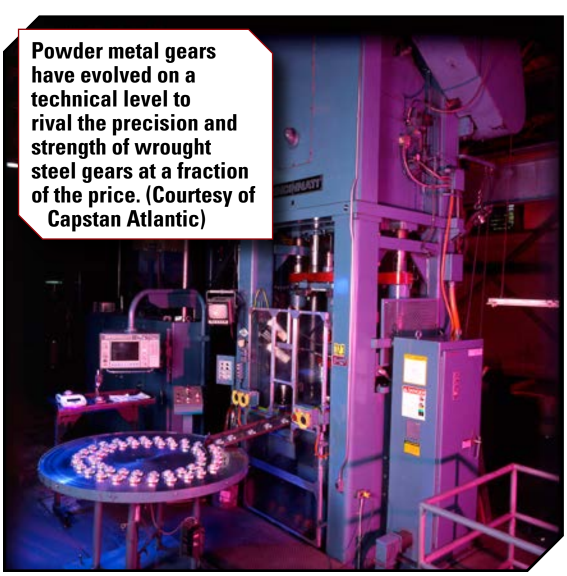
"PM gear strength has evolved significantly over the years, whether it be through the use of chrome-steel alloys, single press high dense technologies, or tooth flank densification to minimize contact fatigue issues (fretting). Bending fatigue strength has improved dramatically by achieving high (>7.4 g/cm^3) core density with high tonnage part compaction, and minimum levels of organics (powder lubricants, etc..) in the raw material," Slattery said.

The PM game in 2017 revolves around all market segments looking for high strength, precise and inexpensive gears. Slattery believes powder metallurgy component manufacturing is the best means to this end.

In the future, Slattery sees precision low cost gears and pulleys for electronically powered gear trains.

And all the talk of additive manufacturing in recent years has had an impact on the PM industry.

"Additive manufacturing for the purpose of rapid prototyping is compressing the development timeline," Slattery said. "I find this technology fascinating, and I'm excited to see where this technology takes PM in the future."



Powder metal gears have evolved on a technical level to rival the precision and strength of wrought steel gears at a fraction of the price. (Courtesy of Capstan Atlantic)

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PM Industry News

HERE'S SOME OF THE LATEST PM-RELATED NEWS AND EVENTS FROM 2017:

Powder Metal MPIF Elects New Officers

John F. Sweet, PMT, president & CEO, FMS Corporation, Minneapolis, MN, has been elected as the 29th president of the Metal Powder Industries Federation (MPIF), succeeding Patrick J. McGeehan, Ametek Inc., Eighty Four, Pa. His two-year term will take effect at the conclusion of the Federation's annual Powder Metallurgy (PM) Management Summit and 73rd Annual MPIF Business Meeting, October 21–24, 2017, in Naples, Fla.

One of the Federation's six associations will also instate a new president following the Summit. Dax Whitehouse, NetShape Technologies, Floyds Knobs, IN, has been elected president of the Powder Metallurgy Parts Association (PMPA). Meanwhile, Dean Howard, PMT, North American Höganäs, Hollsopple, Pa., was re-elected to serve a second term as president of the Metal Powder Producers Association (MPPA), while Thomas Houck, Carpenter Technology, Tanner, Ala., will serve a second term as president of the Metal Injection Molding Association (MIMA).

Sweet has worked for FMS Corporation for 27 years, sustaining a family tradition as a third-generation entrepreneur. He most recently served as president of the Powder Metallurgy Parts Association and has served the association and MPIF actively for many years. Sweet received MPIF's Distinguished Service to Powder Metallurgy Award earlier this year during POWDERMET2017—Las Vegas. He has been a member of APMI International for 29 years, is a certified Level I Powder Metallurgy Technologist, and serves on the APMI Board of Directors.

Sweet has also been an elected trustee of the Center for Powder Metallurgy Technology. He was a co-op student in the R&D Laboratory of Hoeganaes Corporation for 3 years and earned his BS in materials engineering from Drexel University. Sweet is also a member of Alpha Sigma Mu Professional Honor Society for Excellence in Materials Engineering. In his local community, he has been serving on the Elder Board of the Redeemer Bible Church for the last ten years. (*www.mpif.org*)

New Industry Talent Attends PM Short Course

The annual Basic Powder Metallurgy (PM) Short Course recently pressed out another batch of students. This year's course, held August 14–16, received excellent feedback from attendees, with over 93% stating that they would recommend the course to others.

This year there was a broader range of attendees than reported in 2016. The largest represented industry segment was still engineering (33%); however, quality control and testing, and sales employees made up 19% and 20% of the audience, respectively. Production (12%), other (12% — mostly R&D), and management (5%) rounded out the short course attendees.

The Basic PM Short Course is a vital educational tool for the entire industry. Each speaker is an expert in their field and provides invaluable knowledge. Combined, the speakers have an incredible total of over 450 years of relative in-industry experience. The course is specifically designed for those who want to expand their knowledge of PM; enhance their opportunities to advance; and for those who are looking to deepen their understanding in the specialized area of PM. (*www.mpif.org/Meetings/basic-short-course.asp*)

GKN Expands Global Footprint, Wins PM Material Awards

The acquisition of Tozmetal Ticaret Ve Sanayi AS (Tozmetal) was completed in June 2017. The powder metal part manufacturer based in Turkey will expand the global footprint of GKN Sinter Metals, the world's largest manufacturer of sintered components which now comprises production locations in 10 countries and over 7,000 employees.

Tozmetal focuses much of its output on hydraulic pump components for European automotive customers. At a celebratory event, employees of Tozmetal were welcomed by Wolfram Messner, president, Global Small Segment Operations.

During the event, Messner said: "Tozmetal is an excellent fit and provides increased access to new customers in the Middle East region. I am delighted to announce that Hüsnü Özdüral, who for years has been managing and growing the company successfully, will continue to lead the plant. We will work closely with the local team to make the site a strong platform to help grow our business and support our customers in the region," Messner added.

GKN Sinter Metals has received two Grand Prize Design Excellence Awards from the Metal Powder Industries Federation (MPIF). The awards were in the Automotive Transmission category and the Automotive Chassis category.

The MPIF Design Excellence Awards recognize companies who use the flexibility of Powder Metallurgy (PM) materials to push new designs and concepts into a progressive industry. GKN accepted the awards at the annual PowderMet Conference in Las Vegas, Nevada.

In the Automotive Transmission category, GKN Sinter Metals' planetary carrier assembly for Ford Motor Company's 10-speed transmission won the Grand Prize. The sinter-brazed copper-steel assembly is comprised of a cage and a flanged hub, and features a novel twist-lock geometry as a bearing retainer.

The twist-lock retainer allows the flanged hub to only require a simple turning operation for functionality. The technology's design reduced the stress by over 50 percent, resulting in a PM product that outperforms in a competitive process and cost.

GKN's copper-steel output pulley for Nidec Automotive Motor Americas won the Grand Prize in the Automotive Chassis category. The pulley includes a compacted, net-shape groove for an electric reclining mechanism in a mini-van rear seat application, significantly reducing cost.

The part's unique groove was designed for PM production, providing full functionality as a net-shaped product. The application required a small footprint design with lightweight parts, resulting in the success of the compacted technology of the output pulley.

MPIF recognized eight products across the industry at the conference for elite awards, and GKN is the only company in 2017 to win two Grand Prize awards. MPIF is an international federation with a mission to advance PM and particulate materials.

"GKN is pleased to receive two awards in 2017 and recognizes MPIF's role in promoting the PM industry," said Alan Taylor, Vice President Lightweight Technology, GKN Sinter Metals. "The two winning parts detail the breadth of design opportunities when using PM and provided our customers' exceptional value when compared to other metal working processes." (*www.gkn.com*)

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Backlash and Axial Movement

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

QUESTION

What is the relationship between angular backlash and mean or normal backlash, the axial movement of wheel gear, and mean or normal backlash for bevel and hypoid gears?

Expert response provided by Bob Wasilewski, Engineering Services Manager, Arrow Gear. In order to understand the requested relationships, we should be clear as to what the backlash values are on bevel gears, what they mean and how they are determined.

Both ISO and AGMA specify that the backlash on bevel gears is defined as:

Outer normal backlash at the tightest point of mesh.

There are several important items in that description.

First, that backlash is taken at the tightest point of mesh. The values tabulated in AGMA and ISO standards give a suggested range of backlash values for the *tightest* point. They are not the total range of backlash. Backlash at any other point on the bevel gear can and likely will be higher that the tabulated range. Any reputable bevel gear manufacturer will find the tightest point of mesh in the set, measure the normal backlash there and mark both that backlash and the mating teeth where the measurement was taken. It is important to note that that tightest point of mesh was determined in a test machine with precision bearings and minimal runout in the work holding tooling. The components in your gear box will have different runout that may end up shifting that tightest point to another set of teeth. It is always a good idea to verify that your gear set has proper backlash in installation.

Second, the backlash measurement is taken at the outer diameter of the gears, not at the mean or midface.

Third, the backlash is the normal backlash, meaning it is perpendicular to the tooth surface.

One simple way to describe that direction is to envision placing the base of a thumb tack on the tooth at the outer diameter. The point of the thumb tack will point in the normal direction. That is the direction that a measuring device should be used to measure the backlash movement. That direction is a result of the tooth's pressure angle. On straight bevels that is the only angle to consider. On hypoids, spiral bevels and Zerol bevel gears the tooth is curved and that adds the additional factor of the spiral angle at the outer end. That angle is not the same as the mean spiral angle specified in the gear set geometry, it is always greater.

To determine the angular backlash from the normal backlash some calculation is required. First, you have to calculate the transverse backlash. To do that calculation, you need some values from the gear set geometry, including some that are not often readily available. The following values are necessary:

J_n = Normal backlash
R_e = Outer cone distance
βe = Spiral angle at R_e
R_m = Mean cone distance
βm = Spiral angle at R_m
α_n = Normal pressure angle
r_{c0} = Cutter radius

The two values that are not always readily available are the spiral angle at the outer cone and the cutter radius. These values are not always tabulated in the gear data block on the gear set drawing but are determined for the machine calculations necessary to manufacture the gear set. You may have to get them from the gear manufacturer. Actually, if you can determine the cutter radius you can calculate a value for the outer spiral angle using the following equation:

$$\beta e \cong \arcsin \frac{2R_m r_{cO} \sin \beta_m - R_m^2 + R_m^2}{2R_e r_{cO}}$$

Using the outer spiral angle you may calculate the transverse backlash with:

$$j_{et} \cong \frac{j_n}{\cos a \cos \beta e}$$

Where:

j_{et} = Transverse backlash

The transverse backlash, of course, is a linear distance that you can convert to angular using the pitch diameter. Transvers backlash is the value you want to use if you measure the backlash outside the gear box at a diameter equal to the pitch diameter. It is generally easier to measure the backlash on the shaft with the wheel member (larger gear).

Axial movement for a change in backlash

To calculate the axial movement for a change in backlash, calculate the amount of axial movement for *each member* using the formulas below. (If the shaft angle is 90 degrees, the ratio of wheel mounting distance change and pinion mounting distance change is equal to the gear ratio, z_2/z_1).

$$\Delta j = \Delta j_1 + \Delta j_2$$

$$\Delta j_1 = \frac{\Delta j \tan \delta_1}{\tan \delta_1 + \tan \delta_2}$$

$$\Delta j_2 = \frac{\Delta j \tan \delta_1}{\tan \delta_1 + \tan \delta_2}$$

$$\Delta a_1 = \frac{\Delta j_1}{2\tan \alpha_n + \sin \delta_1}$$

$$\Delta a_2 = \frac{\Delta j_2}{2\tan \alpha_n + \sin \delta_2}$$

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backlash

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Where:

Δj is total change in backlash

Δj_1 is change in backlash for pinion

Δj_2 is change in backlash for wheel

Δa_1 is axial movement of pinion

Δa_2 is axial movement of wheel

z_2 is number of wheel teeth

z_1 is number of pinion teeth

α_n is pressure angle

δ_1 is pinion pitch angle

δ_2 is wheel pitch angle

When adjusting backlash for lower ratios, it might be necessary to move both wheel and pinion members to maintain acceptable tooth contact. For higher ratios the effect of pinion axial movement on backlash is small and moving the wheel alone may be sufficient. *NOTE: These formulas are for bevel gears but may also be used for hypoid gears as a first approximation.*

All of this material is described in the national standard ANSI AGMA 2008-D11 Assembling Bevel Gears. That document has a considerable amount of other information that is not only valuable to the assembler but for the gear box designer as well.

That standard is available from the American Gear Manufacturers at *www.agma.org*.

Robert F. Wasilewski is Engineering Services Manager at Arrow Gear Company and Chairman of the AGMA Bevel Gearing Committee.

Tooth Contact Analysis—Off Line of Action Contact and Polymer Gears

Paul Langlois

A loaded tooth contact analysis (TCA) model combining an FE representation of bending and base rotation stiffness of teeth with a Hertzian contact formalism for contact stiffness is presented and applied to polymer gears. Comparison with full 3-D FE contact analysis is made. The aim of the study was to apply such a specialized tooth contact analysis method, well-used within the steel gear community, to a polymer gear application to assess what modifications need be made to these models for them to be applicable to polymer gears. It is shown that it is important to include the phenomenon of extended contact at the tips of the gear teeth in such polymer gear tooth contact models for correlation with FE analysis. It was further shown—for the example considered—that the standard assumption made by such models, i.e.—that the points of contact do not move from their theoretical involute contact positions—should also be relaxed in order to capture accurately the shape of the transmission error curve. This may also be the case in certain situations for steel gears. Both effects were implemented in the author's models and with their inclusion correlation with the 3-D FE contact analysis is good.

Introduction

Gear-loaded tooth contact analysis is an important tool for the design and analysis of gear performance within transmission and driveline systems. Methods for the calculation of tooth contact conditions, with a particular focus on metal gears, have been discussed in the literature for many years. A number of commercial tools are available that perform such calculations (Ref. 1). Such specialized tools are used extensively within the industry for steel gears due to their fast set-up and analysis times. While similarities between tools are significant, they differ in implementation and significant differences in results can be found. The most significant difference between methods is in the representation of gear tooth and blank stiffness used. Methods using a combination of finite element models to capture the bending and base rotation stiffness, and Hertzian formalisms to capture the local contact deflections, are considered among the state of the art.

There are significantly fewer studies in the literature on tooth contact analysis models for polymer gears than there are for steel. Further, the use of such models in the industry is much lower due to questions of validity. Due to their inherent non-linearities, low modulus of elasticity, and significant temperature dependence of material properties, polymer gear tooth contact conditions are significantly more complex than those for steel gears. This study aims to apply an existing, specialized gear TCA model to polymer gear tooth contact and to present modifications that take significant steps towards a model that can be efficiently used as a design-and-analysis tool within the industry.

Performing loaded TCA in a general FE package requires a very fine mesh in order to accurately capture the Hertzian deflections local to the contact, and are therefore very time-consuming to set up and run. As a result, such an approach is rarely used in industry as a design-and-analysis tool. However, it can be considered a benchmark analysis, providing a means of validation of the assumptions made within specialized gear tooth contact analysis models.

In this paper validation results are presented between the author's specialized gear tooth contact model and the results of a full FE TCA using a commercial FE package showing good correlation for TE, root stress and contact stress.

Gear Tooth Contact Analysis and Polymer Gears

Polymer gears have a number of polymer-specific properties, as compared to steel gears, which may contribute significantly to their tooth contact conditions and therefore a number phenomenon which may need to be included in a specialized gear tooth contact analysis model to accurately model their contact behavior. These include:

- ***A larger deflection to permissible load ratio.*** Due to their lower modulus of elasticity, deflections are high and the effect of extended tip contact outside the theoretical path of action must be included for polymer gears. As a result, load sharing and operating contact ratio are significantly different from steel gears.
- ***Material non-linearity***. The majority of polymer gears are manufactured using thermoplastic materials. Thermoplastics have, for example, different modulus of elasticity under tension and compression, and in a fully detailed analysis their visco-elastic behavior would need to be considered.
- ***Temperature dependence of material properties***. Polymers have material properties, such as modulus of elasticity and friction coefficients, which vary significantly with temperature.
- ***Humidity dependence of material properties.*** As well as temperature dependence, some polymers have significant humidity-dependant material properties.
- ***Temperature dependence of geometry.*** Polymers have relatively large coefficients of thermal expansion. As such their geometrical dimensions change in a non-negligible way with temperature.
- ***Friction.*** Friction at the contact is often neglected in the tooth contact analysis of steel gears. However, particularly in the case of dry-running polymer gears, coefficient of friction at the tooth contact is high and can contribute significantly to the tooth contact conditions.
- ***Wear***. Certain polymer gears can wear significantly; as they wear, their surface geometry changes and, as a result, their

tooth contact conditions are constantly varying.
- Polymers have lower accuracy and therefore larger manufacturing errors — such as pitch errors. Any specialized gear tooth contact program should provide the option to include these errors as input to the analysis.

It is not the intention of this study to cover all these contributing factors to polymer gear tooth contact analysis. The aim of the study is rather a first step in the process — to begin with a class of specialized tooth contact analysis methods that are well-used within the steel gear community and to apply them to a polymer gear application to assess what modifications need be made to these models to make them applicable to polymer gears. The focus of this paper is the first item above, i.e. — the larger deflections experienced by polymer gears and the resulting changes in load sharing and operating contact ratio. The non-linearities due to the effect of the tooth deflections on the change in contact location are considered and modifications to the author's tooth contact models are validated against full FE.

Some important considerations for polymer gears, such as the temperature dependence of the material, are largely ignored within this study, although an appropriate modulus of elasticity corresponding to the operating conditions is used. It is not expected therefore that the TCA results obtained reflect the full detail of the real tooth contact conditions of the polymer gears under consideration.

