gear TECHNOLOGY®

JUL 2016

ON CLOSER INSPECTION

- LAB QUALITY ON THE SHOP FLOOR
- AUTOMATED OPTICAL INSPECTION
- CLOSED-LOOP GEAR MANUFACTURING

CHECKING UP ON YOUR HEAT TREATER

IMTS2016 — FIRST LOOK

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JUL 2016

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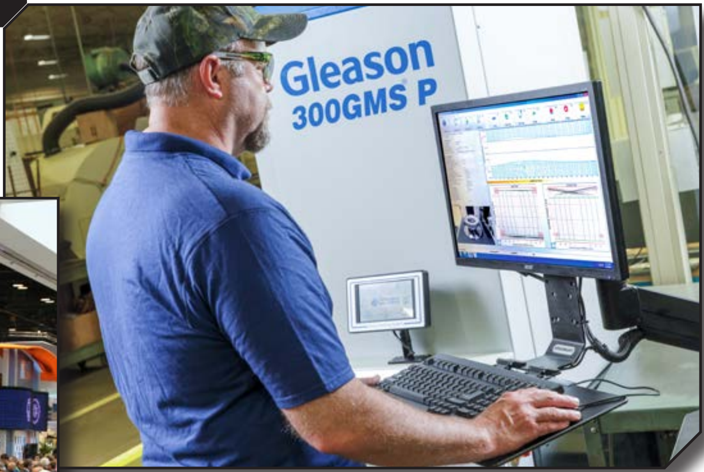

38

features

technical

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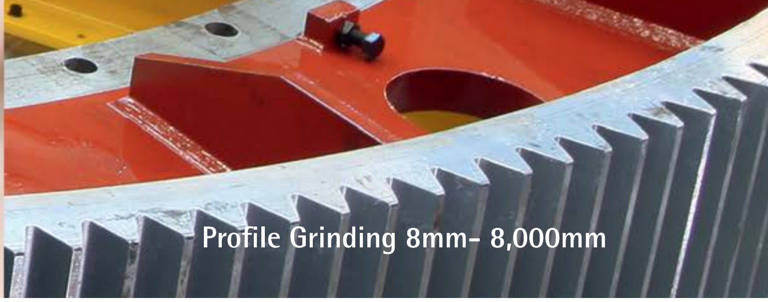

A QUIZ

Question 1:

What do you want? A machine that will grind your parts perfectly and efficiently, so you can go home and be with your family.

Question 2:

What do we have? See answer to question 1.

See the ZE 800 and KX100 in our booth at IMTS.

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Vol. 33, No. 5

departments

Cover photo by David Ropinski

THE GEAR INDUSTRY'S INFORMATION SOURCE

www.geartechnology.com

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Photo courtesy of Star SU

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This Month's Highlighted Topics:
Grinding
Heat Treating

Photo courtesy of EMAG

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BPA WORLDWIDE BUSINESS

Life in High Gear

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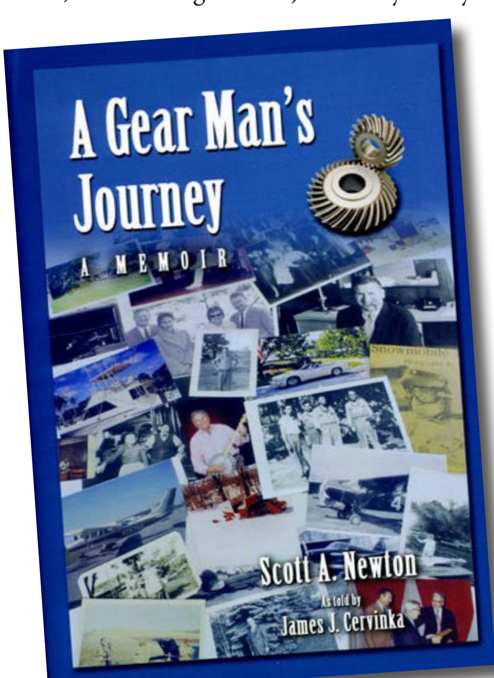
Most books related to the gear industry are more about the business side or the technical aspects of what we do. Rarely are they about the people in it. But the industry is made up of people, and sometimes those people have an impact that extends beyond their own company or their own time. James J. Cervinka, founder of Arrow Gear, was one of those people. And now his story is available for everyone to enjoy and learn from. If you haven't already done so, I highly recommend that you pick up a copy of A Gear Man's Journey--A Memoir. It's Jim's story, told in his own words, as related to his biographer, Scott A. Newton. Jim passed away in 2012 at the age of 92, and this book is a fitting tribute to his remarkable life.

The book is lighthearted and folksy, but apart from being entertaining, I found I could relate to it on a number of levels. Throughout my career, I've had a very close association with Jim and Arrow Gear. After the war, Jim and my father both started their own businesses — my father as a used machinery dealer specializing in gear equipment, and Jim as a gear manufacturer. When I started working for my dad, Arrow Gear was already a good customer, and so I was often over there to work out a deal or assist with delivery. On these occasions, I'd often sit in Jim's office, and we'd just talk.

On top of the direct personal connection, I found some valuable and instructive themes in Jim's story that are reflective of a whole generation of men who came out of World War II, founded companies — often from very humble beginnings — and whose perseverance and dedication represent the American Success Story. These men built things, and their can-do attitude is what made America strong. My father was one of those men, and I recognize in Jim's story many of the traits I grew up with. I suspect that many of you had similar experiences. My father, Jim, and those like them built America and instilled qualities in their offspring that failure was not an option, hard work was normal, and curiosity was encouraged.

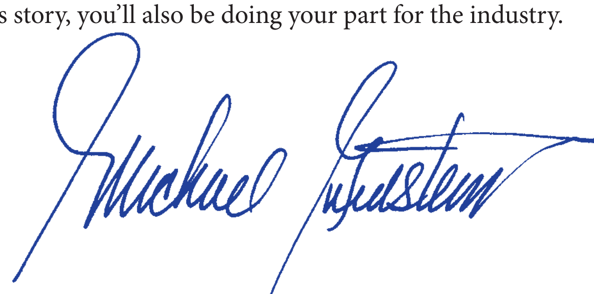


I believe most of you will appreciate the stories about a man who tasted every aspect of life and whose many passions revolved around all things mechanical. Maybe you'll recognize a bit of yourself in the young boy with mechanical aptitude who fixed his mother's washing machine, or the teenager who attached a motorized propeller to a sled and drove it around town.

If it had a motor or an engine, Jim probably, drove it, flew it, tinkered with it or repaired it. He was a pilot, who owned and flew more than half a dozen airplanes. He raced snowmobiles. He owned fishing boats and motor homes and automobiles. He souped up golf carts. And many of his stories involve clever and creative ways he used his mechanical ability to keep those machines working, like the time he was forced to make an emergency landing in a farmer's field. He scrounged up parts from the farmer's barn to make a replacement push rod. He repaired his engine, then flew the rest of the way home without incident. I'm not sure most of us would trust our own abilities in a situation like that, but that's the kind of man Jim was. When faced with a challenge, he didn't wait for someone to come and help him. He figured out a way — whether making gears, running a company or living his life.

Many of you will also find interest in the history of Arrow Gear itself. Founded in 1947, the company has grown to become one of the world's premiere manufacturers of spiral bevel gears for aircraft applications, with customers around the world. But reading this book you'll get the inside story about all the good decisions, bad decisions, lucky breaks and hard work it took to build this company.

A Gear Man's Journey is available from *www.lulu.com*. Just search for James Cervinka or *A Gear Man's Journey*. The price is $19.95 plus shipping, but all profits will be donated to the AGMA Foundation, according to the author. So by reading Jim's story, you'll also be doing your part for the industry.



Closed-Loop Gear Machining

A MAZAK/DONTYNE SYSTEMS/RENISHAW COLLABORATION

Randy Stott, Managing Editor

Mazak and Dontyne Systems, with the help of Renishaw, have developed a flexible gear machining solution that combines the multi-tasking capabilities of Mazak's 5-axis machine tools with Dontyne Systems' gear production software solutions and CMM inspection.

Through this process, shops with full 5-axis multi-tasking capabilities can productively and profitably produce tight-tolerance gears in small and medium volumes. This technique also makes it possible to generate more complex and specialty forms that offer better overall gear performance.

Mazak and Dontyne employees were introduced to each other at Gear Expo 2013 in Indianapolis, IN, and have since developed their joint Closed-Loop Gear Machining solution with the help of Renishaw. They've exhibited the solution at Gear Expo 2015 (Detroit, MI); Mazak's Discover 2015 (Florence, KY); PRI 2015 (Indianapolis, IN); and AeroDef 2016 (Long Beach, CA). The solution will also appear at IMTS 2016, where developers promise additional improvements and advances to make it even more effective and productive.

The closed-loop process includes three major components, says Mike Finn, senior application development engineer for Mazak. The first is gear design software. The second component is CNC machining in a 5-axis or multi-axis machine. The last component is gear inspection.

Dontyne's *Gear Production Suite* software generates design and load analysis models for the engineer, while providing the manufacturer with links to machine tools and inspection equipment and easy evaluation of incoming measurement data.

"Our software is aimed at improving not just the design, but also the manufacturing, the productivity, and ultimately, the gear performance," says Dontyne co-founder Dr. Michael Fish.

Designers can create spur or helical gears, splines, planetary systems or bevel gears (using generic bevel gear types). The software can design the parts for manufacture using either standard tools, such as end mills, or custom tooling, such as hobs.

In the design stage, the software can be used to produce optimized gear profiles based on the required load capacities for the particular application at hand. It can also simulate how that gear system will react in the gearbox and under specific loads — the level at which components will bend and/or deflect. With such a simulation, the software can then compensate by altering the surface of the gear according to those conditions. Once the appropriate profile is determined, the software exports a 3-D model of the part.