Although less extensive than the literature regarding steel gear tooth contact analysis, there still exist many notable contributions regarding polymer gear TCA within the literature. It is not the intention here to present a full literature review; however, we shall introduce some relevant papers of interest — particularly those with regards to FE and specialized gear tooth contact analyses.

The importance of operating contact ratio and the effect of extended tip contact on polymer gear performance has been discussed in the literature for many years. Indeed, several studies concern tooth contact analysis of polymer gears using finite element methods. For example, Walton et al (Ref.2) considered the operating contact ratio of polymer gears using a 2-D plain strain FE method; extensive discussion of extended tip contact is given. The increase in real contact ratio is also presented in non-dimensional form. The effect of premature contact on the wear behavior of acetal gears is discussed.

Van Melick (Ref. 3) performed FE tooth contact analysis of a plastic steel gear pair to investigate the resulting stresses and kinematics of the meshing process; polymers PA 46 (Stanyl) and 30% glass fiber-reinforced PA 46 were used. They show that load sharing affects bending stress significantly compared to steel gears — particularly in cases where the operating contact ratio was pushed above 2 due to extended tip contact. Comparison of stresses is made with ISO 6336, VDI 2545 and *Kisssoft*. Van Melick hypothesized that the reciprocating motion of extended tip contact is the governing mechanism for wear.

Similar to Van Melick, Karimpour et al (Ref. 4) used a 2-D dynamic FE model and compared stress results for a pair of acetal gears to results obtained from the ISO steel gear rating standard ISO 6336. Frictional effects were considered and shown to have a significant effect on contact stresses. Premature and post mature contact outside of the theoretical path of action were discussed, and their effect on load sharing and thus calculated stresses presented. They determined a need for a new polymer gear standard — not based on steel gears — that accounts for the idiosyncrasies of polymer gears. Although a dynamic model was used, no indication or argument was given regarding the requirements for their conclusions, as compared to a quasi-static model.

As well as papers regarding TCA for polymer gears using general FE methods, several discuss specialized gear tooth contact models in the context of polymer gears.

Although not explicitly presented in the context of polymer gears, Singh and Houser (Ref. 5) presented extensions to the well-known TCA models of *LDP* and *CAPP* that include the effects of off line of action and extended tip contact in these analysis models.

Tsai and Tsai (Ref. 6) discussed similar modifications to gear tooth contact models developed for steel gears by Houser, to include extended tip contact and to show its importance for polymer gears.

Extended tip contact in the context of polymer gears has been investigated by Eritenel et al (Ref. 7). The focus was the proposed problem of unloaded flank tooth contact due to excessive bending. Eritenel et al used the TCA program *CALYX* to show that this does not occur in their examples, and the deflection on the backside increases with increasing load due to the relative contributions from Hertzian and bending deflections.

Letzelter et al (Refs. 8–9) developed a model using a specialized, gear-loaded tooth contact analysis that includes the visco-elastic properties of the materials via the use of the generalized Kelvin model. Results of the model are presented for Polyamide 6/6. Validation via predicted and measured TE is presented, showing relatively good agreement. No thermal or mechanical coupling is considered in the model. Cathelin et al (Ref. 10) develop a related method for computing the loaded mechanical behavior of fiber-reinforced polymer gears. The influence of the fiber orientation is considered via the FE models used in the method for the bending and base rotation influence coefficients. Results are presented for Polyamide 6 with 30% glass-fiber reinforcement.

Raghuraman (Ref. 11) developed a pre-processor to the tooth contact analysis program *LDP* — "*Plastic Gear Program* (*PGP*)" — to consider the effect of temperature/humidity and tolerance by altering the microgeometric and macro-geometric parameters before a loaded TCA is performed in *LDP*.

Methodology

Specialized loaded tooth contact analysis model. The specialized loaded tooth contact analysis model used in this study is presented in detail (Ref. 1). As was assumed for steel gears (Ref. 1), dynamic effects are not considered in this study.

A common assumption made (in (Ref. 1) — and usually in the type of specialized gear tooth contact analyses discussed here — is that deflections and microgeometry are sufficiently small that the contact points and normals do not move from their theoretical no-load locations.

This assumption is implicitly not made in the FE analyses presented, where surface-to-surface contact elements are used and the region of contact calculated during the analysis. This assumption is also relaxed during this study. A modification to the model presented (Ref. 1) is made to take into account the change in contact point up the gear tooth profile resulting from the deviation from involute geometry due to applied flank modifications. It is shown that this modification is required for good correlation of our specialized models with our FE contact analysis results.

A brief description of the method is presented here for brevity, further details can be found in (Ref. 1).

Inputs to the calculation include torque, gear macro and micro geometry (flank modifications) and misalignment at the gear mesh. The analysis is quasi-static. At each time step, unloaded, potential contact lines are first calculated from the gear macro geometries, relative locations and rotations. Potential contact lines are divided into strips and contact points expressed in a 2-D coordinate system as distance along face width and roll angle.

Points that could come into contact at the tips of one of the gears due to tooth deflections are included in the discrete set of potential contact points. The gap between the contacting flanks at these points is calculated according to (Ref. 5).

During the process of this study, modifications to the calculation presented (Ref. 1) were made to account for the change in potential contact points in terms of their positions up the profile due to micro geometry modifications. Figure 1, for example, shows the points that would come into contact as the driving gear, top of the picture, rotates anti clockwise due to bending, into contact with the tip of the driven gear. Without tip relief on the driven gear the contact points indicated by triangles will contact first, while with tip relief the contact points indicated by squares will contact first. The gap between flanks due to the micro- and macrogeometry at the points indicated by the triangles and squares is different, and so the calculated transmission error is different depending on which pair is taken as the points of potential contact. At each mesh position the calculation was modified to search the flank in the profile direction around the nominal contact points (without microgeometry) to find those with the minimum gap between flanks when the designed microgeometry is included; these points were used as the potential contact points in the rest of the calculation, instead of the nominal, no microgeometry, points.

Compatibility and force equilibrium conditions relating the discretized contact points are formulated and solved.

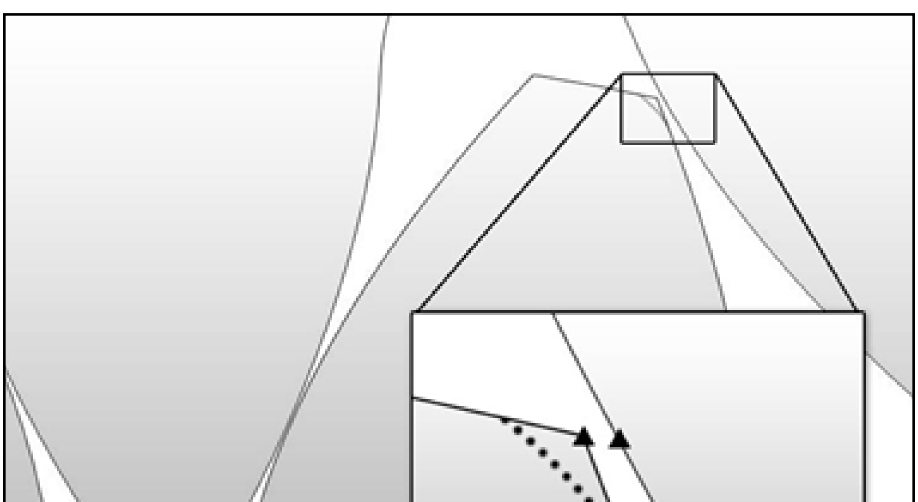

Figure 1 Potential contact points under tooth bending. Triangles — without microgeometry; squares — with microgeometry (parabolic tip relief).

Results include the load distribution across the contact lines, the elastic deformations at each contact point pair, and transmission error. Load distribution results are further used to calculate contact stresses on the gear flanks.

In the class of models considered here, the elastic deformations are separated into two parts. The bending stiffness and base rotation of the teeth are included via an FE model of the gear. The Hertzian contact stiffness of each strip is considered separately via a Hertzian line contact formalism.

In our implementation the FE mesh used for bending and base rotation stiffness for each gear is generated from the exact gear macrogeometry using the same code that generates the full FE tooth contact analysis meshes discussed later. Via this FE representation, the compliance due to loads on adjacent teeth is naturally considered. The stiffness with respect to the regular FE grid on the gear flanks is calculated via Guyan reduction of the FE stiffness of the full gear. The stiffness with respect to potential contact points, which will not coincide with the nodes of the regular grid, is interpolated using the shape functions of the FE elements. Root stress influence coefficients are also calculated from the FE model for unit loads at each flank location.

It is only required to perform these steps once for each gear macrogeometry. It is reasonably assumed that the microgeometry modifications do not significantly affect the bending stiffness of the FE model. Therefore microgeometry and misalignments can be changed, and the TCA rerun without having to recalculate the bending stiffness.

The local contact between potential contact points is considered as a line contact between cylinders. The compression of each tooth between the point of load and the center line is also included, as this is removed from the stiffness represented by the FE model. In our implementation, the approach of Weber (Ref. 12) was chosen.

The load distribution calculated during the analysis together with the root stress influence coefficients from the FE model are used to calculate the root stress in the gears throughout the mesh cycle.

Loaded Tooth Contact Analysis Model in FE

For validation of our model, loaded tooth contact analysis was performed in *ANSYS*. The method used to set up and run the FE tooth contact analyses in *ANSYS* was presented in detail in (Ref. 1).

The geometry was specified in SMT's *MASTA* software (Ref.13). An algorithm was written to define the FE mesh node locations in an *ANSYS Parametric Design Language* (*APDL*) script directly from the geometry, thus avoiding issues that can arise if the geometry is constructed via a CAD model. Microgeometry flank modifications were included. The algorithm generates a 3-D mesh for a single tooth section that is then duplicated, rotated and merged to generate a mesh for multiple teeth. A sufficient number of teeth are included in the FE model to capture the effect of adjacent teeth on those teeth in contact. The rest of the gear blank is generated as a cylinder from bore-to-root diameter. Misalignment is included by modifying the node positions. Gears were positioned in mesh and backlash was removed by a further rotation of the pinion, as it is not included in the specialized gear tooth contact calculations used.

The solid mesh consists of quadratic SOLID186 elements, as required for accurate calculation of the contact pressures between teeth. Linear elements were used (Ref. 1), as the focus there was TE — *not* stress. Surface-to-surface contacts were defined between the potentially contacting teeth. The Lagrange method was used to maintain the contact constraints purely via Lagrange multipliers, as such no penetration between contacts was allowed.

Figure 2 shows the boundary conditions applied to the FE model. Zero displacement boundary conditions were applied to all degrees of freedom at the bore of the wheel. The torque was applied at the pinion bore via a pilot node at its center. The pilot node was rigidly connected to the pinion's bore in all degrees of freedom using rigid node to surface constraints. Zero displacement boundary conditions were applied to all degrees of freedom, except rotation about the pinion axis, at the pilot node.

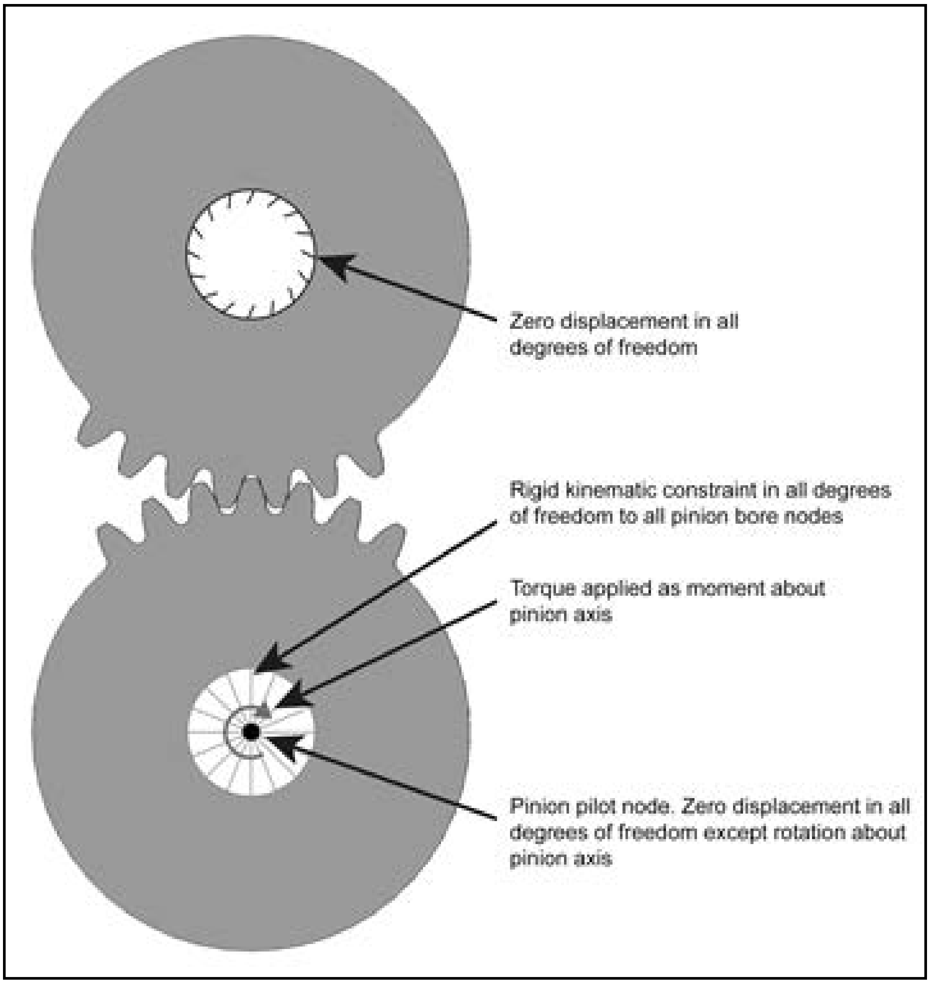

Figure 2 A schematic diagram showing the displacement and force boundary conditions applied to the FE model.

A static analysis was run at 32 mesh positions and the rotations of the pinion about its axis were written to file. Linear TE was calculated as the pinion rotation multiplied by its base radius. Maximum contact pressures and maximum principal tensile root stresses at each mesh position were also written to file. Geometric non-linearity was included in the analysis. Force convergence was checked.

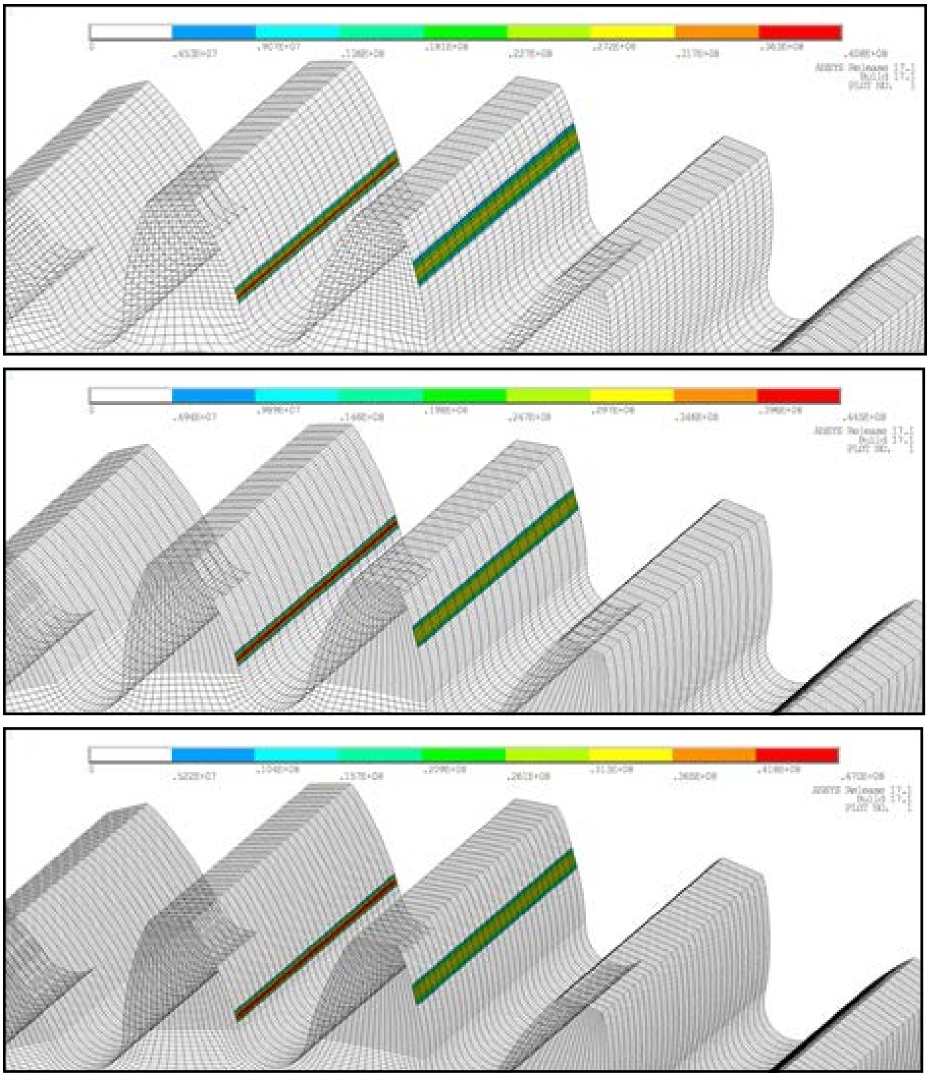

Figure 3 **Contact results showing contact stress for the 3 meshes considered at a single roll angle of the 12 Nm load case; from top to bottom — Mesh 1, Mesh 2, Mesh 3.**

Table 1 Machine-cut acetal spur gear pair example (Ref. 14)		
	Pinion	**Wheel**
Number of Teeth	30	30
Normal Module (mm)	2	
Normal Pressure Angle (degrees)	20	
Face Width (mm)	15	
Cutter Edge Radius (mm)	Max	
Bore Diameter (mm)	16	
Tooth Thickness at Reference Diameter (mm)	3.14	3.14
Contact Ratio	1.67	1.67
Material	Delrin 100	Delrin 100
Modulus of Elasticity (MPa)	1700	1700
Poisson Ratio	0.35	0.35

A mesh refinement study was performed for all results. The critical area for refinement in a gear tooth contact problem is at the tooth contacts themselves. A mesh fine enough to capture the Hertzian contact deformation is required. For the increasing levels of mesh refinement the mesh was refined in all areas, with more refinement at the contacts. Figure 3 shows examples of the meshes used and results obtained from the FE analysis.

It is informative to note the relative run times for the 3 meshes considered. Using a 64-bit system with Intel Core i7-5820K CPU @ 3.30 GHz and 64 GB of RAM, for 32 mesh positions the analysis for Mesh 1 ran in approximately 17 hours. Mesh 2 ran in approximately 42 hours while Mesh 3 took approximately 230 hours. This indicates why full FE analysis is rarely used as a design-and-analysis tool for gear tooth contact and why specialized gear tooth contact models, which have run times of the order of seconds to minutes, are used extensively in industry.

Results

The machine-cut acetal gear set presented (Ref. 14) was chosen as our test case. These are standard gears, cut using a standard basic rack and operating at the standard center distance. The gear geometry and material details are presented in Table 1.

It was assumed that the modulus of elasticity was 1,700 (MPa), a value for Delrin 100 at approximately 60 degrees centigrade. The temperature dependence of the modulus was not considered. This is a crude assumption for polymers, as discussed in the previous section.

Both gears had 50 µm of parabolic tip relief.

Figure 4 shows the transmission error trace for the 10 Nm load case for a number of models. A number of conclusions can be made from these results. One, it is clear that the closest correlation with the *ANSYS* results is for the author's model that includes the effect of extended tip contact and the effect of the change in contact position due to microgeometry. Correlation between these models is good in terms of peak-to-peak TE, mean TE and the overall shape of the TE curve, indicating close agreement in all harmonics of TE. The author's model with extended tip contact, but not including the change in contact position due to microgeometry, agrees well in terms of mean and peak-to-peak TE with the *ANSYS* results. However, the shape of the TE trace is significantly different. The results for the author's model without extended tip contact, together with the observations above, show that extended tip contact is playing a key role in the peak-to-peak, mean and shape of the TE trace in this case.

Figures 5 and 6 present mean transmission error and peak-to-peak transmission error against torque for a range of loads. As with the results presented above, it was observed at all loads considered that the effect of the change in contact point due to microgeometry on the author's results for mean and peak-to-peak transmission error is negligible. Results are therefore only presented with this effect included. A number of conclusions can be made from these figures.

One, for mean transmission error there is reasonable correlation between all models. At higher loads the author's model, including the effect of extended tip contact, deviates slightly from those without the effect of extended tip contact where these tip contact points are taking some load resulting in a stiffer mesh. The author's results with extended tip contact match those of *ANSYS* very closely.

For peak-to-peak transmission error, clear differences exist in results between some models. For loads at and below 6 Nm, correlation between results is reasonably good. After 6 Nm the extended tip contact points begin to be loaded and the author's results with extended tip contact deviate significantly from those without. Again, correlation between the author's results with extended tip contact and the *ANSYS* results match very closely.

Figure 7 presents the operating contact ratio as calculated by the author's models. It is clear that the theoretical contact ratio is exceeded at around 2 Nm; this indicates that at this point the extended tip contact points are coming into contact. At approximately 6 Nm the operating contact ratio increases above 2. Figures 5 and 6 show that it is at 6 Nm that the mean and peak-to-peak transmission error are significantly affected by the extended tip contact. This is expected for spur gears, as the extended tip contact points come into contact earlier; the region of single

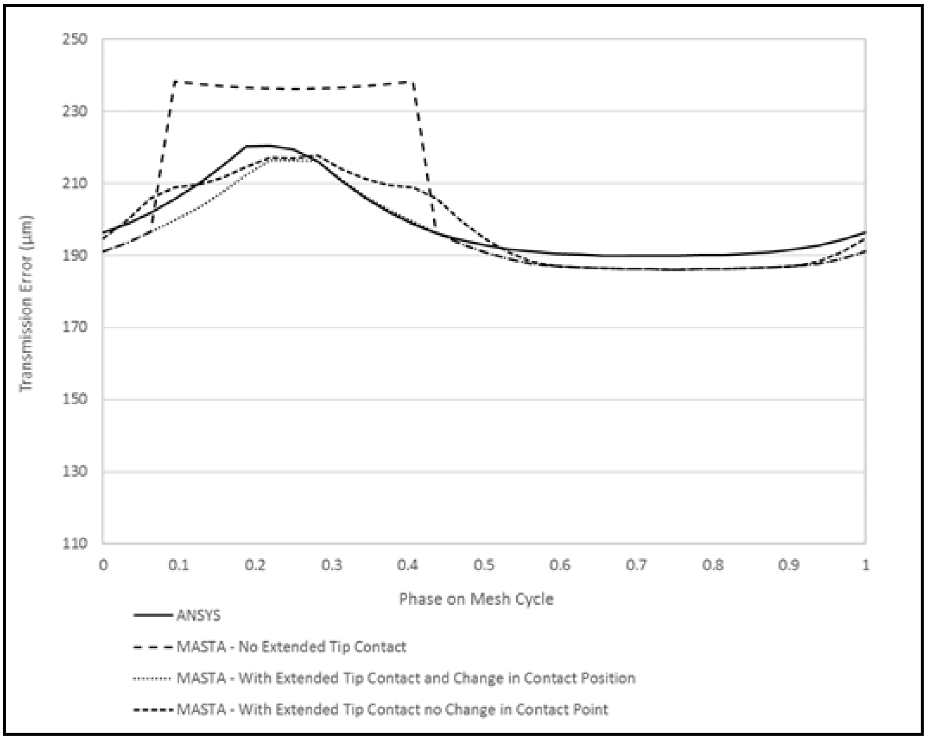

Figure 4: Transmission error curves for one mesh cycle for the 10 Nm load case.

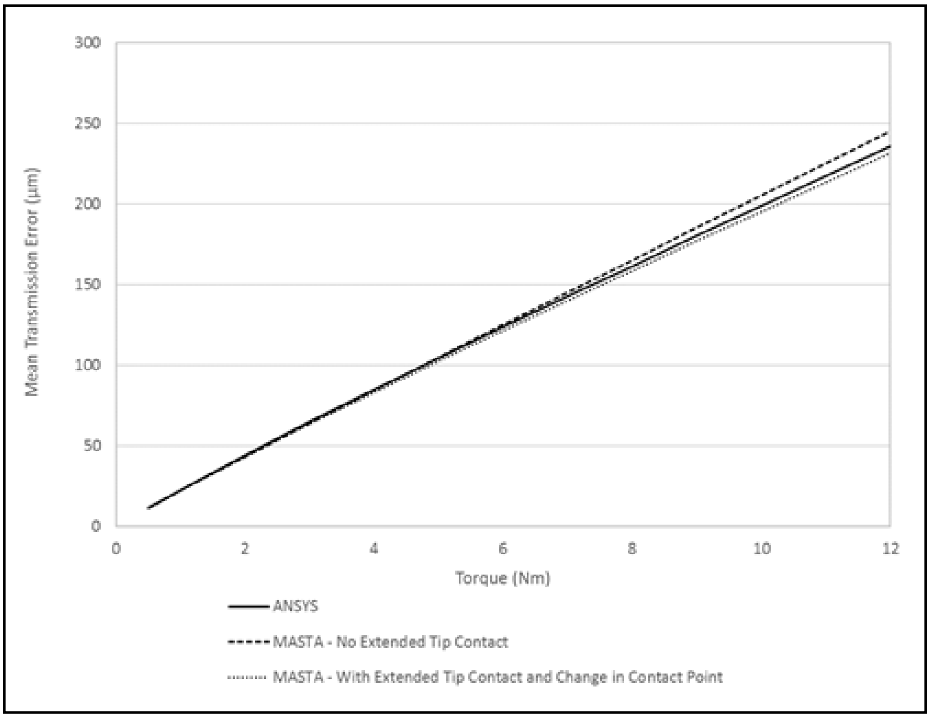

Figure 5 Mean transmission error against torque.

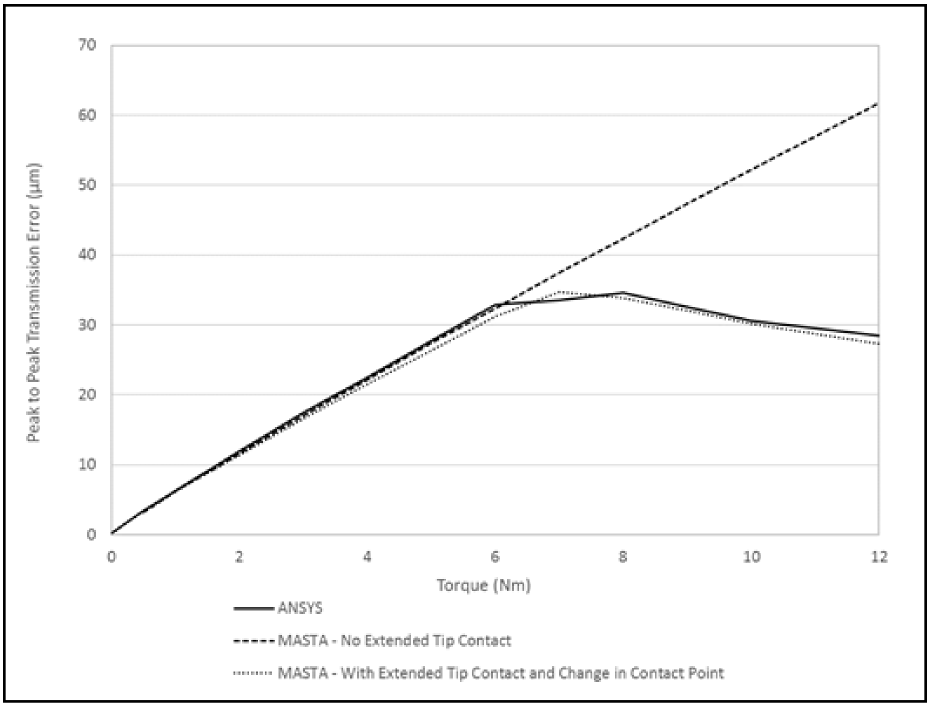

Figure 6 Peak-to-peak transmission error against torque.

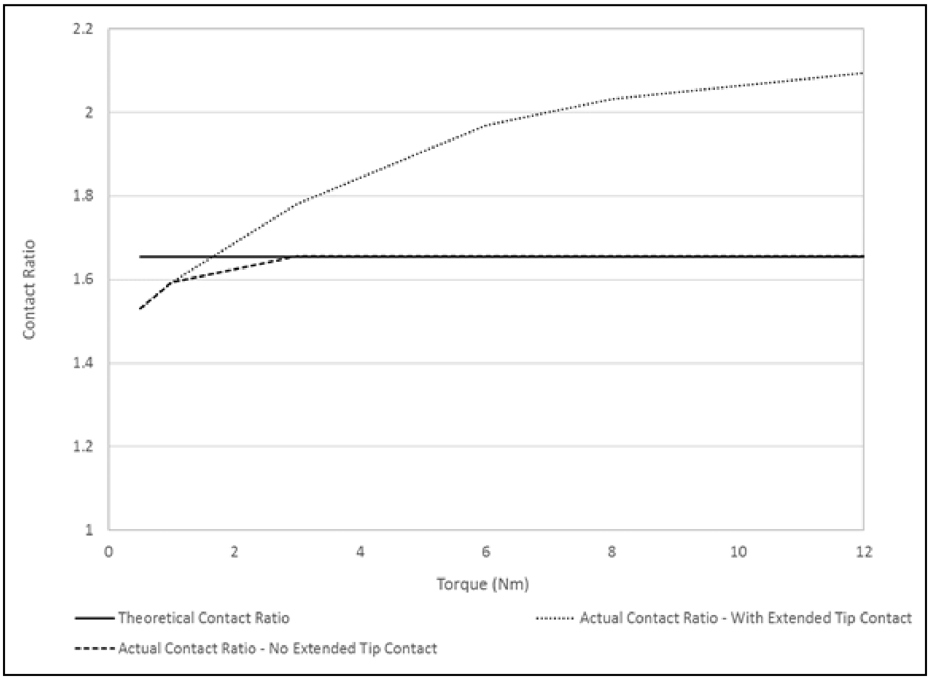

Figure 7 Calculated contact ratio using the author's models (MASTA).

tooth contact shrinks as load increases, until the point where the operating contact ratio is pushed over 2 and no region of single tooth contact remains.

Figure 8 presents the results for maximum principal tensile root stress on the pinion; the *ANSYS* and *MASTA* results agree well at all loads.

Figure 9 presents the results for maximum contact stress. Contact pressure results for such a general surface-to-surface contact problem in FE are among the most difficult results to obtain accurate values for. The *ANSYS* results presented are for a quadratic mesh where the maximum contact pressure curve against phase of gear mesh has been smoothed using a Savitzky—Golay filter. Convergence has been checked on the smoothed results. Smoothing of the contact pressure results is required due to numerical errors and inaccuracies in the details of the contact algorithm in *ANSYS*. The results show good agreement with the author's models. It is worth noting that the author's model post-calculates the contact pressure from the calculated load distribution using a Hertzian formalism by assuming each contact point pair as cylinder-on-cylinder contact.

Conclusions

- A specialized gear tooth contact analysis model based on a hybrid FE and Hertzian contact formalism has been presented and applied to an example pair of polymer gears.
- An extensive comparison was shown between the results of this model and a 3-D FE tooth contact analysis using *ANSYS* showing excellent correlation in transmission error, root stress and contact stress results.
- It was shown that, as expected for polymer gears, the extended off line of action tooth contact at the gear tips plays a critical role in transmission error. It was further shown that the standard assumption made by such models—that the points of contact do not move from their theoretical involute contact points—also should be relaxed in order to capture accurately the shape of the transmission error curve for the polymer gears under consideration. This effect can also be important for steel gears.
- The presented solution has been implemented in SMT's *MASTA* software

(Ref. 13).

- This study provides a step towards developing a TCA tool that can be efficiently and accurately applied to the design and analysis of polymer gears.
- The author considers the main step remaining in the analysis of the tooth contact conditions of polymer gears is the inclusion of a more detailed representation of the temperature dependence. For a proper treatment of this behavior, a coupled thermal and mechanical model will be required.

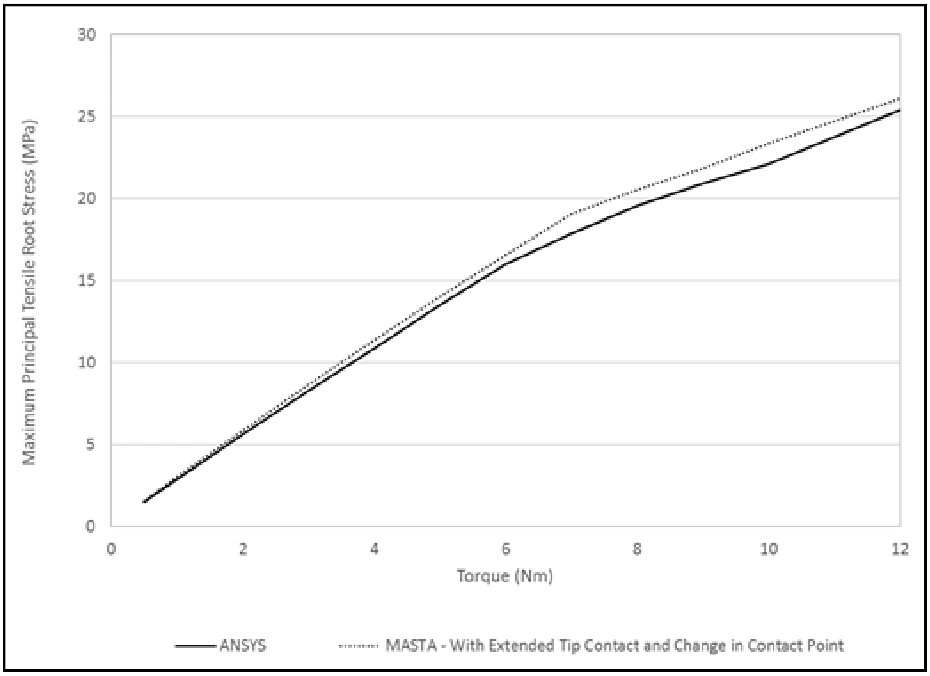

Figure 8 Maximum principal tensile root stress.