The 3-D model can then be used to generate G-code using CAD/CAM software. "Programming the machine is rather simple," Finn says. "It's really no different than programming any other 5-axis part. Once you get the model, you really don't need to think of it as a gear. It's just geometry."

The G-code is loaded into an Integrex machine and the part is cut with no special gear knowledge required on the part of the operator.

"The next step of the process is to take the part out of the machine and put it onto the CMM," says Finn. The closed-loop process can be used with any CMM machine, but it has been developed specifically in conjunction with inspection equipment that uses Renishaw's probes and inspection software.

Dontyne has a long-established interface to Renishaw CMM equipment for gear and spline evaluation. According to Dan Skulan, National Sales Manager for Renishaw, the same solid model that's used to generate the G-code for the Mazak machine is also used by the Renishaw *Modus* software, so that the part that's manufactured and the part that's inspected are both based off the same theoretical model.

Parts can be inspected on a CMM using scanning technology. Renishaw has the ability to scan in full 5-axis using Revo technology or compared against a master using Renishaw's Equator gauging system, which provides thermally compensated measurement on the shop floor. It's also possible to measure parts directly on the Mazak machine, which is especially advantageous for larger gears. Machines can be equipped with high-precision probing, such as an RMP600 strain gauge system or even scanned using new Sprint technology. Machine positioning accuracy can be established by using tools like the QC20W ballbar that quickly verifies the linear positioning and Axiset/Mazacheck that ensures proper adjustment of the axis centers of rotation. "With the right calibration and setup," Skulan says, "it's very possible to measure gears right on the machine and provide the same output data that's required by the Dontyne software."

Once the part is measured, the CMM data is then fed back into the Dontyne software, which analyzes the inspection data, looking for any differences between the manufactured gear profile and digital master. In instances where errors are identified, the software identifies necessary adjustments that are made to the cutting operation and the cycle repeats. The loop continues until the desired gear tolerance levels are achieved.

Depending on the tolerances required, though, the process might require just one iteration, Fish says. "If it should need correction, we just press a button, it modifies the file, feeds it back into the machine, and the next part should be spot on."

The closed-loop system provides a viable option for manufacturers who need to produce gears in small- to medium-sized batches, who don't have dedicated gear machinery or who wish to produce gears using standard tooling, Finn says. This includes many applications in small-lot manufacturing and prototyping.

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www.dontynesystems.com

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5277 Trillium Blvd.
Hoffman Estates, IL 60192
www.renishaw.com

See Mazak's Mike Finn explain the closed-loop gear manufacturing process here: *www.youtube.com/watch?v=eQzLDryzz3Y*

See a live demonstration of a straight bevel gear being cut on a Mazak machine here: *http://downloads.dontynesystems.com/BevelInMazak.MOV*

Forest City Gear

INSTALLS KEYENCE IM SERIES INSTANT MEASUREMENT SYSTEM

Quality Inspector Amy Sovina says she's not a big fan of turning the knobs on an optical comparator. Not only is it time consuming and tedious, but measurement results are often subjective as well. So when she learned that her employer, Forest City Gear, was purchasing an IM Series automated inspection machine from Keyence, she looked forward to the time it would save on incoming inspection of gear blanks from outside suppliers. Little did she know the Keyence IM would soon become one of the busiest pieces of metrology equipment on the shop floor.

"Overall, the Instant Measurement has received a very favorable reception," says Sovina. "It's especially popular with the people in the turning department. They're able to get accurate dimensional checks very quickly, and it's reduced a lot of the hands on work with height gages and micrometers. The more they use it, the more confident they are with the results."

Forest City Gear sits a short distance from the Rock River, in the heart of Roscoe, Illinois. The company has been in business more than 60 years, machining high-quality gears for the aerospace, medical, transportation and other industries that require hobbed, skived and precision-ground geared components. This includes helical, spur, spline and worm gears, some with tolerances to ten-millionths of an inch and diameters larger than a bicycle wheel.

"With those accuracy requirements, the company had to invest millions in gear form measurement and analysis equipment, but was looking for a quick and easy way to measure other part features," explains Dennis Atchley, quality manager at FCG. That need arose with the recent contract from a robotics manufacturer that supplies pick and place machines for use in the warehouses of a major online consumer products reseller. "Forest City Gear has traditionally focused on very high-tech, low-volume work—gears for unmanned drones, satellites, aircraft components, etc. A big order to us was 100 pieces. Suddenly, we were faced with inspecting 100,000 parts per year."

Atchley turned to Keyence for help. The IM-6700 Series Image Dimension Measurement System measures multiple part features simultaneously, without the need for positioning fixtures—simply place the workpiece on the measurement stage and press the measure button. Within three seconds, up to 99 part features and hundreds of points are identified and measured, and the results automatically recorded.

Lines, circles and arcs are automatically recognized, and a special algorithm applied to fit such features within a user-definable number of points. Chips, burrs, and debris are likewise filtered, improving accuracy and ease of use for the operator. Most importantly, the IM is accurate to within ±2 µm.

This was all good news for Atchley, who is especially pleased with the IM's ability to calculate 6sigam, CPK and other statistical analyses. "We had a job running just last week where the customer was asking for a process capability study on a ground taper," he says. "We set it up so the operator could take in-process measurements of the gage line as the parts came off the machine. It's been very useful for things like that, especially with our higher part volumes."

Another area where the IM has come in handy is statistical process control (SPC) of subcontracted operations. Atchley said one of the new part families is comprised of 16 different components and requires thousands of measurements per month. Having the ability to simultaneously check all the lengths on a gear shaft, for example, or multiple bearing journal diameters, has greatly increased throughput on receiving inspection, and at the same time makes data capture and report generation much simpler. "It gives us greater confidence in the subcontractor's process control."

As the one responsible for taking all those measurements, Sovina is quite happy with the IM's speed and easy setup. "Programming was quite easy to learn," she says, and it took no more than half a day with the Keyence representative for her and her team to become familiar with the system. As a result, she's expanded the IM's role beyond inspection of the parts coming in the receiving door.

"Quite often I can use the same program for the subcontracted gear blank and final inspection of the workpiece," she says. "Some of the dimensions will have changed during our in-house machining and gear cutting operations, but the IM is still able to pick up the part features. Because I only have to program it once, it saves us a lot of time. Long term, the Instant Measurement will be a big benefit to the company."

For more information:
Forest City Gear
Phone: (815) 623-2168
www.forestcitygear.com

Keyence Corporation of America
Phone: (888) 539-3623
www.keyence.com

Gleason Threaded Wheel Grinding Machines

COMBINE MAXIMUM PRODUCTIVITY WITH MINIMUM IDLE AND SETUP TIMES

Gleason Corporation recently introduced the 200GX and 260GX Threaded Wheel Grinding Machines, its latest addition to the highly successful Genesis series. The twin spindle concept combines maximum productivity with minimum idle and setup times. The machine allows users to setup the GX Series from one workpiece to another in just 20 minutes using a single tool.

"First Part Cycle" features a fully automatic workflow from setup to grinding the first workpiece. In addition, the machine is equipped with latest innovative technology features such as: Twist controlled grinding, automated process data proposal, variable rate method (VRM) for a favorable surface structure and polish grinding for an excellent surface finish. The ability to directly interface with Gleason GMS Analytical Gear Inspection machines via simple scanning of QR codes further enhances the productivity of the GX Series. In addition, the GX series productivity is further enhanced when paired with automation solutions from Gleason Automation Systems.

Easily accessible machine components make maintenance simple and efficient while standard dimension grinding wheels allow you to use your existing tools along with precision dressing tools from Gleason. All of this in an energy efficient, small footprint machine designed to meet the needs of customers in high-productivity, high-quality environments.

The 200GX and 260GX are supported by the Gleason Global Service network with strategically located spare parts centers and over 250 service professionals in all major markets worldwide.

For more information:
Gleason Corporation
Phone: (585) 473-1000
www.gleason.com/260GX

EMCO

OFFERS PORTAL-STYLE 5-AXIS MILLING CENTER

The Umill 1800 from Mecof, part of EMCO Group, offers milling and turning solutions designed to meet the needs of mold makers, aerospace, automotive and precision engineering users. Umill 1800 is a 5-axis milling center in a bridge design with moving table and cross-beam permitting loading from the top or the front of the machine.

Umill 1800 has a working range of 2,150 mm on the longitudinal axis Y, 1,800 mm on the cross X axis, and 1,250 mm in the vertical Z axis. Fourth and fifth axes are separately on the table and on the head, both with unique characteristics. The 5-axis machine can be equipped to work as a milling machine or as a multi-tasking solution for milling and turning operations. The table can be dedicated to milling (and therefore with a rotation speed of 10 rpm, transmission by means of torque motor, by 1.700 × 1.400 mm plate and a load capacity of 10 tons) or turning (up to 250 rpm, transmission by means of torque motor, plate with 1,800 mm diameter and a load capacity of 5 tons. Rapid traverse is 60 m/min. The movement of the table is carried out on two guideways size 65 with three trucks per guideway.

With these dimensions, the maximum workable piece has a diameter equal to 2,500 mm. In case of turning operations, the spindle is locked by using a Hirth coupling/ face gears, thus disengaging the spindle and bearings from their stresses.

Umill 1800 is equipped with two specific types of numerical controls, the Siemens 840D Solution Line or the Heidenhain TNC 640 HSCI able to manage both milling operations and turning operations. The head is available in two versions, which differ in the type of motor: a high-speed motor spindle (45 kW and 300 Nm in S1, HSK 100 and 12,000 rpm and beyond) and as an alternative, a 38 kW solution with mechanical transmission, tool taper ISO 50 or HSK 100, 600 Nm of torque in S1 and a rotation speed of up to 6,000 rpm.