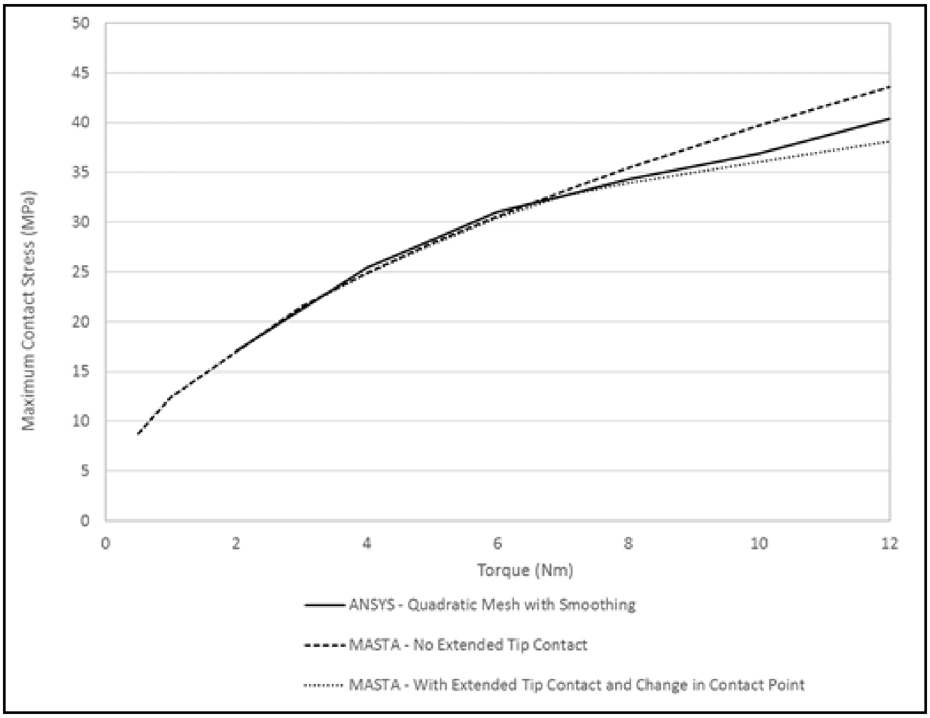

Figure 9 Maximum contact stress.

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Wear Investigation of Finish Rolled Powder Metal Gears

Anders Flodin and Michael Hirsch

When manufacturing powder metal (PM) gears lead crowning is not achievable in the compaction process. This has to be accomplished either by shaving, grinding or honing. Each of these processes has their merits and draw backs. When employing rolling using a roll burnishing machine lead crowning can be accomplished but due to errors in profile a hard finishing operation such as grinding is used by the industry (Ref. 1). In this paper a helical PM gear that has sufficient tolerance class after rolling has been tested in a test rig for durability and the wear has been studied.

Introduction

Powder metal gears for automotive transmissions are becoming a reality and GKN is the first company to deliver PM gears for car transmissions (Ref. 2). However, these gears are surface rolled and likely to be hard finished. Adding both processes will take away some cost advantage. It would be preferable to have only hard-finishing or surface rolling. So far, the rolling technology cannot meet the tolerances obtained by hard-finishing and hard-finishing cannot give the high-dens layer on the gear teeth that boosts mechanical properties to solid gear steel levels. Rolling can still deliver tolerances compared to shaved gears, but with a surface that is smoother and more comparable to superfinishing technology than traditional gear grinding or honing. In a joint-development effort, a finish-rolled gear replaced the original 6:th driven gear in a 6-speed manual transmission (Fig. 1). The entire transmission was put in a test rig and the gears were tested for durability and vibration. The findings are presented in this paper.

Figure 1 **Top: two views of 6:th output gear; Bottom: gearbox before case is bolted together; 6:th output gear is clearly seen (see arrow).**

Testing

The test sequence used was an OEM test cycle for a European premium car and equivalent to 300,000 km service life of the drivetrain. For the 6th gear the cycle was set as follows: 230 Nm input torque, which is maximum engine torque, for 21.6 million cycles at 3,000 rpm. This corresponds to a contact pressure of 1,285MPa and root bending stress of 677MPa.

The gears were measured before and after running on a Wenzel GearTec gear inspector for comparison. The output from the gear inspector was filtered both mechanically and in the software, but it still gives an understanding of the amount of wear that has taken place throughout the testing (Figs. 2–3).

Results

Wear results were recorded by measurement of profile and eyeball inspection. Figure 2 demonstrates that a high degree of accuracy is obtainable with the finish rolling process. There is good convex curvature on top of the involute, with tip relief visible on the driven flank; very little to no waviness. What cannot be seen on these measurements is the mirror-like surface finish (Fig. 4).

Figure 3 shows some wear of approximately 5–8 microns, and the convex crowning of the involute has worn away. So now the tooth shape is closer to the perfect involute. Some waviness can be seen, and around the pitch point there is a hump in the involute curve indicating the no sliding zone or rolling point. This is in line with what can be found in the literature (Refs. 3–6). Figure 4 displays photos of the gear teeth — before and after running.

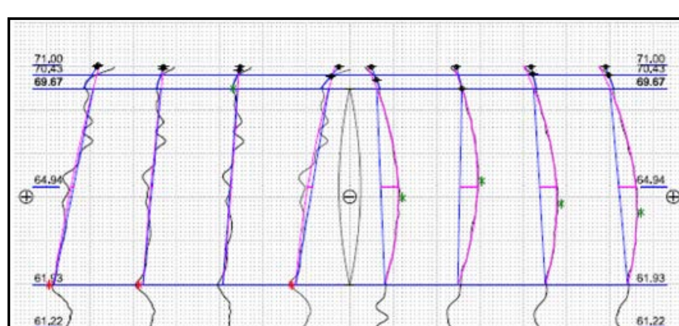

Figure 2 **Left and right flank of four gear teeth on tested gear before testing.**

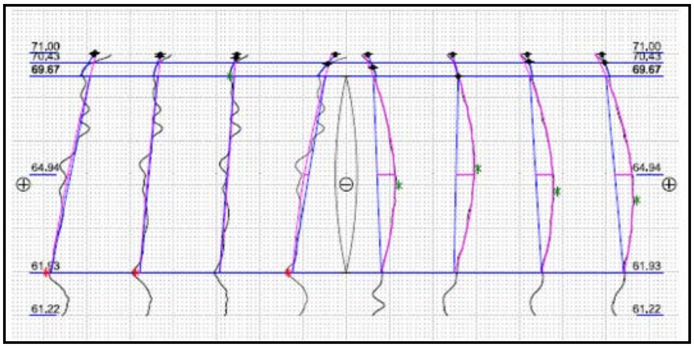

Figure 3 Gear flanks after testing; left flank is driven flank and right flank is the coast flank that has not seen any contact.

In Figure 4 the left column photo reveals some wear marks with the pitch line and some gray areas that are micropitted. Since this is end of life for this gear and equivalent to 300, 000Km driving, there seems to be more life left in the tooth, with no macro-pits and no noticeable NVH increase occurring during testing — a very good result. Vibration was also tested for this gear and was found to be considerably lower than for the reference gear, i.e. — OEM ground steel gears (Fig. 5).

Figure 5 shows a very significant difference between PM and the reference steel gears to the advantage of PM. The test was done at several different torques and speeds, with the same advantage for PM in all tests. The interested reader can go to the Höganäs Youtube channel and listen to the PM gears versus the original steel gears; it (is more informative) than the graph in Figure 5.

Summary

The 6:th output gear has been finish rolled and hardened, with no further machining on the teeth and bench-tested in a 6-speed manual transmission. The gear showed, after a full durability cycle, some mild wear of around 5–8 microns — but no significant failures such as pitting or tooth root breakage were observed. The gear mated with another hard finished gear pair in PM and displayed a significant reduction in vibration levels for all torques and speeds.

Conclusion

In this paper a finish rolled gear in a commercial automotive 6-speed manual transmission has been tested in test rigs for durability, wear and vibrations. The results were very promising and show that finish rolling to a high degree of accuracy is possible with results that meet and exceed OEM standards for durability, vibration and wear.

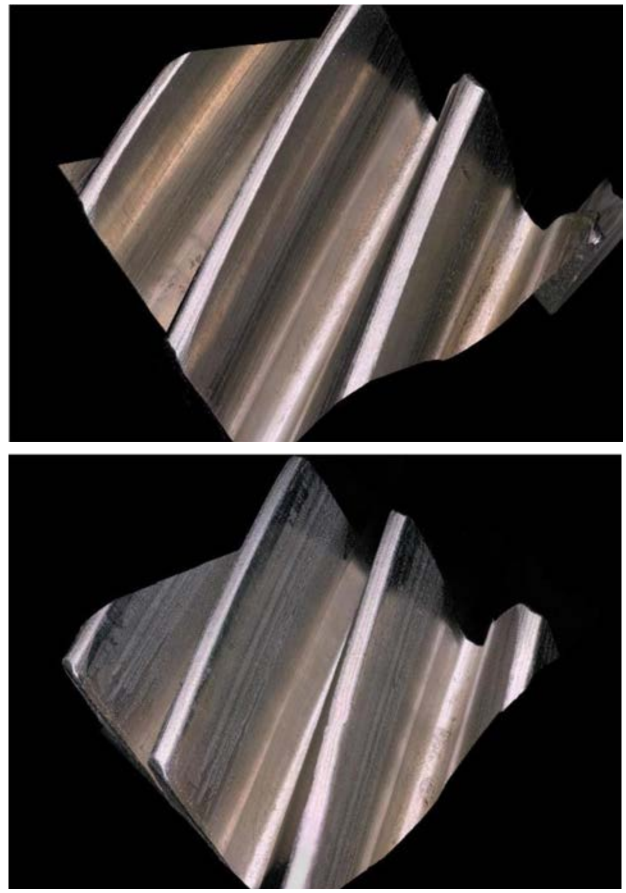

Figure 4 Top: non-worn gear; Bottom: worn gear after completed durability cycle.

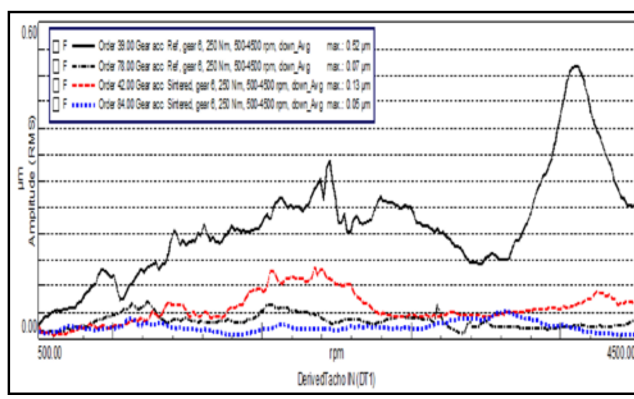

Figure 5 Acceleration amplitude from pick-up on gearbox housing: black lines are reference steel; red and blue lines are PM gears.

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Analysis of Excitation Behavior of Two-Stage Gearbox Based Upon Validated Simulation Model

Christian Brecher, Christoph Löpenhaus and Marius Schroers

In order to reduce costs for development and production, the objective in gearbox development and design is to predict running and noise behavior of a gearbox without manufacturing a prototype and running expensive experimental investigations. To achieve this objective, powerful simulation models have to be set up in a first step. Afterwards, those models have to be qualified and compared to experimental investigations. During the investigation procedure of gearboxes, there are two possibilities to evaluate the running and noise behavior: quasi-static and dynamic investigations. In times of engine downsizing, e-mobility and lightweight design, the dynamic excitation behavior is becoming increasingly important. Opposed to the quasi-static excitation, the dynamic excitation behavior of the gearbox regards increased load at resonance points caused by the dynamic behavior of the complete drive train.

The dynamic behavior of one-stage gearboxes has been the subject of scientific research for many years. In contrast, there have been few reports which investigate the running behavior of multi-stage gearboxes in the last few years. Most of them are based on computational investigations. However, to utilize the results of those simulation models for design purposes, it is indispensable to compare simulation results with experimental results.

Additionally, the objective of this paper is the analysis of the excitation behavior and the development of a simulation model for a two-stage gearbox. Based on a reference test variant, several gear parameters, such as helix angle and number of teeth, are varied in both stages by changing the gears and are investigated. Subsequently, a simulation model is presented which is able to calculate the dynamic excitation behavior of the two-stage gearbox tests.

Introduction

Multi-stage cylindrical gearboxes are used in the entire drive train technology. In addition to a sufficient load capacity and high gearbox efficiency, the acoustic behavior has to be taken into account. The increasing demands on the acoustic behavior appear in customer requirements and amended law restrictions, e.g., in automotive or wind industry (Refs. 21; 19). For a single-stage gearbox, several research projects have been carried out (Refs. 3–4; 13; 15–16). Because of the mutual interactions between the gear meshes at a two-stage gearbox, the knowledge cannot be transferred directly without restrictions.

The excitation behavior of gearboxes is mainly determined by the gear mesh excitation. A selection of influence factors is shown in Figure 1. In order to reduce the parametric excitation, an integer contact ratio is recommended by changing, for example, the helix angle or the face width (Ref. 23). On the one hand, flank modifications influence the path-dependent excitation. On the other hand, they are often used to reduce the impact excitation. The consideration of parametric, path-dependent and impact excitation in the acoustic-oriented design of single-stage gearboxes is state of the art, especially for quasi-static and partly for dynamic conditions (Refs. 11; 16–17).

For multi-stage gearboxes, additional parameters have to be taken into account. Firstly, the gears of the first stage enter mesh related to the line of action. Due to the gear geometry, the time when the gears of the second stage enter mesh is mostly temporally displaced. This phenomenon is called phase shift. Furthermore, the stiffness of the connecting shaft between the gear meshes influences the interaction of the single gear stages. Due to a differing number of teeth in the two stages, the noise behavior of the entire gearboxes changes, as well. In this report, the influence of the phase shift between the gear meshes is investigated by means of calculations. Hence, discrete values of the phase shift are inserted and investigated. The calculation procedure was validated based on tests with a single-stage gearbox and enhanced to a two-stage gearbox.

State of the Art

The excitation behavior of single-stage gearboxes is topic of many research activities (Refs. 3–4; 13; 15–16). Based on these researches, there are scientific publications dealing with multi-stage gearboxes. Mostly, the excitation behavior is discussed by means of calculated theoretical models and rarely compared with empiric investigations.

Gold conducts numerical and experimental investigations with three-stage gearboxes. Hence, he develops a vibration model using only the torsional degree of freedom. This model is extended to a spatial system using all six degrees of freedom to perform a dynamic analysis. His work indicates the necessity of spatial simulation models to identify the Eigen frequencies of multi-stage gearboxes. Only in special cases can the lowest Eigen frequencies be calculated by using torsional vibration models. In order to get results close to reality, the coupled

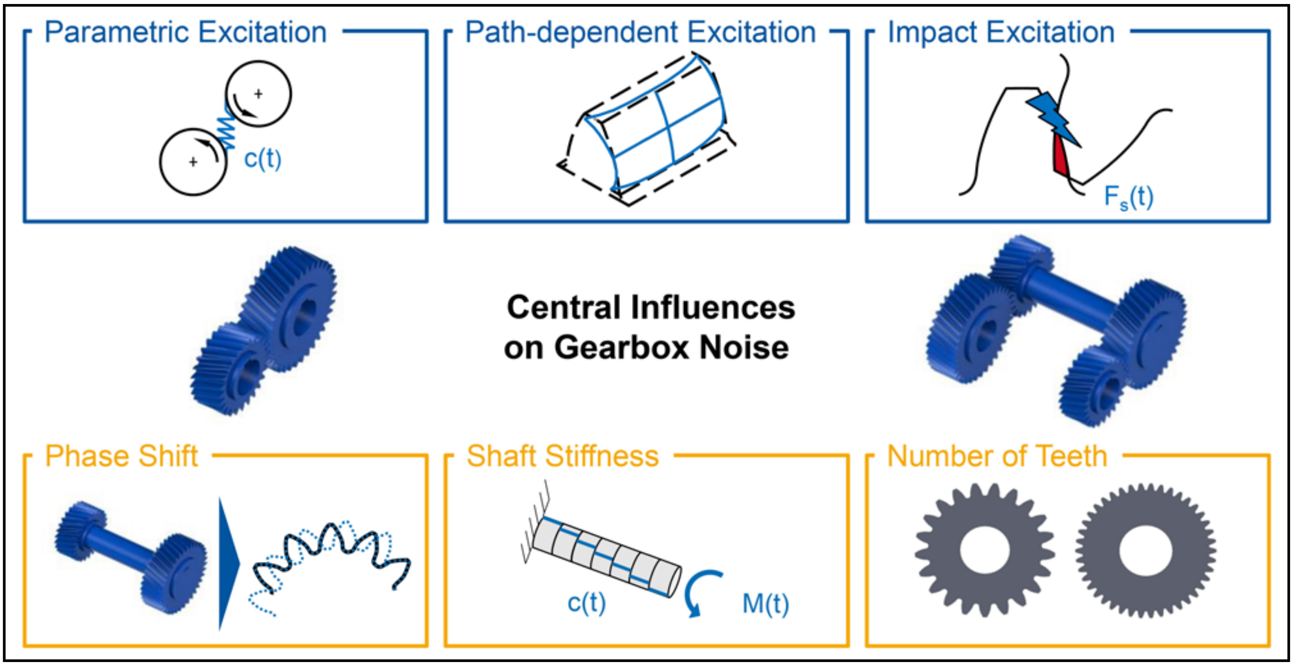

Figure 1 Central Influences on Gearbox Noise.

elements like shafts and machinery have to be included in calculation (Ref. 9).

Vinayak et al. describe the equation of motion for single-stage gearboxes, including all six spatial degrees of freedom. The simulation model is expanded to analyze a gear chain using three gears and a two-stage gearbox. There is an investigation of the model using temporal variable (*LTV* = linear time variant) and temporal constant parameters (*LTI* = linear time invariant). The numerical results show the existence of an interaction between the gear meshes (Ref. 20).

Sattelberger investigates the dynamic behavior of single- and two-stage cylindrical gearboxes by means of experimental and mathematical results. The focus of his analysis includes coupling stiffness and phase shift between both gear meshes. Concerning the coupling stiffness, he discovers that the gear meshes are not affected by each other for a low coupling stiffness. In contrast, for a high stiffness, the stiffness between individual gear meshes can be relevant. Regarding identical or similar tooth contact frequencies of the gear meshes, the adaption of a phase shift of a half pitch is usable for excitation reduction. This result can be confirmed by a parallel connection of two cylindrical gears that are distorted a half pitch against each other (Ref. 18).

The results of Sattelberger are verified by the investigations of Cheon. In his paper he also studies the phase shift mathematically by parallel connection of two cylindrical gears. The model has a minimum of excitation when the cylindrical gears are distorted a half-pitch against each other (Ref. 5).

Kuber et al. also use a model with six degrees of freedom for theoretical analysis of multi-stage gearboxes, which can contain any number of gears. The model is validated through experimental results of a single-stage gearbox. Subsequently several parameters are varied on the basis of a two-stage gearbox. The effect of the change of the intermediate shaft length, the bearing stiffness, the phase shift, and the orientation of the helix angle on the tooth and bearing force is evaluated (Ref. 12).

Zhou et al. conduct acoustical research on two-stage gearboxes — theoretically and experimentally. The comparison between measurement and simulation shows good correlation. Additional to the gear mesh frequency, there are also modulation frequencies that indicate an interaction between the gear meshes. The analysis of the appearing orders identifies the gear mesh responsible for the modulation (Ref. 22).

Hesse investigates the excitation behavior through variation of gear mesh excitation experimentally. The gear mesh excitation is varied by changing the topography of the tooth surface. The analyzed test setup consists of a manual gearbox. Together with the gear stage on the countershaft, the setup matches a two-stage gearbox. The gearbox is connected by a constant velocity joint shaft to the hypoid gear stage. Because of the large distances between the stages and the influence of the drive train stiffness, there are minor interactions between the gear meshes. According to this, the behavior of the drive train elements between gear sets has significant influence (Ref. 10).

As the state of the art shows, the minority of the reports focuses on the dynamic excitation behavior of two-stage gearboxes. Furthermore, there are fewer reports which regard the dynamic interactions between the different influences on noise behavior of two-stage gearboxes mathematically as well as experimentally.

Table 1 Nomenclature

b_i	Face Width
i	Gear Ratio
m_n	Module
n_{in}	Rotational Speed
T_{in}	Torque
z_1 / z_2	Number of Teeth
α_n	Pressure Angle
β_1 / β_2	Helix Angle
ε_α	Contact Ratio
ε_β	Overlap Ratio

Objective and Approach

The objective and the approach of this paper are presented in Figure 2. The objective is the evaluation of dynamic excitation behavior of two-stage gearboxes with a focus on phase shift. For this reason, a two-stage test gearbox is developed and designed based on an existing single-stage gearbox. In order to analyze the excitation as well as noise behavior, measurement equipment is integrated in the test setup to detect the machine-acoustic noise generation. For single-stage gearboxes, a simulation model is presented. The simulation model of the single-stage gearbox is validated with experimental results. Based on this model and its parameters, an enhanced model is developed which enables analysis of the dynamic behavior of two-stage gearboxes. Consequently, the model is used to analyze the influence of dynamic interactions on the excitation behavior. Thereby, the focus of this analysis is on the phase shift between the gear meshes.

Test Setup and Test Specimen

For the investigations of this work, both test gearboxes in Figure 3 are taken into account. The setup of the single-stage gearbox is described in detail (Ref. 4). Based on this concept a two-stage gearbox prototype has been developed. The central component of the gearbox is the housing, which is constructed in a shell construction of upper and lower shell. For easier handling during assembly, the upper shell is manufactured in two parts. The housing is mounted on damping elements in order to decouple vibrations of the test rig. To change the emission characteristics of the test gearbox, the strength of the thin-walled side elements can be varied.

The shafts with the bearings are mounted through bushings in the housing. The tapered roller bearings are designed in X-arrangement. By cover

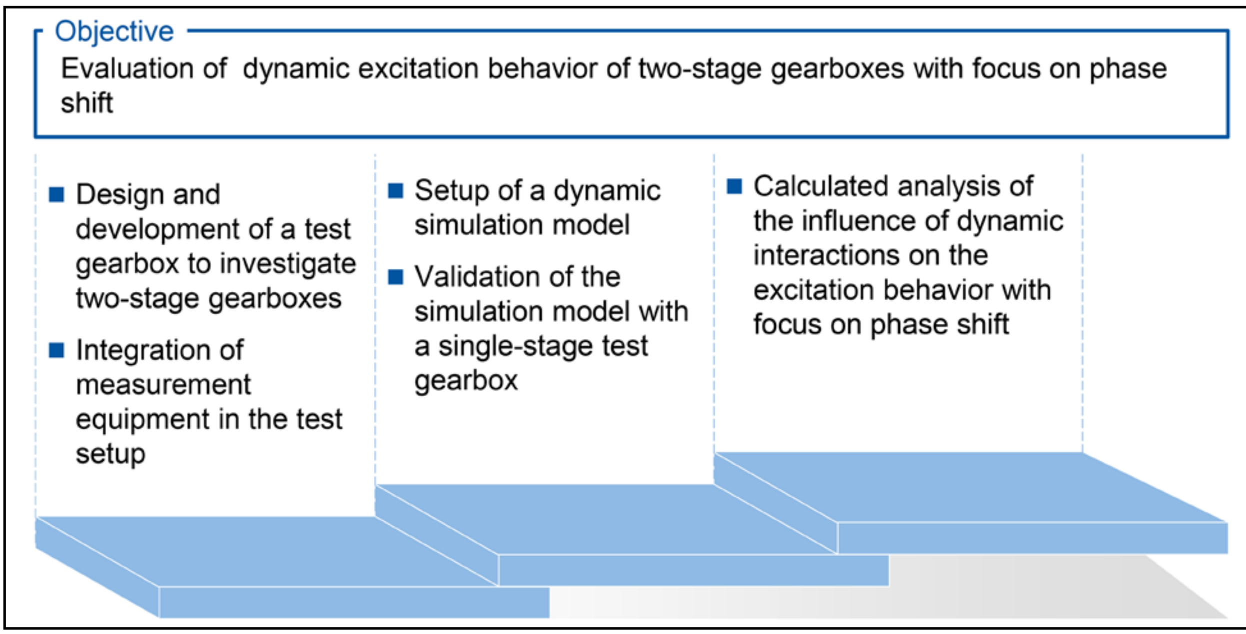

Figure 2 Objective and Approach.

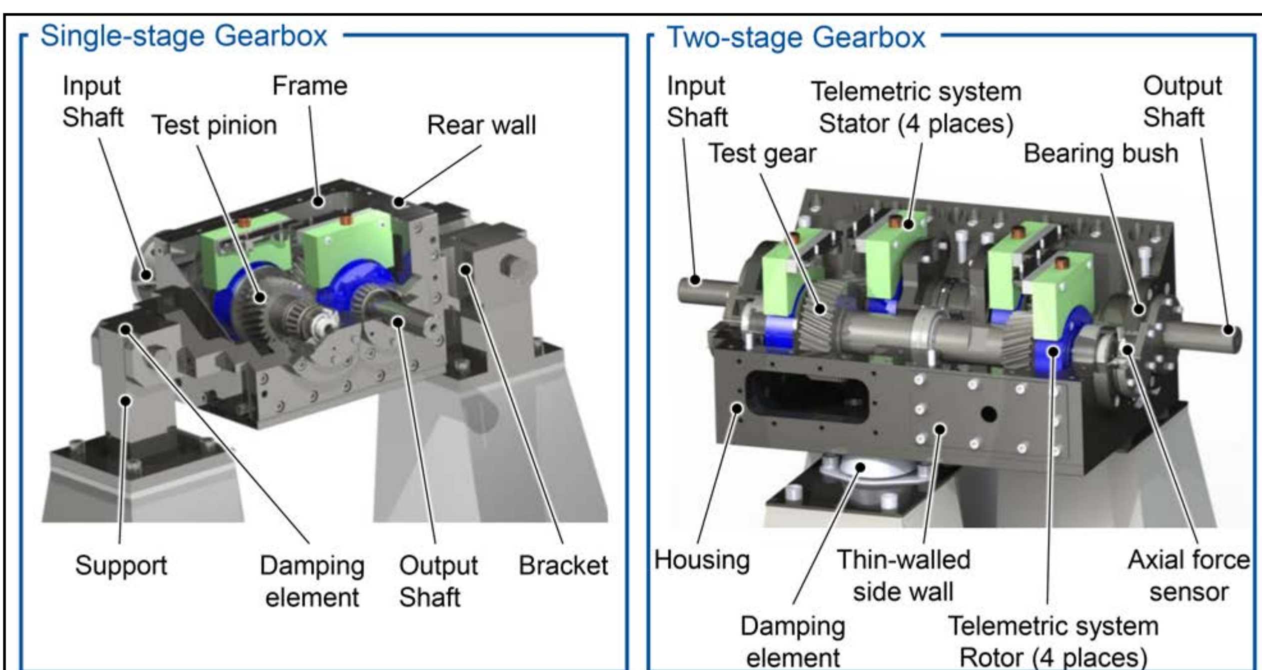

Figure 3 Design of the Test Gearboxes.

plates, the bearing pre-load can be adjusted. A piezoelectric force sensor can be integrated in the test setup. Thereby, it is possible to flexibly measure and adjust the axial pre-load force of the tapered roller bearings. Furthermore, a support bearing can be mounted optionally on the connecting shaft between the gear meshes in order to reduce the bending of the shaft. During the investigations, gears with the same macro geometry are mounted at each gear stage (Table 2). In the bottom plate, the exhaust system for the oil sump of the injection lubrication is mounted. An external unit with a constant temperature-controlled tank supplies the oil. The supply of oil to the gear meshes is realized via a pipe duct to the rear wall of the test gearbox and a tangential injection into the incoming gear mesh. The bearings are supplied via pipe ducts with oil as well. The flow distribution was adjusted to an optimal supply.

To analyze the excitation and noise behavior of the gearboxes, different measurement equipment is integrated in the test setups. Figure 4 gives an overview. The measurement equipment is divided into three groups along the machine-acoustic noise generation: source, path and receiver. Firstly, the source of the excitation is represented by the gear mesh. In principle, the gear mesh excitation can be analyzed by measuring dynamic tooth force, tooth root strain or torsional vibrations. The first two methods mentioned are not feasible, due to either the difficult realization or to design limitations. Therefore, the torsional vibration measurement has been established to measure the gear mesh excitation (Refs. 2; 14). Hence, the angular acceleration of each shaft is measured. In (Ref. 7) the angular acceleration is converted in a translational differential acceleration in the line of action using Equation 1. For an adequate characterization of the excitation, the position of the angular measurement systems is to choose the closest to the gear mesh as possible (Ref. 10).

$$\ddot{\Delta} = r_{b2} \cdot \ddot{\varphi}_2(t) - r_{b1} \cdot \ddot{\varphi}_1(t) \qquad (1)$$

where

$\ddot{\Delta}$ is difference acceleration

r_{bi} is base circle

$\ddot{\varphi}_i$ is angular acceleration

The angular measurement systems are integrated into the test setup; see Figure 4 on the right. These consist of a rotor, which is co-rotating with the shaft, and a stator, which is fixed to the housing. On the rotor, two acceleration sensors with an offset of 180° are mounted. By adding the acceleration signals of both sensors, radial vibration components can be compensated and only the tangential acceleration is measured. The power supply is provided via the inductive coil. Following the machine-acoustic noise generation in Figure 4 on the left, the next step is the structure-borne noise.

The structure-borne noise is measured on the surface of the gearbox housing with accelerometers. Due to the large surfaces, it is not possible to measure the structure-borne noise simultaneously at all surfaces. Therefore, single measurement points are selected as reference points according to (Ref. 8).

The last step of the machine-acoustic noise generation is the receiver. The received airborne noise is measured under free field conditions with electrostatic microphones. Hence, five microphones are placed around the gearbox. Four microphones are in the axis plane of the gearbox. The last microphone is placed above the gearbox with the same distance. Thus, the five microphones describe a cuboid.

Table 2 gives an overview over the gear sets whose influence on the excitation behavior is to be evaluated in this paper. All gear sets can be manufactured with the same tool. Therefore, all gear sets have the same pressure angle $\alpha_n = 20°$ and module $m_n = 3.5$ mm. The face width of all gears is equal as well. The variants vary in the helix angle and the number of teeth. Gear sets 1 and 3 are helical gears with a helix angle of $\beta = 19.3°$ (Ref. 1) and $\beta = 20°$ (Ref. 3). Gear set 2 is a spur gear ($\beta = 0.0°$). Gear set 1's gears have 25 and 36 teeth, which leads to a gear ratio of $i = 1.44$. The gear sets 2 and 3 have an

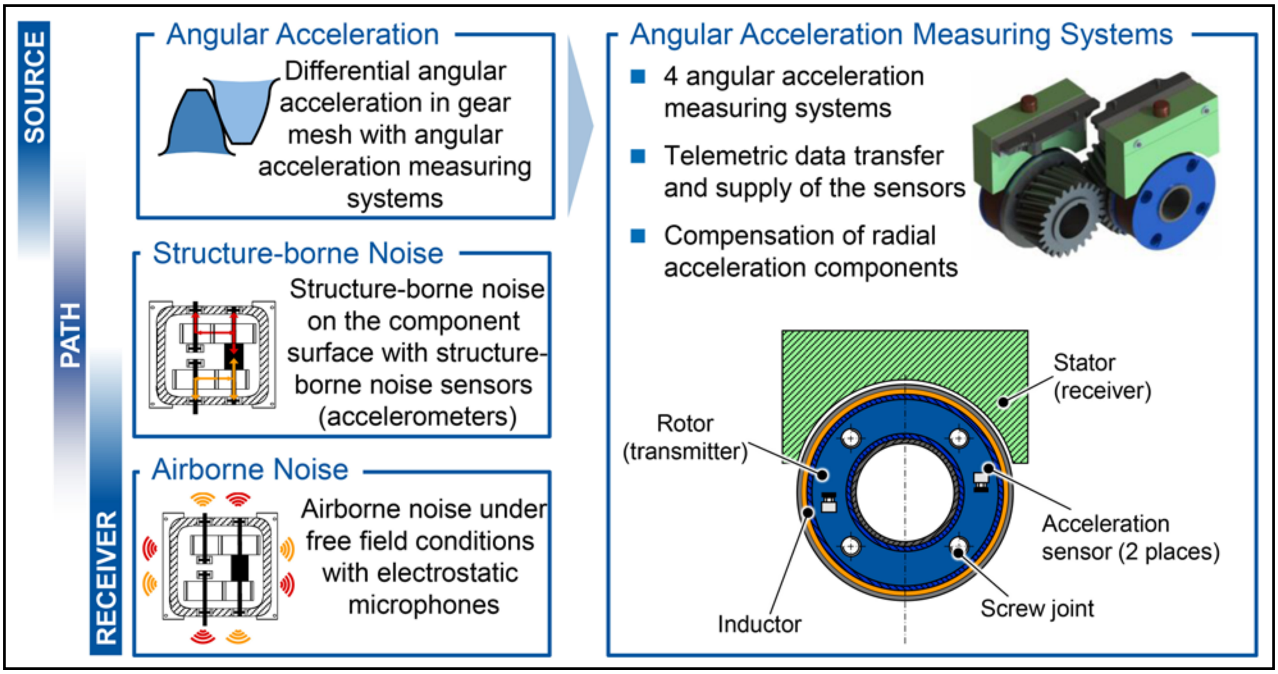

Figure 4 Measurement Equipment.

identical number of teeth for both gears and therefore a gear ratio of $i = 1$. For the two-stage gearboxes, gears with the same macro geometry are mounted at both gear stages, as mentioned before.

Table 2 Investigated Gear Sets				
		Gear Set 1	Gear Set 2	Gear Set 3
Pressure Angle	α_n	20°	20°	20°
Module	m_n	3.5 mm	3.5 mm	3.5 mm
Helix Angle	β_1 / β_2	–19.3 / 19.3°	0°	–20 / 20°
Gear Ratio	i	1.44	1	1
Number of Teeth	z_1 / z_2	25 / 36	32 / 32	30 / 30
Tooth Width	b_1 / b_2	41.5 / 44 mm	41.5 / 44 mm	41.5 / 44 mm
Contact Ratio	ε_α	1.75	1.7	1.6
Overlap Ratio	ε_β	1.25	0	1.3

Setup and Validation of the Dynamic Simulation Model

Due to varying requirements and working conditions during the operational use of gearboxes, the operating conditions (for example torque and rotational speed) are not constant. For special operational points, the overload can be critical for the load carrying capacity and the excitation behavior. Mostly, the critical operational points occur when the excitation frequencies coincide with Eigen frequencies of the test setup. In this case, a quasi-static investigation is not effective, and a dynamic analysis is necessary. For both test gearboxes shown in Figure 3, a similar approach to build up a dynamic simulation model is selected. Figure 5 illustrates the two main components and their interaction. The force coupling elements represent the gear mesh, and the drive train model includes the properties of the gearbox and the entire drive train.

The force coupling element requires a subroutine of the tooth contact analysis FE-Stirnradkette (STIRAK) that is developed at WZL (Ref. 1). STIRAK enables the calculation of excitation maps based on input data; see Figure 5. As data is put in the gearbox structure, the macro and micro geometry of the gears and tool data, for example. the properties of the tooth flank can be set via nominal data or be imported either by data of a manufacturing simulation or by real measurement data. Based on the input data, a spring model is set up and solved. As a result, the excitation maps are obtained. Depending on the load-dependent transmission error and the current angular position of the gear, actual excitation forces and torques can be determined.