The head has another unique feature connected to the rotary axis: its shape allows positioning the tool for working in undercut up to -15 degrees. In the horizontal position the tool axis is exactly aligned with the direction of the table movement. Other machines cannot orient it in the same way; and then to perform an operation along the Y-axis they must interpolate the axes X and Y. Being able to engage a single axis, however, has accuracy advantages, thrust force benefits, and a reduction of complexity in programming.

The structure of the Umill 1800 is composed of three main parts rigidly attached to each other; so installation time is minimized. The machine can be located on the workshop floor without having to build expensive foundation and without interfering with current production.

The machine configuration supports optimum machining dynamics at any point within the working volume: the head overhang is the same regardless of the position of the axes. Without components such as rams that modify the geometric conditions, it ensures maximum repeatability and precision.

For more information:
EMCO Maier
Phone: (248) 313-2700
www.emco-world.com

Sandvik CoroMill 745

OFFERS MULTI-EDGE MILLING CONCEPT

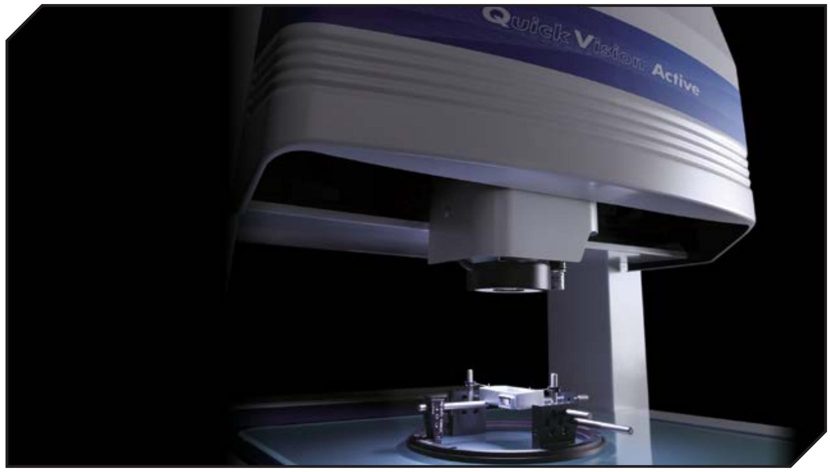
Offering high productivity and a low cost per edge, the CoroMill 745 has a double-sided, multi-edge design that is ideal for large batch productions. With its tilted insert positioning system and sharp cutting edges, this milling cutter offers a light cutting action at low power consumption.

With a total of 14 cutting edges per insert, the CoroMill 745 is a cost-efficient choice for face milling. The assortment includes three pitch versions. The differential pitch design of the MD pitch is best when vibration is a factor and is radially compensated to ensure equal chip thickness for every insert. The M pitch is best for general applications and the H pitch has a higher number of teeth making it the best choice for higher productivity. The M and MD pitch both have the same number of teeth.

Designed to make insert indexing quick and easy, the unique insert positioning system in the tip seat and heptagonal insert design keep the inserts securely in the pocket when mounting. The inserts are tilted in the tip seat to create a positive cutting action. Inserts geometries and grades are available for steel and cast iron materials. For roughing to semi-finishing applications, the strong and light cutting inserts provide reliable face milling in all types of milling machines.

According to Matts Westin, global product manager for milling, "You might see other multi-edge concept milling cutters on the market but none have the performance of the CoroMill 745. The science behind it is impressive. The unique double-sided, multi-edge insert design has 14 positively tilted cutting edges which are spaced out at different positions resulting in a milling cutter that is quiet and soft. For our customers, that means that they get a highly-productive milling cutter, increased tool life at a lower cost per component."

For more information:
Sandvik Coromant
Phone: (800) 726-3845
www.sandvik.coromant.com



Mitutoyo America

ADDS QUICK VISION ACTIVE SERIES TO MEASUREMENT SYSTEMS

Mitutoyo America Corporation recently announced the addition of the Quick Vision Active series to the line-up of vision measurement systems. This CNC vision measuring system is an easy-to-operate, space-saving model with advanced functionality to meet many contact and noncontact measuring needs.

The Quick Vision Active is highly efficient and flexible, offering a wide field of view with interchangeable objective zoom lenses to meet the challenges of measuring small to large features. The eight-step zoom lens can achieve a magnification range of 0.5× to 7× while maintaining crisp image quality. The 1× optional objective achieves a magnification range of 0.5× to 3.5× with a working distance of 74 mm. The 2× option can achieve a magnification range of 1× to 7×.

Quick Vision Active is available with measuring ranges of 10 × 8 × 6 inches (250 × 200 × 150 mm) or 16 × 16 × 8 inches (400 × 400 × 200 mm), with or without the touch-probe measuring option. *QVPAK* software uses edge detection and pattern recognition to locate and orientate the coordinate system with minimal operator input, ensuring accuracy and repeatability of the measurement results.

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

Bell-Everman Inc.

INTRODUCES ROTARY STAGE COLLET CLOSER

Bell-Everman Inc. has developed a compact, air-driven collet closer that can precisely secure cylindrical goods in the company's rotary stages. The collet closer solves a common workholding problem in inspection, metrology and laser engraving applications. This new collet closer squeezes into through-hole openings as small as 15 mm and extends just 42 mm from the face of the stage. The initial offering, "ER-16," collet closer handles cylinders with diameters from 1 to 10 mm. The collet closer has the ability to close without changing the workpiece's axial position. It also offers the ability to customize the opening and clamping behavior: The same air cylinder that closes the collet can be set to open it, making it easy to set it up as a spring-close, air-open device. The collet closer can optionally be integrated with a single-axis controller to handle indexing tasks and process fourth-axis motion commands for contouring. Bell-Everman has designed larger sizes that can accommodate cylindrical parts up to 30 mm in diameter and withstand higher side loads—opening up the possibility of some light CNC machining applications.

For more information:
Bell-Everman
Phone: (805) 685-1029
www.bell-everman.com

Oelheld

EXPANDS GRINDING OIL PORTFOLIO

Oelheld U.S. Inc. has added SintoGrind TC-X 630 to its portfolio. The oil is designed for flute grinding, profile grinding and outside and inside diameter grinding. It works on a wide variety of materials including tungsten carbide, HSS, PCD, CBN, cermet and ceramics. SintoGrind TC-X 630 was especially formulated for demanding grinding tasks and delivers exceptional feed and speed rates with superior surface finish. SintoGrind IG 540 is designed for flute grinding, profile grinding, and outside and inside diameter grinding. It works on a wide variety of materials including tungsten carbide, HSS, PCD, CBN, cermet and ceramics. Its lubricity lends to extended wheel life and minimal heat build-up, which in turn eliminates surface cracks and burns.

ToolGrind TC-X 620 is based on additive technology borrowed from Oelheld's flagship SintoGrind series. ToolGrind TC-X 620 is formulated with highly refined base oils that have very good viscosity and temperature characteristics combined with low misting and aromatic content. ToolGrind TC-X 620 promotes clean grinding wheels, low grinding temperature and less wheel wear. It prohibits workpiece corrosion and is suitable for most filtration systems.

For more information:
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www.oelheld.com

The Wait is Over for Lab-Level Shop Floor Inspection

Schafer Gear Works greatly reduces gear inspection queue time and adds precious capacity by installing Gleason's new 'shop-hardened' 300GMS P gear inspection system.

As Operations Manager at Schafer Gear Works' 100,000 sq. ft. South Bend, Indiana facility, Paresh Shah is justifiably proud of the investment his company has made in a new generation of gear grinders to meet the demand for precision ground spur and helical gears as large as 250 mm in diameter. Two highly automated hard finish grinding cells now give Schafer the capacity to produce some 15 to 20 different gears in volumes ranging from 5,000 to 100,000 each annually. These include tight-tolerance applications such as the twin turbochargers that help power the hot-selling Dodge Challenger Hellcat, and Schafer's own 'Driveline' golf car axles, reputed to be the quietest axles in the industry.

Schafer Gear and Shah sought to squeeze more capacity out of the operation. This meant focusing attention on the quality lab which, according to Shah, had now become an expensive bottleneck. "We have eight grinders that each require perhaps one new gear setup a day — and each setup requires a first-part inspection in the gear lab and acceptance before the operator will run the next part," he explains. "Shuttling these parts back and forth between the machine and the quality lab can take upwards of 20-30 minutes, multiplied by the two or three times it typically takes to dial in the machine. If this is happening just once a day for our eight machines, you're looking at expensive idle time for many millions of dollars of machinery that should be making parts."

Additionally, Schafer's quality lab also must support, two or three times a day,

Putting the 'shop-hardened' 300GMS P in close proximity to Schafer's two high-volume hard finish grinding cells saves hours of queue and transport time every day.

the typical in-process inspection of a sample gear produced on each grinder during a production run. Finally, even these priority gears must compete for lab time, and sometimes wait in queue with parts produced throughout Schafer's blanking, hobbing, shaping, shaving and bevel gear production areas. When a decision was made to add much-needed capacity to the lab and Schafer's existing inspection systems, Shah and his team had a better idea: why not eliminate the wait altogether by bringing the lab to the grinders?

Shop-hardened inspection adds throughput. Gear inspection bottlenecks of the type faced by Schafer have increased significantly in recent years, as low noise, increased power density, greater reliability and other factors have all combined to increase gear complexity and the inspection requirements that come with it. The search for a true 'shop-hardened' inspection solution — one that could work alongside and service gear production equipment on a moment's notice — has proven futile, with typical shop floor temperature variations, vibration and contamination proving to be too much for machines built for pristine lab conditions. So when Shah came across the new Gleason 300GMSP Analytical Gear Inspection System on display for the first time last fall at Gear Expo 2015, and said to be the first truly 'shop hardened' gear inspection system, he was intrigued. "Seeing is believing, and we came away from a demonstration convinced that the 300GMSP could be put out on the shop floor — essentially part of the grinding cells themselves — to eliminate hours of queue time every day, and even impervious to the considerable vibration coming from nearby shaping operations," recalls Shah. "Even better, the machine was so user-friendly that our machine operators could easily perform the inspections independent of the lab technicians."

Today, this show machine is now nestled in among the other Gleason machines that make up most of the two finish grinding cells. According to Shah and the two machine operators running the cells, queue time for setup part inspection has been reduced from 20-30 minutes on average, to as little as five minutes — savings that are multiplied by two to three times every day for each machine. Machine operators Jim Smith and Steve Allmon are particularly excited about the new inspection technology. "What a difference the system has made — walk over, set up the part, load a probe and start the inspection program with the touch of a

> "Shuttling these parts back and forth between the machine and the quality lab can take upwards of 20-30 minutes, multiplied by the two or three times it typically takes to dial in the machine. If this is happening just once a day for our eight machines, you're looking at expensive idle time for many millions of dollars of machinery that should be making parts."
>
> **Paresh Shah**, Operations Manager, Schafer Gear Works

button," says Smith. "While that's running I'm back at the cell making sure there are plenty of parts for these hungry machines. No more waiting for inspection results — we're in control."

Both operators agree that the system is remarkably easy to learn and operate. "We learned everything we needed to know in a day: calibrating probes, load/unload, how to pull up programs," says Allmon. "Fast and easy. This checker's the way to go!"

Machine operator Jim Smith now performs setup and in-process part inspections independent of the quality lab, saving precious time. The 300GMS P is essentially part of the grinding cell, so he can perform in-process inspection, check charts and make machine adjustments on the fly.

Adding value in a shop environment. When asked if the 300GMS P is operating just as well on the shop floor as it would in his tightly controlled lab environment, Schafer Quality Technician Jim Shinall says that he's seen no evidence in the inspection results that vibration or temperature are in any way having an impact. "If that nearby shaping hammering was effecting anything we'd see spikes in the charts, and there's been nothing," says Shinall. "And while the shop is, to some degree, temperature controlled we will have temperature swings out there of plus or minus 10 degrees F and this has not had any effect. We had an older inspection machine and if the temperature fluctuated just a few degrees it wouldn't operate without a probe re-calibration. This machine works and performs as advertised in the production area, pure and simple."

The 'shop-hardening' of the 300GMS P required a completely new design starting with a proprietary machine base material that's better suited than granite for the sustained higher temperatures experienced on the shop floor. The use of this new base material, coupled with a completely new patent-pending 'H' base design with active leveling system, has proven to be an excellent solution. The new base design consists of a bottom base with four air springs mounted on risers, which support the machine work platform. These air springs detect, and automatically compensate for, vibratory forces on the fly, such that the machine work platform (axes, table and workpiece) is both isolated from, and immune to, vibration.

> "What a difference the system has made — walk over, set up the part, load a probe and start the inspection program with the touch of a button. While that's running I'm back at the cell making sure there are plenty of parts for these hungry machines. No more waiting for inspection results — we're in control."
>
> **Jim Smith,** Machine Operator, Schafer Gear Works

This new Gleason Genesis 200GX Gear Grinding Machine offers Schafer many performance advantages, including dual-spindles for load/unload in parallel with machining, and integration of Gleason Automation Systems' stackable tray automation to reduce floor space requirements and add capacity as compared to typical conveyor automation.

The high precision guidance systems used to position linear and rotary axes on inspection systems are inherently susceptible to even minor temperature changes. The use of enclosed glass scales ensure exceptional accuracies, but also come with a thermal co-efficient. The 300GMS P development effort also addressed this challenge, with a new type of scale made from a material that has essentially zero thermal expansion within the typical shop floor temperature range. While scales of this material type must be left open rather than enclosed, they are exceptionally resistant to dirt. In addition, the GMS P's new design helps mitigate the collection of particulates that can build up on scale surfaces and reduce accuracy and reliability.

Finally, the 300GMS P incorporates a system of new software and sensors that work in combination to detect, and compensate for, typical thermal fluctuations found on the shop floor. This ability to identify and apply compensation for factory floor temperature influences contributes greatly to 300GMS P's exceptional accuracies in an uncontrolled temperature environment.

"It has lightened up lab work load considerably, thus adding capacity overnight to the quality lab for the rest of the facility," says Shinall. "Most importantly, the machine operators love it. They put a part on, click 'start program,' say OK and it runs. I also like the fact that you can take a picture of the setup with the Advanced Operator Interface pendant and it's on the screen so there's no way you can not put the probe in the right place before the start of a program."

This user-friendliness stems from *GAMA 3*, Gleason's object-oriented Windows 7 compatible operating software that puts a host of powerful features right at the operator's fingertips, creating a simple, intuitive human/machine interface. With *GAMA 3*, creating a new program is as easy as point and click, and can be done in a few easy steps regardless of experience level, language requirements or the gear or application type. *GAMA 3* now supports VDI/VDE 2610 GDE (Gear Data Exchange) capability as standard, a significant capability for reducing redundant programming and allowing gear data/parameters to be transportable between different machines.

A total gear solutions approach.

Schafer has also invested heavily in the latest Gleason high-volume gear grinding technologies, including Gleason Genesis 160TWG and 300TWG Threaded Wheel Grinding Machines and Gleason's next-generation Genesis 200GX Gear Grinding Machine. All are fully automated. The 200GX is particularly noteworthy because of its twin-spindle design that allows load/unload to take place in parallel with machining, thus eliminating several seconds of non-productive time for every part; and the use of a Gleason Automation Systems' stackable tray-type load/unload system that is both extremely compact and enables the machine to run unattended for much longer than possible with the typical conveyor system. This automation system also incorporates a 'spin' station that spins off coolant so that parts can be packaged directly from the machine completely dry.

"It has made great sense to source a complete system with Gleason," adds Shah. "With Gleason's help, we have never been better positioned to take on the high-precision, custom-engineered gear projects that Schafer excels at."

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Checking Up on Your Heat Treater

What Quality & Performance Characteristics Should You Look For?

Matthew Jaster, Senior Editor

"On the left, you'll see our state-of-the-art heat treating facility that includes two carburizing furnace systems and a large, custom-designed quench press." Over the years, I've toured many a gear manufacturing facility where the heat treat department stole the show. Maybe it's the massively deep pit furnaces, the Star Trek-esque control rooms and the large overhead cranes moving components around the facility. Perhaps it's simply all the pyrotechnics remind me of a really great rock concert. Regardless, heat treating is such a critical step in the gear manufacturing process it's no surprise several manufacturers have brought it in-house.

Others continue to outsource the work to a heat treat provider that provides stability, quality and a trouble-free end product. Why do they work with the same companies time and time again? How do these relationships form in the first place? What steps should you take to determine what heat treat company you should work with? We asked gear manufacturers, heat treat providers and consultants to weigh in on these and other related issues.

The Manufacturers Perspective-Nordex

Nordex Inc. manufactured standard components in the 70s and early 80s before turning to custom work giving the company's engineers more freedom to design new products and bring innovative ideas to its customer base. Nordex's custom components have appeared in aerospace, marine and medical applications to name a few. By combining electro-mechanical expertise with clean room capabilities, the company now performs manufacturing systems integration for semiconductor and analytical equipment as well as precision machining, gear design and production.

Nicholas Antonelli, senior engineer at Nordex Inc. provided *Gear Technology* with some insight on outsourcing heat

Three important factors when selecting a heat treater include technology, material handling and technical knowledge and expertise (photo courtesy of Dreyfus + Associates Photography).

treatment services. "The first thing Nordex would look for is accreditation by an outside agency such as Nadcap for process specific certification as well as general quality system certification to an ISO or AS standard," Antonelli said. "We would also need to ensure that the supplier has the equipment needed to perform the desired operation, as well as verify that the process has been performed correctly."

Auditing a supplier to verify that they are qualified to perform the processes you have specified is always a good idea, according to Antonelli. "The auditor should be experienced and have a good working knowledge of the heat treating process as well as general process control, inspection and verification, calibration and record keeping."

At the very minimum, Antonelli believes a certification of conformance is required (all the required responsibilities and heat treat services are met and recorded in a certified document). "Depending on the requirements of the end customer, we might also request an inspection report detailing actual hardness readings," he said.

Reviewing the heat treater's preventive maintenance program is another important step. Antonelli believes the heat treat provider's preventive maintenance program should mirror the gear manufacturer's program. "Our own equipment is maintained with a comprehensive preventive maintenance program and our equipment is calibrated to known standards on a regular basis. We would require our heat treating sub-contractors to have the same level of control on their own equipment," he said.

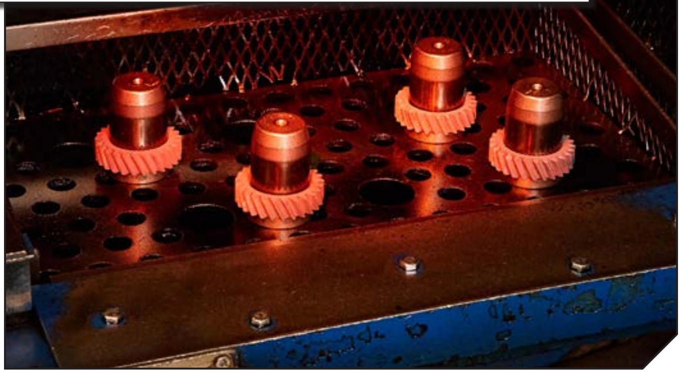
"The primary concern when heat treating the gears is the possibility that the gear will distort or change in size," Antonelli said. "To allow for this, the gear manufacturer needs to ensure that sufficient extra material is left on the part so that the post heat treatment machining can bring the features back into specification."

Sounds pretty straightforward, right? Of course, things don't always go according to plan and miscommunication can cause a number of problems.