The approach to build up the drive train model is presented in Figure 5 on the right. The objective of this step is to provide the system matrices for the simulation (inertia, stiffness, and damping). In this paper, only the torsional degree of freedom is regarded. Due to the domination of rotational excitation of the gear mesh, this assumption is suitable (Ref. 4). In order to identify realistic Eigen frequencies and Eigen modes of the test setup, a model of the complete test rig is regarded. The setup contains the motor and the generator and includes each part between the two machines, such as the gearbox and constant velocity joint shafts. The first step in the approach to design the drive train model in Figure 5 is the discretization. In this step, the drive train is divided into discrete inertias. Each inertia is connected to its neighboring inertias by massless spring-damper units. The closer a mass is placed to the gear mesh, the more finely it is discretized to accurately represent the vibrational behavior near the gear meshes. Subsequently, the numerical values of the parameters are determined. Simple components can be parameterized using analytical equations. Furthermore, the inertia of the non-cylindrical components can be extracted from CAD models. However, some parameters are difficult to calculate, such as the contact stiffness of frictional connections, form closures, and damping. An iterative procedure has been established to compare measurement and simulation results when setting parameters for these components.

The first two steps of the approach

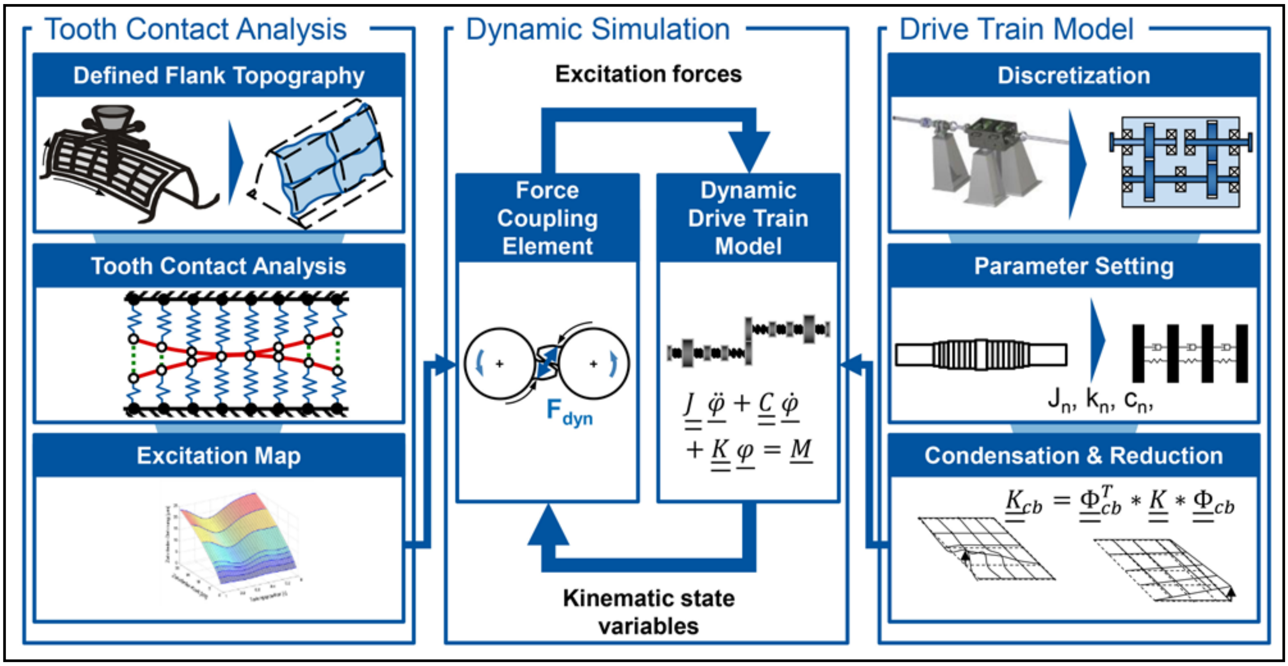

Figure 5 Components of the Dynamic Simulation Model Referring to [4].

generate models with a high number of degrees of freedom. Hence, the numerical solution of those systems would be uneconomically long, and the numerical accuracy would be decreased. To avoid both disadvantages, a modal reduction of degrees of freedom by Craig and Bampton is performed (Ref. 6). For this procedure, the rotational vibration and the external torques are inserted at the external degrees of freedom. The external and the modal degrees of freedom of the lowest Eigen frequencies can be maintained. The frequencies within the acoustically relevant frequency range are not reduced and only high Eigen frequencies are neglected. Therefore, this reduction method is suitable.

The interaction between the force coupling element and the drive train model is shown in the middle of Figure 5. For each time step, the drive train model transfers the kinematic state variables (angle of rotation and rotational speed) to the force coupling element. Depending on the input data, the force coupling element determines the excitation forces with excitation maps and returns them to the drive train model. The excitation forces are composed of a variable tooth stiffness term and a damping term. The tooth stiffness term is determined by the aforementioned excitation maps from STIRAK. In contrast, the damping term utilizes a velocity proportional approach. With the excitation forces and the generated system matrices, the differential equations can be solved. This procedure will be repeated for each time step.

For the single-stage gearbox in Figure 3, the comparison between experimental and arithmetical results is shown in Figure 6. Table 1 gives an overview about the symbols used in Figures 6 through 9.

The experimental investigations have been performed on a universal gearbox test rig. For the calculated results, a simulation model referred to in Figure 5 has been developed. For this model, the complete setup has been regarded in the drive train model. The investigations are evaluated for the difference velocity. According to Equation 1, the difference velocity is the integrated difference acceleration. The results are compared for two constant driving torques and rotational speed run-ups from $n_1 = 150 \ldots 3{,}500$ min^{-1}. For the averaged frequency spectra in the upper row of Figure 6, there is a high conformity between experimental and simulation results. The averaged frequency spectra enable an identification of the Eigen frequencies of the test setup independent from the rotational speed. Especially for the acoustically sensitive frequency range between 1 and 5 kHz, the amplitudes of the resonance frequencies at 460 Hz, 1,180 Hz and between 3 and 4 kHz correlate well. For the order spectra, the amplitudes of the gear mesh frequencies match well. However, the arithmetical results have greater amplitudes than the experimental results (especially for the higher driving torque). In summary, the validation of the simulation model with the experimental results from the test rig has been successful.

For the two-stage gearbox, a second force coupling element is added. Furthermore, the model setup has to be expanded in order to regard the phase shift between the gear meshes. The phase shift is the temporal offset between the two gear meshes. It is defined as the difference between the points when the gear stages enter mesh (relating to the contact path). Possible numerical values of the phase shift are between 0 and 1 in relation to the beginning point of the first gear mesh. The values 0 and 1 mean a simultaneous beginning of the two gear meshes. For a phase shift between 0 and 1, the gear meshes begin with a temporal offset. The integration of the phase shift in the simulation model takes place in the force coupling element of the second gear mesh. Hence, the drive train model has to be modified as well. The parameter setting is based on the validated model of the single-stage gearbox. Hence, the validated single-stage model has been extended to a two-stage model; compare Figure 3.

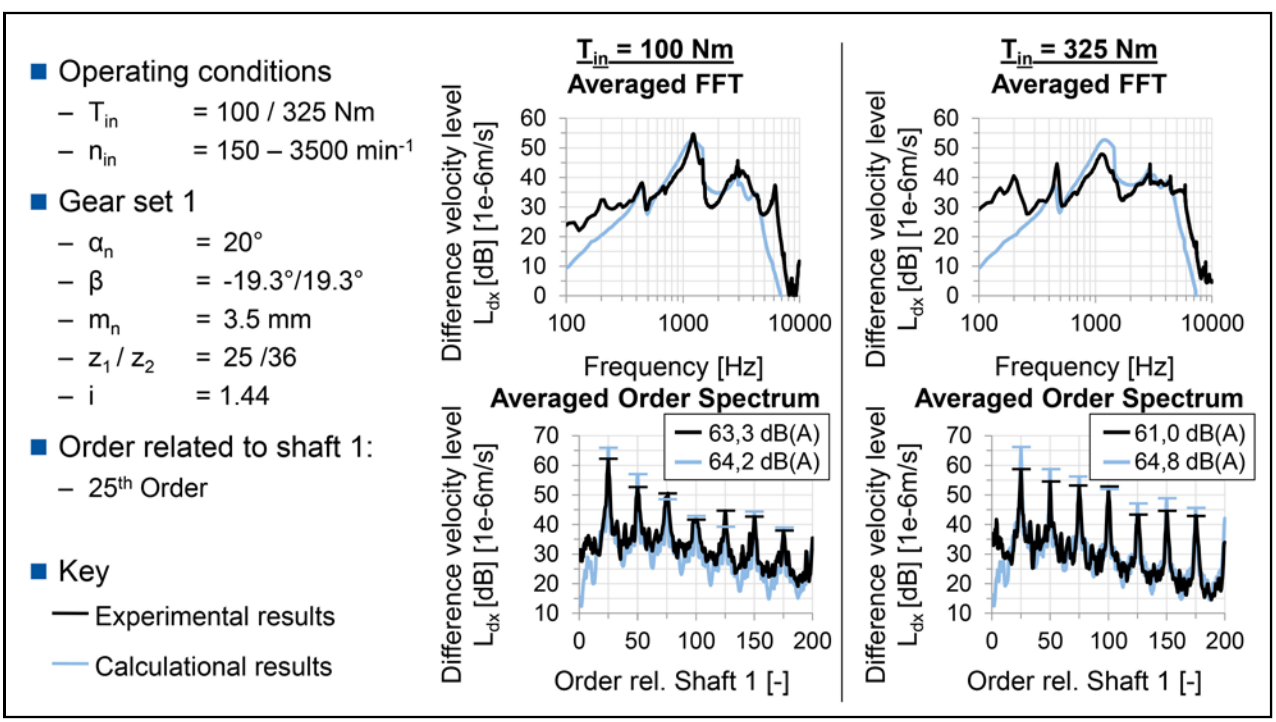

Figure 6 Validation of the Single-Stage Simulation Model [4].

Analysis of Dynamic Excitation Behavior of Two-stage Gearboxes

With the two-stage simulation model introduced in the previous section, the dynamic simulations are performed. Firstly, the excitation behavior of gear set 1 is analyzed. Subsequently, the influence of the phase shift is evaluated by means of the gear sets shown in Table 1. Hence, every gear set is used twice for each of the two stages.

Reference Gear Sets

The simulation model of the single-stage gearbox is validated by means of the experimental results of gear set 1. Therefore, this gear set has been selected as reference gear set for the calculative investigations of the two-stage gearbox as well. In this case, the gear ratio of one stage is $i = 1.44$, which leads to total gear ratio $i = 2.07$ of the two-stage gearbox. The operating conditions are oriented to the torques and rotational speed of the single-stage gearbox. For the averaged frequency spectrum in the upper row of Figure 7, the Eigen frequencies of the test setup can be identified. In the left column, the results of the first stage are shown. The results of the second stage are presented on the right. The little sketches in the upper right corner of the averaged frequency spectrums are an indicator for the investigated gear stage. For both stages, the dominant resonance frequencies occur at $f = 1{,}180$ Hz and between 3 and 4 kHz. The frequency spectrum of the single-stage in Figure 6 was dominated by the same resonance frequencies. These frequencies are characterized by frictional connections and form fits inside the gearbox. Due to the unchanged parameters, the frequencies remain the same for both gearboxes. Within the lower frequency range up to 700 Hz, differences between the single- and two-stage test setup occur. The setup, which consists of constant velocity joint shafts and bearings, is slightly changed for the two gearboxes. Those components have a low stiffness. Hence, the differences within the lower frequency range can be explained. However, a higher excitation can be detected within the acoustic relevant frequency range for the higher driving torque. These differences are more pronounced for the second stage.

For the averaged order spectrum of both stages, both gear mesh orders and their harmonics can be detected. According to the number of teeth, the gear mesh order of the first stage is the 25th order. The order of the second stage is referred to the rotational speed of shaft 1 as well. Therefore, the order of the second stage can be calculated with Equation 2:

$$Ord_{2st} = \frac{n_3 \cdot z_3}{n_1} = \frac{z_3}{i} = 17.4 \qquad (2)$$

where

Ord_{2st} is gear mesh order of the second stage

n_i is rotational speed

z_i is number of teeth

i is gear ratio

For the spectrum of the first stage, the first gear mesh order (=25th) and its harmonics dominate the spectrum. In con-

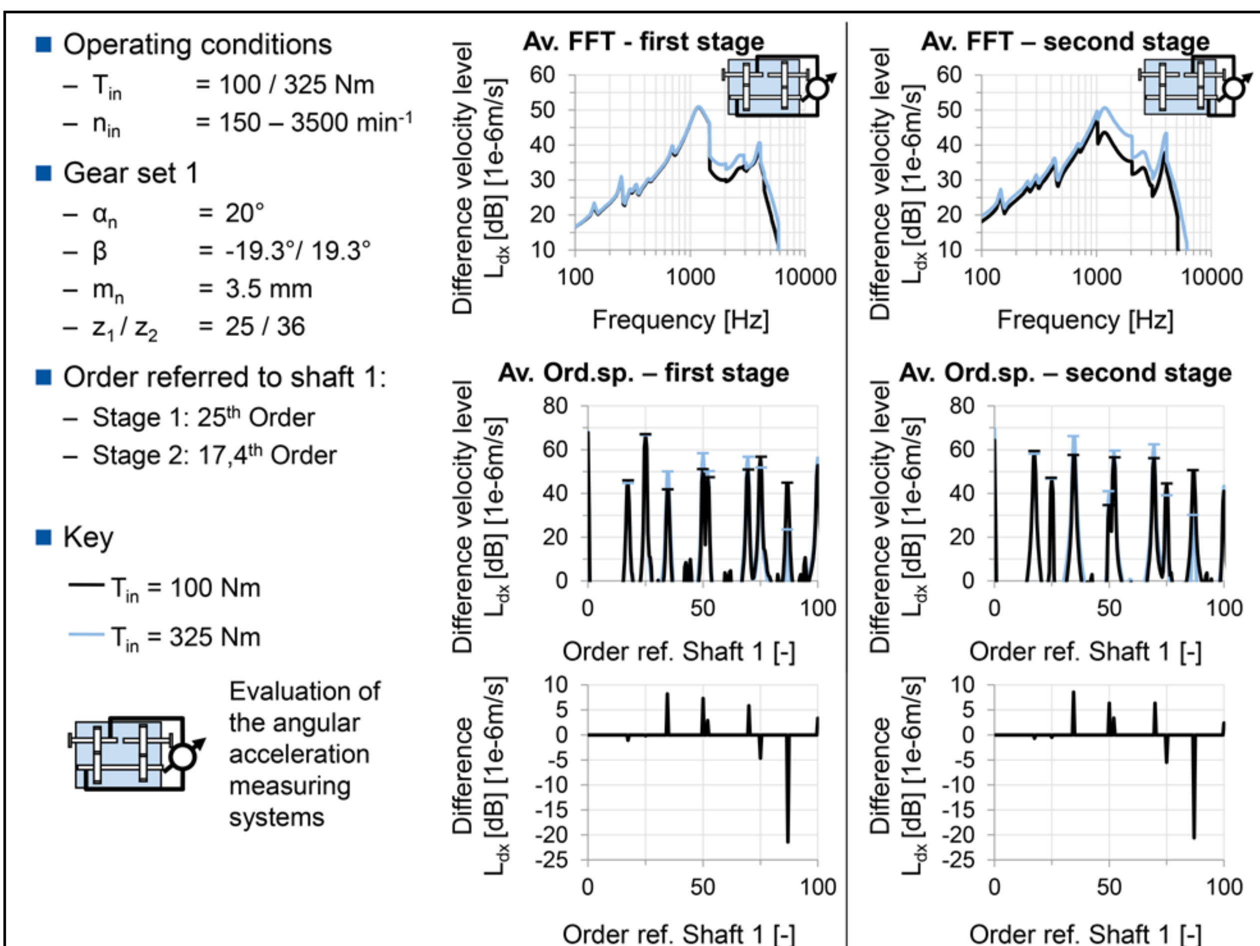

Figure 7 **Excitation Behavior of Gear Set 1.**

trast, the gear mesh orders of the second stage have greater excitation levels in the spectrum than the orders of the first stage. It is also striking that the second gear mesh order of the first stage (50th order) is very close to the third gear mesh order of the second stage (52.1th order). Within this order range, there is an increased excitation. The differences between the two input torques in the order spectrum are confirmed by means of the last row of Figure 7. Mostly, the orders of the higher excitation torque have a higher excitation level.

Phase Shift

The influence of the phase shift is analyzed with the gear sets shown in Table 1. For this purpose, two configurations of the phase shift are regarded, in which the two gear meshes begin either simultaneously ($p=0$) or by a half pitch offset ($p=0.5$). A compensation by the phase shift on a two-stage gearbox is to be expected when the gears on the intermediate shaft have either an equal number of teeth or multiples of the numbers of teeth (Ref. 18).

Firstly, gear set 1 is investigated. Hence, the gears on the intermediate shaft have different numbers of teeth (36 and 25). Due to the different number of teeth of both gears on the intermediate shaft, the start of the second gear mesh shifts from tooth to tooth in each pitch relative to the first. Therefore, the phase shift does not reach a constant value. The aforementioned parameters for the phase shift are only valid at the beginning of the simulation. Due to that fact, no influence of a phase shift on the difference velocity level at the reference gear set is expected. Figure 8 confirms this expectation. For the averaged frequency spectrum, the average order spectrum, and the difference in the order spectrum of the first and the second stage, no deviations can be noted.

Therefore, two alternative gear sets with a gear ratio $i=1$ have been designed (for gear data, see Table 1). Hence, the two gears on the intermediate shaft have the same number of teeth. Gear set 2 has a helix angle $\beta=0°$, and gear set 2 is a helical gear pair ($\beta=20°$). In difference to the analysis of gear set 1, the excitation behavior of gear set 2 and 3 are analyzed by a difference velocity across input and output. Consequently, the influence of the phase shift can be summarized in one parameter. According to the investigated phase shifts with gear set 1, the same phase shifts are analyzed. For these cases, the results are shown in Figure 9. Due to the helix angle and the higher total contact ratio, gear set 3 has a lower excitation behavior than gear set 2. For the averaged frequency spectra in the upper row, differences between the two data sets occur. Within the frequency range between $f=1-2$ kHz, the variant with phase shift $p=0.5$ has a lower excitation level. Because of the high human sensitivity within this frequency range, these data have to be analyzed by the psychoacoustic metrics at a later date. These differences are confirmed by means of the averaged order spectra. In this case, the gear

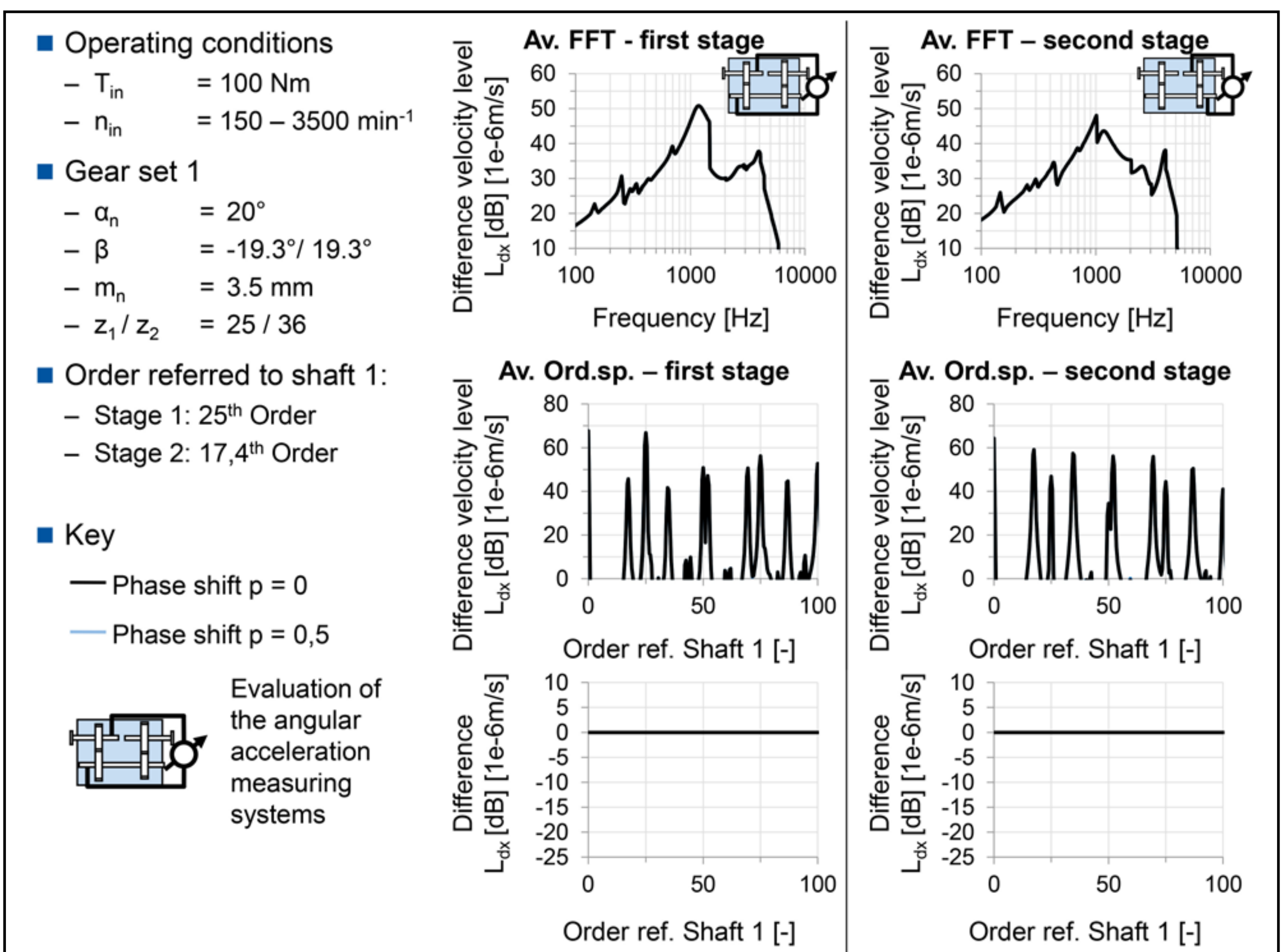

Figure 8 Excitation Behavior of Gear Set 1 with Varied Phase Shift.

mesh order of gear set 2 are the 32nd and of gear set 3 the 30th order. For both gear sets, the excitation level of the first and the third gear mesh order decreases for a phase shift $p = 0.5$. In contrast, the second gear mesh order remains the same. The differences of the orders show a difference around 3.5 dB for the first gear mesh order and around 2.5 dB for the third gear mesh order of both gear sets. Hence, the phase shift enables us to reduce torsional vibrations of the drive train.

Summary and Outlook

Nowadays, multi-stage gearboxes are often used due to the need for high ratio gearboxes. Besides current development trends such as electrification and hybridization of the drive train, increased customer requirements and amended law restrictions result in an increased importance of the acoustic behavior. Existing papers show methods to optimize the excitation and noise behavior of single-stage gearboxes. Due to the interactions between the gear meshes, the methods for noise optimization of single-stage gearboxes cannot be transferred to two-stage gearboxes without restrictions. Among other parameters, the phase shift, the stiffness of the intermediate shaft, and the number of teeth are parameters which influence the excitation behavior. Therefore, the objective of this paper is to analyze the dynamic excitation behavior of two-stage gearboxes with focus on the phase shift.

First, an existing single-stage gearbox is introduced. Furthermore, a two-stage gearbox has been developed and designed which is based on the concept of the single-stage gearbox. Regarding the machine-acoustic noise generation, different measurement equipment is integrated in the test setup. Angular acceleration measurement systems detect the gear mesh excitation. Furthermore, the structure- borne and airborne noise is detected.

Secondly, a simulation model is presented which consists of two main components. The force coupling element represents the gear mesh and a drive train model based on a torsional multi-body-simulation model. For the single-stage gearbox, the simulation model is validated by means of experimental results. Especially within the acoustic relevant frequency range, experimental and analytical results show a good correlation. Afterwards, the validated model is enhanced to a two-stage model.

With this model, the dynamic excitation behavior is analyzed. Hence, three different gear sets are investigated. The first gear set has a different number of teeth on the intermediate shaft. Therefore, the phase shift has no influence on the excitation behavior. Gear sets 2 and 3 have the same number of teeth on the intermediate shaft. Gear set 2 is a spur, and gear set 3 a helical gear pair. In order to investigate the influence of the phase shift, two different phase shifts are investigated ($p = 0$, 0.5). Compared to a simultaneous entering of gear meshes of the two gear stages, a shifted entering of the gear meshes ($p = 0.5$) leads to decreased vibration levels of the gear mesh orders.

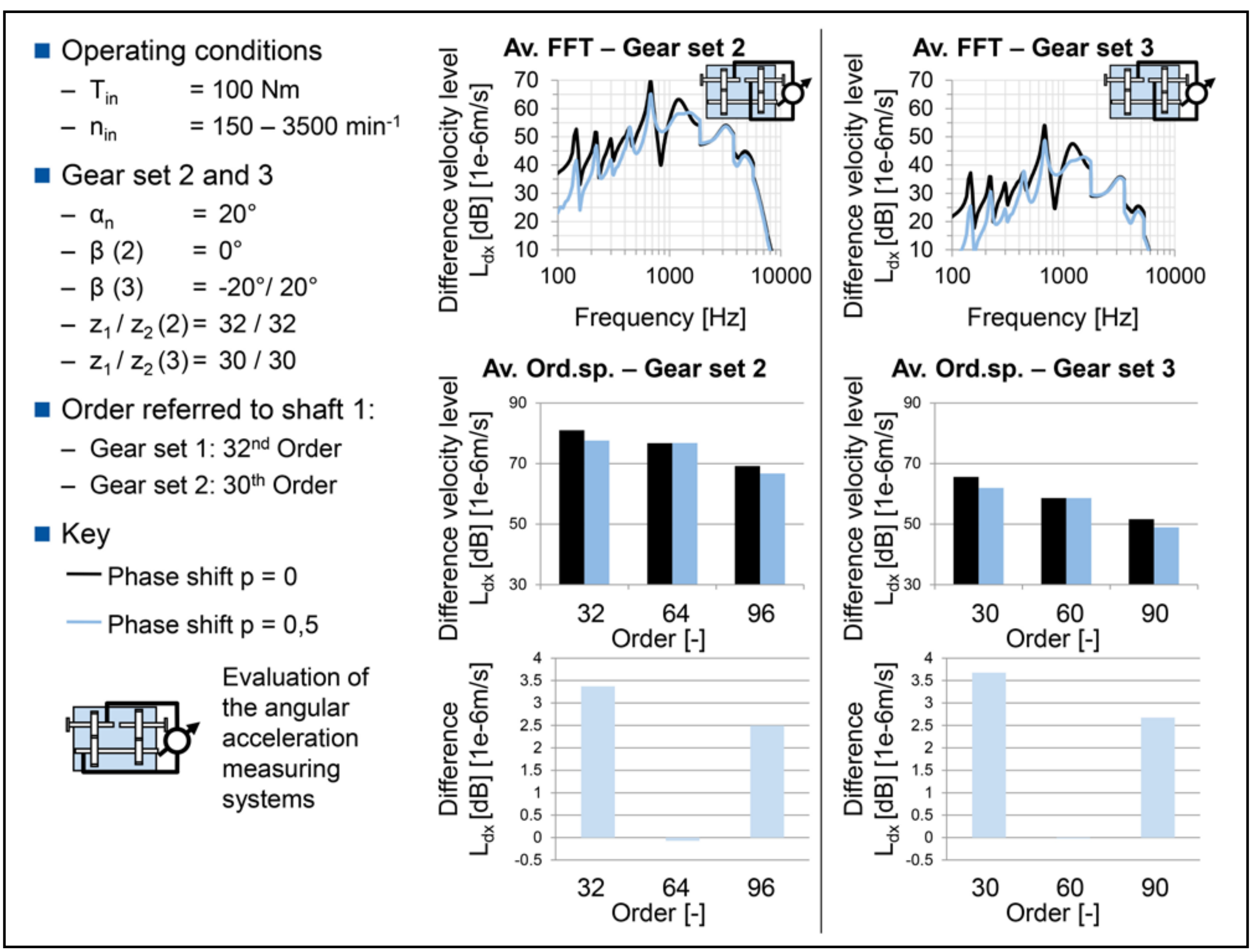

Figure 9 Excitation Behavior of Gear Sets 2 and 3 with Varied Phase Shift.

In the future, the calculated results of the two-stage gearbox model have to be validated experimentally. For that purpose, the two-stage gearbox will be manufactured. Different transfer functions can be obtained by means of the experimental results. On the one hand, the transfer function between the gear mesh excitation and the airborne noise has to be analyzed. On the other hand, the mutual interaction between the gear meshes can be analyzed by a transfer function as well. Furthermore, a detailed parameter study can be performed by calculation based on the validated model. Both experimental and analytical results have to be analyzed with psychoacoustic metrics. The psychoacoustic metrics evaluate noise based on human perception. Consequently, the annoyance of noise can be quantified.

Acknowledgement. *The authors gratefully acknowledge financial support provided by the German Research Foundation (DFG) (BR 2905/66-1) for the achievement of this project's results.*

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Marius Schroers, M.Sc., studied mechanical engineering at RWTH Aachen University till 2015. Since that time, he works as a scientific research assistant in the group "Gear Design and Manufacturing Simulation" in the gear department of the Laboratory of Machine Tools and Production Engineering (WZL). His research activities are focused on the dynamic behavior of multi-stage gearboxes and the correlation between excitation, noise radiation and the perception related evaluation of gearbox noise.

Dr.-Ing. Dipl.-Wirt.-Ing. Christoph Löpenhaus is a 2010 industrial engineering graduate of RWTH Aachen; he received his Ph.D. (local strength and friction models for gears) in 2015. Upon graduation he worked as a research assistant in the gear testing group of the Laboratory for Machine Tools (WZL) of RWTH Aachen and in 2011 was named the group's team leader. Löpenhaus has since 2014 worked as chief engineer of the department for gear technology at WZL.

Prof. Dr.-Ing. Christian Brecher has since January 2004 been Ordinary Professor for Machine Tools at the Laboratory for Machine Tools and Production Engineering (WZL) of the RWTH Aachen, as well as Director of the Department for Production Machines at the Fraunhofer Institute for Production Technology IPT. Upon finishing his academic studies in mechanical engineering, Brecher started his professional career first as a research assistant and later as team leader in the department for machine investigation and evaluation at the WZL. From 1999 to April 2001, he was responsible for the department of machine tools in his capacity as a Senior Engineer. After a short spell as a consultant in the aviation industry, Professor Brecher was appointed in August 2001 as the Director for Development at the DS Technologie Werkzeugmaschinenbau GmbH, Mönchengladbach, where he was responsible for construction and development until December 2003. Brecher has received numerous honors and awards, including the Springorum Commemorative Coin; the Borchers Medal of the RWTH Aachen; the Scholarship Award of the Association of German Tool Manufacturers (Verein Deutscher Werkzeugmaschinenfabriken VDW); and the Otto Kienzle Memorial Coin of the Scientific Society for Production Technology (Wissenschaftliche Gesellschaft für Produktionstechnik WGP).

Bob Errichello Retires

ROB BUDNY AND ANDY MILBURN TO TEACH THE AGMA GEAR FAILURE ANALYSIS COURSE

After teaching the AGMA Gear Failure Analysis course for 27 years, **Bob Errichello** and Jane Muller of Geartech retired from instructing in June 2017. Two highly recommended industry professionals — Rob Budny, from RBB Engineering and Andy Milburn, from Milburn Engineering, Inc. — have been assigned by AGMA to teach this course that has become a staple in the curriculum over the years — as well as the most popular. Budny and Milburn led the facilitation of the course this past June. Errichello and Muller were onsite to assist with the final stages of succession planning.

"We have known Rob for over thirteen years and have cooperated with him on many failure investigations," explains Errichello. "We are confident that they will maintain the high standards that we have set for the seminar."

Budny is president of Petaluma, California-based RBB Engineering — a rotating equipment consultancy with special expertise in gearbox failure analysis. He holds a BSME degree from UMBC in Baltimore, Maryland. Before founding RBB Engineering in 2012, he was a mechanical engineering manager with Clipper Windpower in Carpinteria, California from 2004 to 2012. He previously held the position of mechanical designer and stress analyst with Lockheed Martin in Baltimore, Maryland from 1997 to 2002. In 2014, Errichello, Budny, and Rainer Eckert co-authored the STLE Tribology Transactions paper — "Investigations of Bearing Failures Associated with WEAs in Wind Turbine Gearboxes." This paper won the Edmond E. Bisson Award for the best STLE paper published in 2014.

Andy Milburn is president of Milburn Engineering, Inc. in Vaughn, Washington. He holds a BSME from the University of Washington. Before founding Milburn Engineering in 1990, he was a mechanical designer and failure analyst with The Gear Works in Seattle, Washington from 1975 to 1989. Milburn was an officer in the U.S. Marine Corps from 1971 to 1974. In 1990, Milburn, Errichello and Douglas Godfrey coauthored the AGMA paper — "Polishing Wear."

"I have enjoyed working with Bob and Jane over the last 19 months," explains Casandra Blassingame, AGMA director of education. "I am looking forward to 'what's next' and optimistic that they will continue to partner with AGMA on other endeavors. Going forward, I am looking forward to working with Rob and Andy!"

AGMA is grateful for all the work that Errichello and Muller have done to get *Gear Failure Analysis* where it is.

"We appreciate the hard work that was put in during the last couple decades to make *Gear Failure Analysis* the most popular class we offer at AGMA," explains Matt Croson, AGMA president. "We look forward to continuing this legacy and building upon the educational foundation Bob and Jane helped start.

The next *Gear Failure Analysis* class will be in San Francisco, CA, December 6–8, 2017. People who are interested in signing up can visit: *www.agma.org/education/advanced-courses.*

Siemens Industry Inc.

EXPANDS TECHNICAL APPLICATION CENTER IN ITS ELK GROVE FACILITY

With digitalization and the rapid changes in technology, training is more important than ever to keep employees' skills up to date with the newest industrial technologies. In support of this need, Siemens announces the expansion of its Technical Application Center (TAC) which offers machine tool dealers, importers and end-users of Sinumerik CNCs a complete range of learning opportunities including classroom training, online instructor-led training, and online self-paced training.

Operating since 2009, the TAC provides the ideal setting for enhancing your CNC machining knowledge. Occupying more than 3,150 square feet of dedicated space at our Elk Grove Village, Illinois facility, the TAC is a short ride from O'Hare International Airport. The newly expanded Machine Lab now features three milling machines and one turning center for hands-on learning, plus a Kuka robotic center, and NX-CAM training station. Two state-of-the-art classrooms provide students with instructor-led, hands-on training using our exclusive

SinuTrain software and Sinumerik CNC simulators.