Problems may arise from time to time; however, technology is doing its part by making it easier to collect and process data for each part a heat treater works with. "I don't know if heat treating itself is changing as much as the materials that are being used," Antonelli said. "There are many 'new' stainless and alloy met-

Auditing a supplier to verify that they are qualified to perform the processes you have specified on your part is a key step in the process (photo courtesy of Nordex).

Knowing that your heat treater is processing your gears the same each and every time to reduce variation is an important aspect of a heat treat audit (photo courtesy of Dreyfus + Associates Photography).



als that require specialized treatments. What *is* changing is the data and the information this data yields as well as the ability to track individual parts in each heat treat lot," he added.

The Manufacturer's Perspective-Forest City Gear

Forest City Gear manufactures custom gears in a variety of industries including aerospace and defense, medical, off-highway, transportation and many more. The company recently invested in several systems that allow FCG to prototype, qualify and produce gears in a wide range of sizes and volumes. Jeff Mains, director of technical operations, Forest City Gear, shared what his organization looks for from a heat treat provider.

Mains' first step is going over the basics before shipping the parts. "You need to verify the heat treater's quality system and make sure it's certified and current. If they need to be Nadcap certified this should also be current. It's also important that they have a full-time metallurgist on staff and can perform the heat treat specifications you're asking for. Additionally, can their lab perform the necessary tests in order to certify the product?"

If an audit takes place (and it should), Mains believes it's a good idea to audit all the services you're asking the heat treater to perform. "This should involve the QC manager, purchasing, a process engineer and a quality engineer. If *you* have a metallurgist on staff or have one as a consultant, they should also be asked to attend."

A list of additional capabilities and guidelines necessary when choosing a heat treater include the following according to Mains, "Can they produce their own tooling if necessary? Do they have the capacity to fulfill delivery dates? Do they have the ability to mask if required? How do they handle parts? What kind of work instructions are created on the floor? How well do they stand behind their work if there are problems?"

To keep all heat treating records documented and verifiable, FCG utilizes Kwiktag, a document management system that provides one integrated solution that coordinates every document, department and business process (*www.kwiktag.com*). "Records for heat treating must be retained in case there is a field/test failure and they need to verify the heat treat was performed correctly," Mains said.

The Heat Treat Perspective-Paulo Products Company

Paulo Products Company saw a need for commercial heat treating in 1943. They've built the company on custom systems that can trace every order from receiving through production and shipping. Notably, the company designed its production information and customer service system in-house with help from its own metallurgical experts and engineers. Bob Innes, sales manager, engineered projects at Paulo, discussed considerations that should be made before selecting a heat treat provider.

Three important factors according to Innes include state-of-the-art technology (furnace controls, PLC controls with bar-coding, electronic monitoring and data recorders), material handling systems to prevent damage and the technical knowledge and experience needed for each unique job and application.

"We believe it is critical to audit your heat treater-you are releasing your gears into the control of a supplier," Innes said. "You want to see how they handle your gears to prevent damage, how their furnace controls and inspection procedures ensure you meet print specifications for case depth and hardness. How you know you'll get the same process time-after-time to reduce variation."

At Paulo Products, every lot has a computer-generated shop order with process recipe instructions, loading/handling criteria (with photographs) and inspection requirements. Shop orders become permanent records with operator sign-offs as verification of completion. These are scanned for electronic retrieval, including remotely. Furnace permanent records are also electronic and retrievable remotely. "This is crucial for repeatability and traceability," Innes said. "We keep records for at least seven years and for many customers we keep records for longer periods."

Training and re-training is also pivotal to stay ahead of the competition. "We have a training program that includes Metal Treating Institute (MTI) courses, classroom training, mentoring with existing operators and training with our staff of metallurgists. On the operator level, we have high screening standards, and have a great deal of success using referrals from current employees," Innes said.

Quality control is constantly evolving. "Paulo's QMS is registered to ISO-TS16949, which forms the basis. We take it far beyond the ISO/TS requirements through data and technology," Innes said. "We've developed our own in-house system for process control and repeatability."

Beyond these important steps, Innes stressed the importance of seeing exactly how the heat treating facility is organized. "Is it clean and free of clutter? Is product easily identified? Even if you're not conducting a full-blown audit, you'll want a tour of your heat treater."

Paulo has developed its own in-house system for process control and repeatability of its parts (photo courtesy of Dreyfus + Associates Photography).

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HEAT TREAT HORROR STORIES

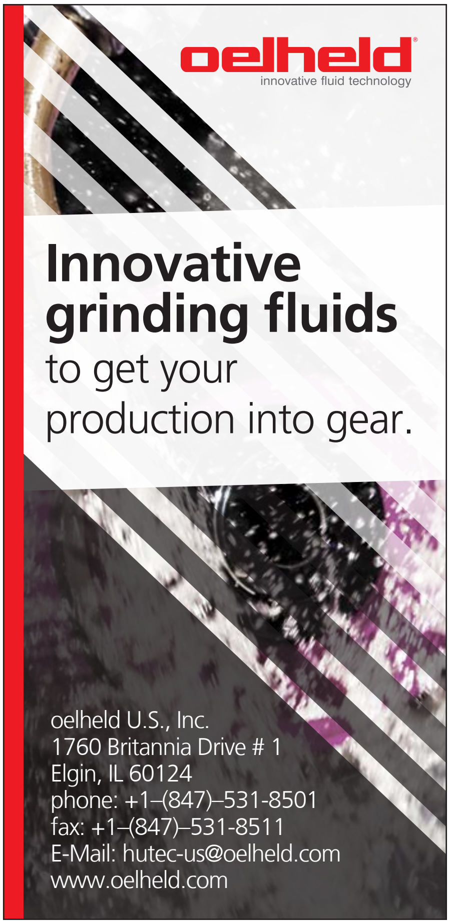
We've all heard stories of gears gone wild. There are gears that look one way when they leave the shop and look entirely different when they come back. There are gears that never come back at all. There are even gears that can't do what they were manufactured to do and end up on a coffee table or on the bottom shelf of a warehouse with the other misfit toys. The takeaway from a good heat treat horror story? You learn something new each and every time things don't go according to plan.

"We had a case where a customer made a frame for a machine out of A2 air hardening tool steel. The frame walls were two inches thick. The customer mistakenly asked for a hardness of 50 Rockwell C when they actually required a hardness closer to Rockwell 60 in the C scale. The heat treater suggested re-treating the steel, but this time quenching the steel in water to get the required hardness. Needless to say, the cracks in the frames were visible from across the room. This was one case where the parts needed to be remade," said Nicholas Antonelli, senior engineer at Nordex Inc.

Jeff Mains, director of technical ops, Forest City Gear, reflected on a heat treat job that caused some problems in the past. The application in question called for the parts to be quench plugged. FCG had done extensive testing to determine the correct recipe and the time had come to process the order. "All went well until we received the parts back. The parts had exploded in size by almost .050," Mains said. "We discussed our findings with the heat treater. He did not know what went wrong. To his knowledge the parts were processed the same as the test pieces. We asked him to do a little investigating. After he dug a little deeper, he called and said that he had found out from the operator that they were having a difficult time inserting the plug. So to make it fit the operator decided to deep freeze the plug -100 below zero. Of course then the plug dropped in with no problem because the plug had shrunk considerably."

The problem was that when they quenched the part it expanded and caused the part to grow much greater (.050) than the test pieces. The operator took it upon himself to do this before asking for assistance, according to Mains. "We lost the entire lot. Their inspection department did not check to make sure the parts had moved the predicted amount as the test pieces did before they shipped parts to us. The reason why the plugs did not fit on the production run, was that it was found the recipe (time/temp) was not followed as instructed."

Have a heat treat horror story about gears? We'd love to hear about it and publish our findings in an upcoming issue of *Gear Technology*. Contact *mjaster@geartechnology.com* with your anecdotes.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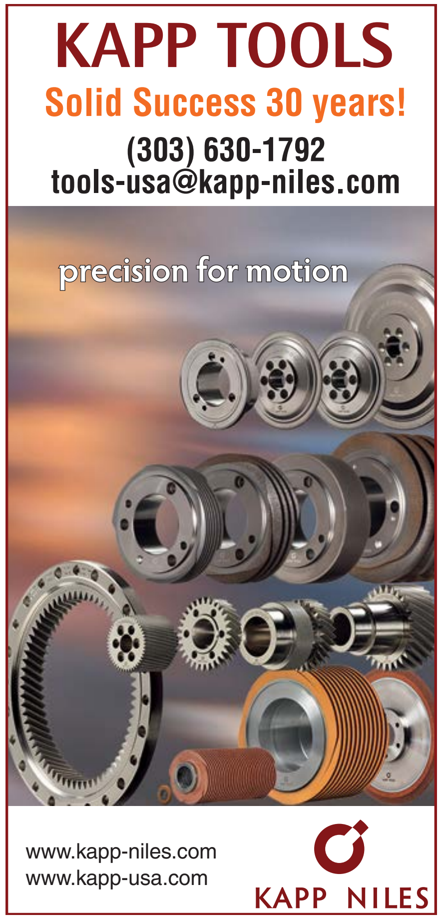
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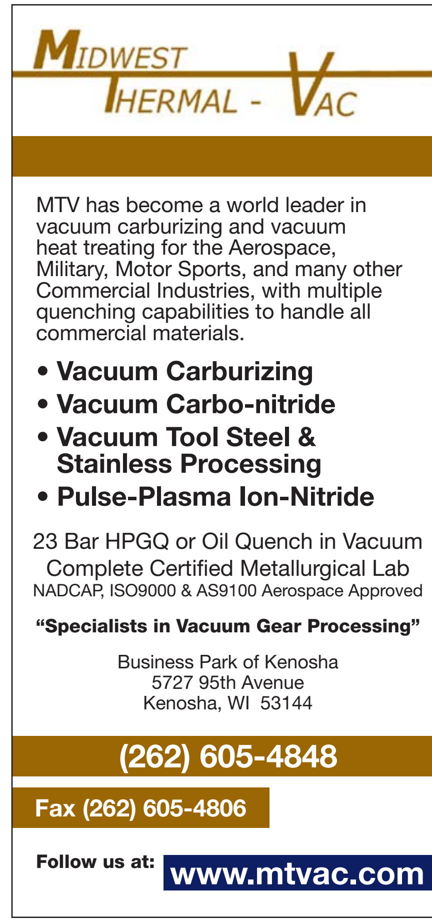
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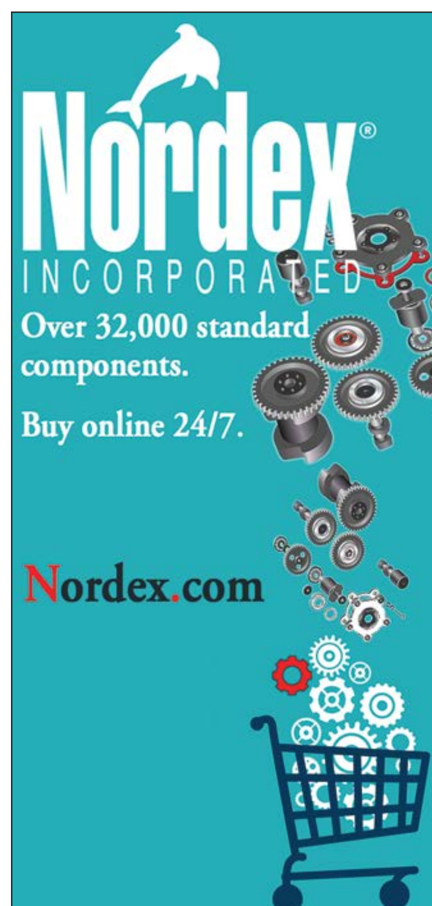
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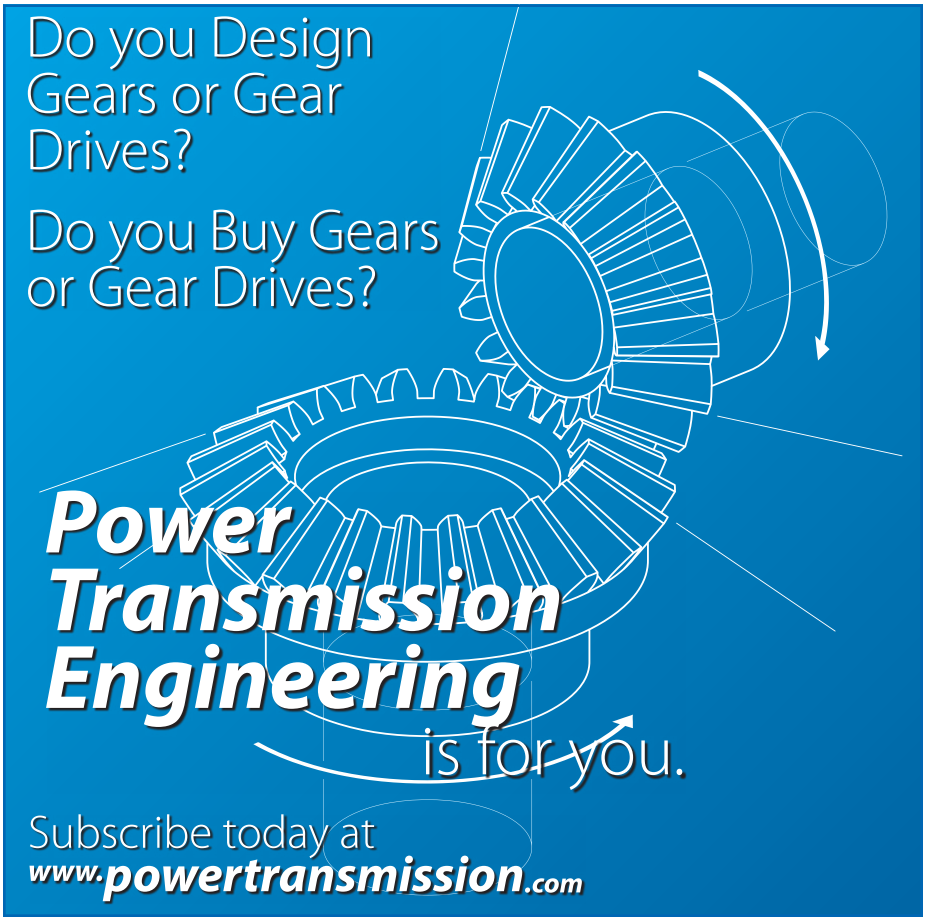
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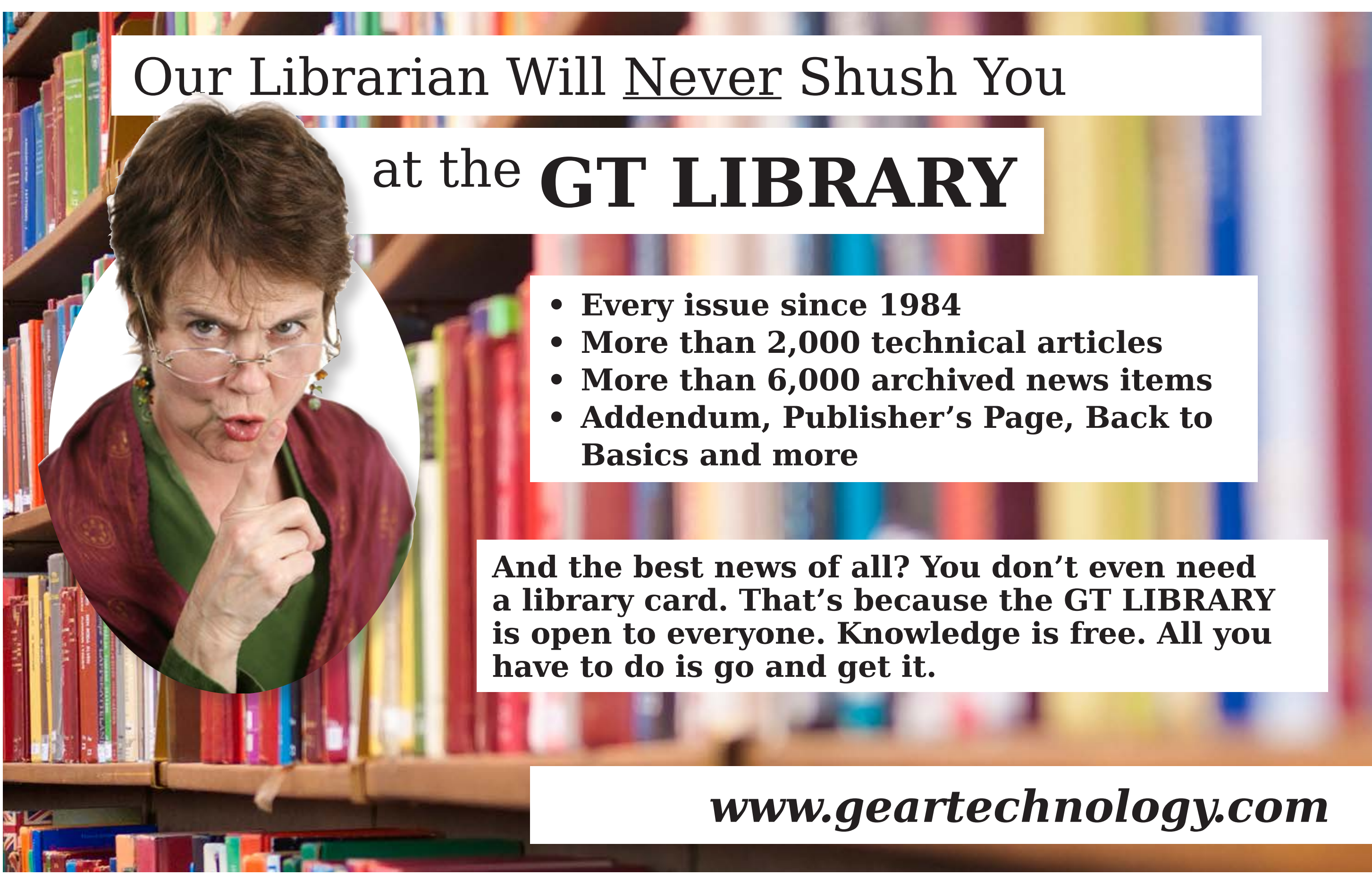
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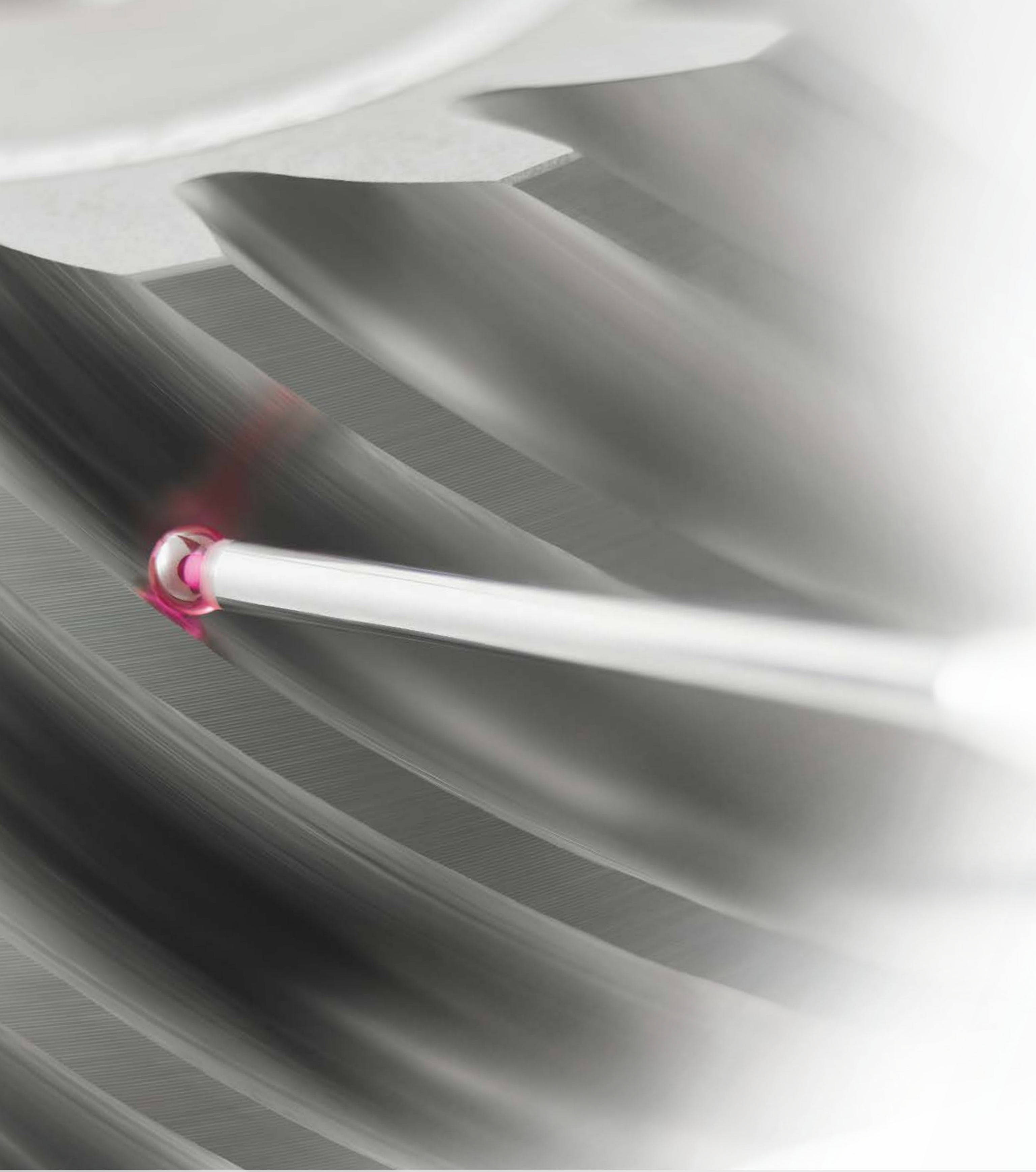