"Manufacturers are continuously looking for ways to train their employees on evolving CNC technologies as they transition to digital factories. Hands-on training and virtual programs like these are extremely important. We're excited to offer machine tool users a more expansive program to develop their employees," says Sascha Fischer, segment manager, Siemens Motion Control, Machine Tool Business.

Siemens offers professional-level training courses ranging from Sinumerik Operation and Programming to Sinumerik service and maintenance. In addition, the advanced training includes classes on mixed technology, flexible NC programming, multi-channel operation and programming, advanced measuring cycles, post-processor development, PLC commissioning and service, 4th-axis integration and part and tool probe installation.

In addition to the expansion of the TAC, a virtual TAC is also available to individuals looking to expand their CNC knowledge. The virtual TAC is open to anyone and available at no cost allowing individuals to watch professional-series webinars online.

Utilizing our exclusive SinuTrain CNC simulation software, these webinars will demonstrate how to maximize investments in Sinumerik CNC right from the comfort of one's own computer. Live training webinars are presented monthly by Siemens Sinumerik experts, covering a range of cost-saving and performance-enhancing insights, techniques and processes. Webinar topics range from Milling and Turning, to General Operations, Maintenance and Service. Attendees will also benefit from engaging Q&A sessions following the main presentation.

All past webinars are available for ongoing career development and viewing in the

ever-expanding archive library. Virtual one-on-one, custom tailored training courses can be requested for larger user groups looking to enhance specific skills of their programmer and operator teams. (*www.industry.usa.siemens.com*)

HBM Holdings

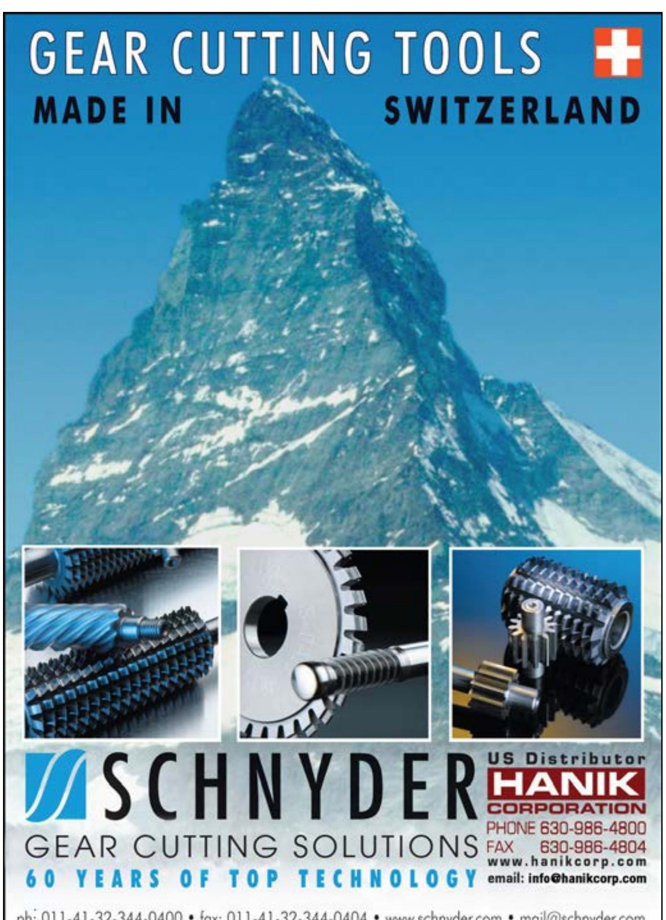
ACQUIRES SCHAFER INDUSTRIES

HBM Holdings (HBM) has announced that it has acquired Schafer Industries (Schafer) of South Bend, Indiana. Schafer is a leading producer of high-precision, custom-engineered gears and machined parts for a wide range of applications, as well as transaxles, brake assemblies and other components for off-road vehicles.

The acquisition of Schafer is a continuation of HBM's long-term strategy to acquire and build market leading manufacturers of industrial products.

"We are thrilled to bring Schafer into our portfolio," said Mike DeCola, HBM's CEO. "Schafer's leadership team has done a remarkable job of growing the company by helping customers solve complex problems. Building on this success, we look forward to further expansion of the business. Schafer is a perfect fit for our model, as the current ownership group is ready to transition the business to reach a new level of capability and success," continued DeCola.

Founded in 1934, Schafer is a privately held company oper-



ating through two vertically integrated divisions: Schafer Gear Works and Schafer Driveline. Schafer Gear Works manufactures gears that power products across a diverse set of markets and custom applications, including aerospace, industrial warehouse equipment, and general transportation applications found in the automotive, agricultural and construction sectors. Schafer Driveline is a leading manufacturer of custom engineered and assembled transaxles and brake components, bringing integrated power delivery solutions to the recreational and off-highway vehicle industries. In total, Schafer operates four facilities in the Midwestern United States, with over 300,000 square feet of manufacturing space.

Bipin Doshi, CEO and president of Schafer, commented, "As we engaged in the process of selling Schafer, our priorities were our employees and our customers. Throughout the process, HBM Holdings stood out not just in value for us as shareholders, but in terms of cultural fit. They understand our markets, technology and resource constraints and have a talent development strategy that will help our people continue to grow and succeed. Their focus on growth will benefit both our employees and our customers."

Doshi, along with his wife Linda, and Stan Blenke, executive vice president and CFO, acquired the business from South Bend Lathe approximately 30 years ago. As a result of their leadership, the company has experienced tremendous expansion organically and through acquisitions. Both Doshi and Blenke will stay involved during a transition period.

Eric Van Rens will become the company's CEO effective immediately. Since 2004, he has served as the vice president, sales and marketing for Mississippi Lime, an HBM portfolio company. He also held prior roles in operations, marketing and general management with Astaris and FMC Corporation. He holds a bachelor's degree in mechanical engineering from University of Wisconsin and a master's of business administration from Rutgers University. (*www.schaferindustries.com*)

Forest City Gear

WELCOMES PROCESS ENGINEER

Forest City Gear has added **Brian Gustafson** to its growing team of process engineers, with responsibility for creating the routings, machine instructions and process drawings that are critical to the success of every precision gear manufacturing project.

Gustafson has 15 years of diversified design and manufacturing engineering experience, ranging from CNC machining and programming to overseeing the shop floor operations of a gear production facility. He has a B.S. degree in Manufacturing Engineering Technology from Bradley University.

Gustafson's extensive manufacturing background made him an ideal candidate for the position, says Forest City Gear President Wendy Young. "His deep understanding of gear manufacturing processes gives him special insight into the needs our customers. He will be an important asset to help ensure that projects flow efficiently from order entry, to scheduling to shop floor production."

For over 60 years Roscoe, IL based, family-owned Forest City Gear has been one of the gear industry's leading sources for the development, manufacture and inspection of the highest quality gears, for use in applications that range from medical devices to motorcycles, airplanes to automation, even including the Mars Curiosity Rover. (*www.forestcitygear.com*)

Felsomat USA

NAMES NEW PRESIDENT/CEO

Felsomat USA, Inc. recently announced the appointment of **Blake Consdorf** to the joint position of president/CEO. Starting on July 10, 2017, Consdorf returned to Felsomat after 10 years at Acieta, LLC, where he rose from engineering management to divisional president during his tenure there.

Consdorf graduated from Purdue University in 1997 with a bachelor's degree in mechanical engineering. Upon graduation, he joined Wes-Tech, Inc., an automation company in Buffalo Grove, Illinois, as a design engineer. During his eight years at Wes-Tech, Consdorf held several positions culminating in becoming vice president of manufacturing and engineering, overseeing 110 employees.

"I'm thrilled to be returning to Felsomat," stated Consdorf, "as it's an exciting time to be involved in all the new developments in automation technology. Felsomat is perfectly positioned to deliver this technology to our customers which enables them to stay at the forefront of today's competitive global manufacturing environment." (*www.felsomat.com*)

Ipsen

OFFERS CREDIT TOWARD NEW HEAT TREATING EQUIPMENT

Ipsen believes that one of the most valuable things a company can do is invest in others. They are also committed to advancing the heat-treating industry with the latest innovations and updated equipment. As part of that commitment, they are investing $1,000,000 in the industry this year.

Companies can take advantage of Ipsen's investment by trading in their old furnace to receive a $50,000 credit toward the purchase of a new Titan vacuum furnace (applies to the 2017 list price of any Titan model). Ipsen will accept a trade in of any brand heat-treating furnace (vacuum or atmosphere) in any condition. To receive this credit, transactions must take place by October 31, and the new Titan furnace must ship from Ipsen's facility by December 31, 2017. Learn more about this opportunity at the website: (*www.IpsenUSA.com/Invest*)

October 4–6—AGMA Steel for Gear Applications Alexandria, VA. This course provides detailed information to make use of steel properties in a system solution and understand the potential that different steel options can offer for various applications. Students will explore the how the production of the steel can affect the performance of the material and also the final component and system. The course will be facilitated by Lily Kamjou, a senior specialist in Ovako's Industry Solutions Development department. It is an advanced level course and qualifies for those individuals pursuing the Advanced Gear Engineering Certificate. For more information, visit *www.agma.org*.

October 24–26—Gear Expo 2017 Karlsruhe Trade Fairgrounds, Germany. Deburring Expo's exhibition portfolio is focused on products, systems, processes and services for deburring and rounding, as well as precision surface finishing for components made of nearly all materials from all industry sectors. The fields of training and technical literature are represented at the event as well. The exhibition includes equipment, systems and tools for abrasive flow machining, belt grinding, ECM, mechanical deburring, thermal energy machining and more. Educational opportunities include a three-day integrated expert forum for examining various deburring theories and practices. For more information, visit *www.deburring-expo.de*

October 24–26—Gear Expo 2017 Columbus, Ohio. For three days, the full range of drive technology experts—design, manufacturing, application engineering, gear buyers and manufacturers—network and build relationships that benefit their respective companies. For the past six years, AGMA's Gear Expo has been growing and expanding with more suppliers and attendees meeting to build new partnerships and explore the latest technology on the market. Attendees represent a variety of industries including off-highway, industrial applications, automotive, and oil and gas as well as aerospace, agriculture and construction. They come from around the United States, international manufacturing hubs, and emerging markets to conduct profitable business transactions and collaborate on the innovations that make their operations more streamlined. The show is co-located with the ASM Heat Treating Society Conference and Exposition. For more information, visit *www.gearexpo.com*.

October 24–26—2017 Quality Show Rosemont, Illinois. This event is the only tradeshow focused exclusively on quality manufacturing and will offer engineers and managers responsible for quality in the manufacturing process for automotive, aerospace, consumer products, electronics, medical devices, machinery, appliances and more two high-profile keynotes and an interactive tradeshow floor with dozens of education sessions and networking opportunities. Education will be another key component of The Quality Show, which is offering two high-profile keynotes by Matthew Napoli, VP of in-space operations for Made in Space, and Harry C. Moser, founder and president of Reshoring Initiative. In addition to the keynotes there will be a dozen free 30-minute education sessions in the Learning Theaters located in the exhibit hall by Coordinate Metrology Society (CMSC), DISCUS Software, Mahr, Zeiss Industrial Metrology, BSI and more. For more information, visit *www.qualityshow.com*.

October 24–26—2017 South-Tec 2017 TD Convention Center, Greenville, S.C. South-Tec draws manufacturing suppliers, distributors and equipment builders from across North America and around the world—bringing them together in Greenville, South Carolina. With hundreds of exhibiting companies, attendees can find all the latest technologies and services—plus the experts who build them—ready to demonstrate solutions that can help them grow their business. Visitors can make side-by-side comparisons, discover integrated equipment, hear about industry trends and forecasts, and leverage their purchasing power. South-Tec is the single best source to discover the next evolution of your industry! For more information, visit *www.southteconline.com*.

November 13–16—China Chongqing International Machine Tool Show Chongqing International Expo Center, Yubei, Chongqing, China. AMT—The Association for Manufacturing Technology and the China Machine Tool and Tool Builders' Association (CMTBA) have announced the launch of the China Chongqing International Machine Tool Show (CCIMT). CCIMT will showcase the latest in manufacturing technology and bring buyers and sellers together from all over the world to the dynamic market of Chongqing and southwest China. With an expanding manufacturing base of domestic companies plus more than 250 Fortune 500 multinationals, Chongqing has established itself as an innovation center for high technology. Chongqing's economic growth was 11 percent in 2015, the fastest growth among 31 provinces in China. Chongqing is China's largest automotive producer, largest laptop computer manufacturing center and a major motorcycle manufacturing location. More than 600 local companies specialize in making motorcycle and related parts with annual motorcycle engine production exceeding 10 million units, of which about 15 percent are exported to overseas markets. For more information, visit *www.amtonline.org*.

November 14–16—AGMA 2017 Detailed Gear Design (Beyond Simple Service Factors) Dallas, Texas. Learn how to improve gear designs and gain new insight into concepts presented through illustrations and demonstrations. Explore all factors that go into good gear design from life cycle, load, torque, tooth optimization, and evaluating consequences. Pre-requisite: Students should have a good understanding of basic gear theory and nomenclature: Online Workforce Education: Fundamentals of Gearing or Fundamentals of Gear Design and Analysis. Gear engineers, gear designers, application engineers, people who are responsible for interpreting gear designs, technicians and managers that want to better understand all aspects of gear design should attend. Raymond Drago is the course instructor. For more information, visit *www.agma.org*.

December 5–7—Power-Gen International 2017 Las Vegas Convention Center, Las Vegas Nevada. Power-Gen International provides comprehensive coverage of the trends, technologies and issues facing the generation sector. More than 1,400 companies from all sectors of the industry exhibit each year to benefit from the exposure to more than 20,000 attendees. Displaying a wide variety of products and services, Power-Gen International represents a horizontal look at the industry with key emphasis on new solutions and innovations for the future. In 2017, Power-Gen is going back to its roots and will cover ALL forms of power generation broken up into 14 tracks. Nearly 300 industry experts from all over the world will present new solutions and innovations for the future. Full conference attendees will also earn 10 PDH credit hours. Conference sessions include energy storage, digital power plant, material handling, business trends, nuclear power and more. For more information, visit *www.power-gen.com*.

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5 → My company's principal product or service is:______________________

6 → How are YOU involved with gears (check all that apply)?

- ☐ My company MAKES gears (20)
- ☐ My company BUYS gears (22)
- ☐ I DESIGN gears (23)
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GUILT by ASSOCIATION

Matthew Jaster, Senior Editor

The definition is pretty straightforward: An association is an organization of persons having a common interest. Basically, it's a group that shares a purpose or mission that exists for the mutual advancement of its members.

The American Gear Manufacturers Association (AGMA) was founded in 1916 to assist in developing gear standards. Today, AGMA includes 495+ of the world's top gearing companies from across more than 30 nations. As we prepare to roam the halls of another Gear Expo, it's important to stop by the AGMA booth and thank those involved in the day-to-day activities for making the gear industry what it is today.

Why are we getting sentimental about AGMA, you may ask? Well it's simple really. We interview and talk with AGMA members on a daily basis. We hear stories about AGMA meetings where goals are actually accomplished, standards are updated and new technologies are examined that will benefit members.

Associations don't always run so smoothly.

My mother was a president of a school association once where the parents were much more dramatic and overbearing than their children. There's a reason homeowner association (HOA) bylaws can be found scattered across the Internet: Many of these laws can be labeled ridiculous, bordering on insane.

Some examples:

A man in Florida was taken to court by his HOA for parking his pick-up truck *in his own driveway*. Perhaps, it was not washed properly. Maybe it had one too many bumper stickers or window decals. It's possible that the HOA just didn't like the make, model and color of the truck. They took action.

A woman in Texas was once fined because the fence around her backyard was an *inch* higher than HOA regulations. You know the end is nigh when a neighbor is standing just outside your yard with a beer in one hand and a tape measure in the other.

Some HOAs flat out ban lemonade stands in the summer. Can you imagine an HOA president walking down the street in his dad socks, clipboard in hand, telling young Scott and Amy they need to shut down immediately?

So much for the American Dream.

I write this after recently moving to a neighborhood with its own 44-page document of bylaws. It's mostly, standard suburban fare: They want the yard nice, tidy and treated organically. No savage or wild animals can be kept in the house. No RVs are permitted on the front lawn. Basketball hoops can't be eye sores. Same goes for the mailbox.

But I hear about power-hungry HOA stories all the time. I hear about school association presidents that attempt to out Trump, Trump. I've been told stories about someone bringing an idea to an association meeting only to end up in tears after being mocked and ridiculed by the group that allegedly "shares a common purpose."

We're lucky to have AGMA. They are a great resource for those new and old to the gear industry. In the years we've covered gear manufacturing, we've never heard anything ridiculous or absurd outside of a disagreement or two about certain technologies — and an argument or disagreement isn't always a bad thing when you're dealing with highly-critical industrial applications.

It's important to get involved in AGMA activities as much as possible.

And it wouldn't hurt to stop by the AGMA booth during Gear Expo, hug an employee or simply say "Thank you."

They don't care what kind of truck you drive, how tall your fence is or if your kids want to make some cash at the lemonade stand.

They just want the gear industry to keep moving forward — one technology at a time.

www.agma.org/documents/2017membershipapp.pdf

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Together, we can change the world.

As a child, you dreamed of changing the world. Today, you build amazing things that impact the lives of everyone around you.

Here at Ipsen, we want to be your partner on this journey – whether it's helping you select a standard furnace to get the job done or turning your ideas into a custom heat-treating solution. We will be there through each step of the process, working tirelessly to push the limits of what's possible.

Our job doesn't stop there. We want to be in the trenches with you, providing tools and support that help you succeed. From a software platform that predicts maintenance needs, to a service person just a call away, we want your equipment to run for years to come.

Changing the world isn't easy, but you've found a partner that believes in being better.