IMTS: Welcome to the Main Event

No matter who you are, IMTS is the show to attend.

Alex Cannella, News Editor

It's hard to think of a show more essential to attend than IMTS. It's the cornerstone event for the industry, the center of the universe for a week, the one show to rule them all. However you want to describe it, IMTS is hands down the biggest and most important U.S. show you can (and should) attend.

"I think everyone can agree that in North America, anyways, it's probably the biggest of them all. No doubt," David Jones, precision workholding manager of Emuge Corp., said.

"We consider it the most important show that we do every two years," Jay Duerr, president of LMC Workholding, said. "We may do some regional shows, but for the most part, we put 90 percent of our show budget towards IMTS."

One might think that this year's soft market would dampen enthusiasm for IMTS, but as we approach the show's opening, both excitement and expectations are high amongst exhibitors.

"You're in this business for a while, so you're not going to stop looking for ways to improve your process," Larry McMillan, Great Lakes regional sales manager at Hainbuch America, said. "And that's really what IMTS is there for is to inform you, educate you."

Perhaps contributing to IMTS's ability to weather the current state of the industry is its record year in 2014. IMTS saw 114,147 attendees in 2014, making it the fourth largest IMTS ever. While a lot can change in two years, people still remember the previous show's impact. Patrick Nugent, VP of metrology systems at Mahr Federal, for example, said that despite concerns about the market, their company is still "approaching the show like it's going to be the biggest show ever because of how good 2014 was."

"Two years ago, IMTS was just a really fantastic show," Nugent said. "We had the best show at IMTS in 2014 that we've ever had… There were days when our booth was so full, you could hardly walk through it with customers. They'd ask about one product and then a second one, and you'd have to kind of swim to the aisle to get free and clear and walk down to the other end of the booth and try to swim back in to that product. It was tremendous."

Duerr thinks that while the market may be flat, businesses tend to save their budgets for IMTS as part of their normal buying cycle, and IMTS will remain profitable.

"We think a lot of people actually wait to go to a show, and then when they go to a show, it's for purchasing purposes," Duerr said. "And I know that we can look at this and we can speak to that, as both an exhibitor and as an attendee. Because we're excited about our exhibition and showing our products and wares, but by the same token, my manufacturing group has

got a 2.5 million dollar budget… And their specific purpose is to go to the show and make the purchase there. They've been studying up to this point, they're getting quotes and all that, and really you go to the show and make the last vetting process and then we'll make those decisions there at IMTS."

Another reason some might expect this year's IMTS to defy the market trend is that the demand for booth space far outstrips supply.

"Regardless of whether or not the economy is good or bad… the nature of our business is cyclical, and if you get out, good luck on trying to get your booth space, because there's someone that wants it," Duerr said. "We've tried for the last few years to get a larger booth and we can't."

Not attending IMTS during a slow year means your spot probably won't be there when you come back for a good one, and seeing as no one wants to give up their seat, that means you'll have a full house, flat market or not. At the very least, you'll find plenty of faces doing research for when business is better later.

And space is indeed at a premium at the show. It's yet another testament to its popularity that 1.3 million net square feet isn't enough space for every exhibitor.

It's not hard to see why IMTS is so popular. It has something for everyone, big or small, buyer or exhibitor. The main draw is, obviously, the massive crowds of potential buyers that flock to the show, and the ensuing crowd of exhibitors that follow them looking to show off their newest and coolest products. For smaller exhibitors in particular, this is a golden opportunity to find new customers that may not have even shown up on a mailing list and have never heard of them.

Hainbuch in particular has benefited from exposure at IMTS over the years. "When I first started with Hainbuch, I had a booth inside of somebody else's booth, like a little table to just promote," McMillan said. "And every year, most people didn't know us that well, so for us, it was great exposure to meet new people."

Hainbuch has come a long way from a single table. This year, they have a 40 square foot booth, and McMillan believes IMTS certainly helped the company grow.

"It truly is not some place to just imitate that you're being a salesman for the day," McMillan said. "People are there for a reason. It's a good show to sell to customers or to develop a relationship to sell to them later."

For companies with broad catalogs like Mahr Federal, the exposure benefits are two-pronged. According to Nugent, IMTS not only allows them to establish new contacts, but also to meet current customers that may not be aware of the full scope of the company and potentially sell them additional products and services.

"Because of the volume of attendees and the wide-ranging industries and markets that they come from, we have the opportunity to reach a lot more people who may not know what we do or they may know Mahr Federal because we make such a broad range of products," Nugent said. "They think of Mahr Federal and they think 'oh, well, those guys, that's where we get our surface finish measuring gauges from.' And then they come and they see Mahr Federal and they go 'wow, you make form measuring systems and gear measuring systems and shaft measuring systems and optical systems, and I didn't know you guys did all this stuff.'"

For companies like Felsomat, IMTS is all about quality face-time — getting to actually sit down with management and company buyers and interacting with customers.

"It's a very good moment to get to spend time outside the office with some of higher level management," Patrick Seitz, president of Felsomat, said. "Take them out to dinner, go have a drink with them and get some facetime not in an office between meetings."

The social side of the show is just as important for many companies as the actual physical sale of products. Whether it's catching up with friends in other companies or talking to business prospects, exhibitors are eager to rub elbows and talk to almost anyone they can.

"If you see something, stop," Jones said. "They want to talk to you. That's what they're there for, that's what we're there for."

For big and small exhibitors alike, the social aspect is also about presence. IMTS, being the massive family reunion it is, can make absences a little conspicuous, and just showing up and having a physical presence at the show has its own value.

"At a big show like this, you need to show presence," Seitz said. "Because otherwise if you don't go, people ask 'where's Felsomat? Where's this guy? Where's that guy?'"

"Gleason has a responsibility to our customers and the markets that we serve, so we need to participate in a show like IMTS, basically in support of the global manufacturing landscape," Gleason VP of Sales John Terranova said.

Another bonus is the ability to learn firsthand about your

customers. Manufacturers naturally spend a lot of effort marketing themselves, but there are precious few ways to really learn about your customer base. IMTS gives an opportunity to converse and really get to know the people that buy, or are thinking of buying your products, better.

"You want to use the time of the customer most effectively and efficiently so that you really get an overview and [you're] not just telling him what you want to tell him, but you also ask the right questions so that you get an understanding of their business," Dr. Thorsten Schmidt, CEO of DMG MORI said.

According to Schmidt, IMTS is critical, but it's also important to remember that maintaining one's presence is a year-round effort. IMTS is good for establishing and deepening relationships, but like any other relationship, the leads you pick up at the show need to be maintained.

"[Attending IMTS] is essential for success," Schmidt said. "But it's also not the only way how to be successful. The investment and the commitment across the year and throughout the last couple of years have been crucial, so that customers understand that you're not just showing up at an exhibition and afterwards you're gone again."

Everyone at the show has different parts that they get excited about, but as has become a growing theme the past few years, everyone has their eyes on automation. It's hands down the number one thing manufacturers attending the show are keen on looking at. The rise of the Industrial Internet of Things (or Industry 4.0 if that floats your boat) is catching on at home, and it's becoming more accessible each year.

"Whereas automation used to be such a scary thing, even small companies such as ourselves are able to put that in place and really make it useful, because it's becoming more attainable," Duerr said. "And the thing we're most excited about there is how we can couple the great machine tool capability that's already there and seeing what the new smart controls and automation are doing."

And they'll certainly have plenty to look at. Even beyond the advances being shown off at IMTS, two other co-located shows, Motion, Drive and Automation North America and Industrial Automation North America, will both feature automation heavily. All co-located shows are being done by Hannover Fairs, USA. On top of MD&A and IA, Hannover Fairs is also starting three new co-located shows this year: Surface Technology NA, which will cover surface treatment and finishing, ComVac NA, which focuses on compressed air and vacuum technology and Industrial Supply NA, which according to IMTS's website "will cover the entire spectrum of industrial subcontracting and lightweight construction."

For such a large show, you would expect there to be a bit more pomp and circumstance around it. A centerpiece concert one night, perhaps, or some other performance added on to give the show that extra coat of glitz and glamour. But IMTS is playing it relatively straight. Not much is changing from 2014 and extra frills are few and far between. The "IMTS Fun Stuff," as their website is calling it, consists of an IMTS-branded hot air balloon on display and the return of Local Motors, who in 2014 3-D printed a functioning car, the Strati, during the show. Local Motors will be setting up a racetrack where attendees can ride in the Strati, along with other cars designed by the company.

But for the most part, IMTS is about business, and that seems to be the show's thing: straightforward, to the point, and filled to the seams with value without too many distractions. It's the big event on everyone's to-do list, the place everyone goes to do business and catch up with what's happening in the industry at large. IMTS is already so massive, they don't really need any bells and whistles to make the show more appealing; everyone's already going, and you probably should too.

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Improved Broaching Steel Technology

Michael E. Burnett

Helical broaching is a highly efficient machining technology used to cut tooth profiles in annulus planetary gears used in car and truck automatic transmissions. The operational costs largely depend on the life of the expensive broach bar, with rapid tooth wear rates leading to very high broaching costs. The wear rate of the broach bar teeth is dependent upon factors including the broach bar material, tooth design, surface treatments, lubricants and the properties of the gear blank material/condition. A laboratory broach machine was developed to study the impact of these variables on the wear rate and life of the broach tool material. Extensive testing has been performed utilizing this test, with an emphasis on the effects of the gear blank material on the life of the broach tool. Effects of base material composition, hardness and microstructure on the life of the broach tool have been studied in detail. Testing results reveal the current typical ferrite/pearlite microstructure of gear broach blanks can cause high tool wear rates, whereas a non-pearlitic structure can result in a 100% to 500% improvement in broach tool life. Tested steels include both carburizing (SAE 5120, 8620, 5130, etc.) and induction hardening (SAE 1050, 1552, 5150, etc.) grades, with ferrite/pearlite, ferrite/bainite and martensitic structures. This paper describes the laboratory broach test, a summary of the testing performed, significant findings resulting from the test and the metallurgical correlations between the base material and the broach tool life.

Introduction

Broaching is a machining technique commonly used to cut gear teeth or cam profiles for the high volume manufacture of power transmission parts used in vehicles (Refs. 1–2). The part tooth profiles can be formed in a single machining operation with minimal overall time, making it ideal for cost-sensitive applications. However, in order to accomplish the broaching operation in a single station and operation, the broach machine must perform the entire roughing, shaping and finishing of the desired part profile in one step using a long, multi-piece, high-speed steel broach tool. The broach tool is relatively expensive to manufacture and can only be redressed or sharpened a finite number of times before the tool is no longer usable (Ref. 2). The precise broaching and tooling cost per manufactured part is highly dependent upon the number of parts that can be manufactured between broach tool redressings. With tooling and redressing costs over the life of a helical broach bar on the order of $50,000–$100,000, and total parts manufactured on a single broach bar currently in the range of 10,000–80,000 parts, the cost to broach a part is typically in the range of $0.60–$5.00, or more. Hence the broach tooling cost represents around 15%–50% of the total manufacturing cost for a finished part. Therefore, whereas broaching represents a time- and space- efficient method to cut gear tooth profiles into annular

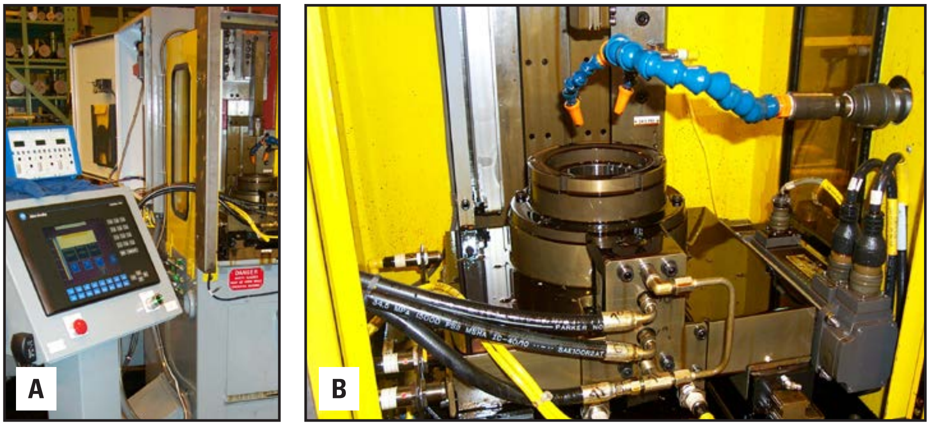

Figure 1 **Shown: a) broach machine, control stand and dynamometer modules; b) control table, clamping device with test ring inside and coolant lines.**

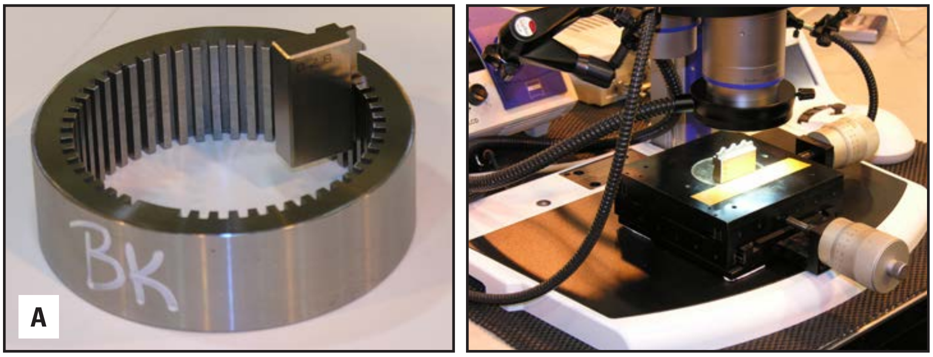

Figure 2 **Shown: a) tested broach ring with broach tool resting in finished slot; b) a broach tool under microscopic examination for tool wear measurement.**

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Table 1 Compositions of SAE grades tested, weight percent

Grade*	C	Mn	P	S	Si	Cr	Ni	Mo	Cu
5120	0.21	0.88	0.009	0.032	0.29	0.86	0.10	0.03	0.20
8620	0.21	0.87	0.008	0.018	0.28	0.57	0.64	0.21	0.17
4027	0.27	0.83	0.008	0.030	0.23	0.18	0.07	0.27	0.19
15V27	0.28	1.50	0.016	0.048	0.59	0.15	0.09	0.03	0.21
5130	0.30	0.92	0.010	0.029	0.22	0.81	0.10	0.03	0.13
5135	0.36	0.76	0.012	0.024	0.32	0.98	0.10	0.04	0.21
4040	0.41	0.91	0.010	0.022	0.25	0.11	0.11	0.25	0.20
5046	0.46	1.06	0.008	0.029	0.27	0.20	0.09	0.03	0.15
1050	0.50	0.82	0.008	0.040	0.19	0.08	0.08	0.02	0.20
5150	0.52	0.92	0.010	0.034	0.26	0.86	0.12	0.03	0.21
1552	0.53	1.46	0.009	0.026	0.27	0.11	0.10	0.03	0.20
1060	0.60	0.72	0.007	0.016	0.28	0.12	0.09	0.04	0.20

*15V27 also contains 0.11 wt. %V, all are Al killed

Table 2 Structure, hardness and broach life of steels in each condition

Grade (SAE)	Structure (+Ferrite)	Hardness HRB	Broach Life*		Structure (+Ferrite)	Hardness HRB	Broach Life*
5120	Pearlite	85.8	15,000			-	-
8620	-		-		Bainite	89.0	12000
15V27	-		-		Bainite	95.7	12000
4027	-	-	-		Bainite	88.0	11000
5130	Pearlite	88.6	4600		Bainite	95.3	9600
5135	Pearlite	92.2	2400		-	-	-
4040	-	-	-		Bainite	90.9	9500
5046	Pearlite	92.6	1200		Bainite	94.7	8700
1050	Pearlite	91.8	1200		-	-	-
5150	-	-	-		Bainite	95.7	8800
1552	Pearlite	94.3	900		Bainite	92.4	6200
1060	Pearlite	93.9	220		Bainite	98.6	3500

*Cuts to failure, 1.5" (38.1mm) each in length, average of two tests

steel parts, the tooling cost to perform this operation represents a significant portion of the total manufacturing cost.

Experimental Procedure

Reduction of broaching costs is typically accomplished through advancements in tooling materials, coatings, lubricants and processing parameters, without as much attention given to the influence of the material condition of the part being broached (Ref. 3). In order to study the influence of steel material condition on broach tooling life, a laboratory broach test machine was conceived, developed, built and used to perform numerous studies on the broaching characteristics of various steel grades and metallurgical conditions. The test unit enables the quantitative measurement of broach tool wear characteristics resulting from repeated broach operations for each of the input steel grades and conditions. The machine development and subsequent testing performed on the various material conditions resulted in a more thorough understanding of the metallurgical variables affecting broach tool life and subsequent part manufacturing costs. This paper describes the broach test unit and discovery of the optimal broaching condition for various steel types, and also provides a summary of testing performed to date.

Test set-up. The broach test machine was developed to simulate the machine design, operation parameters, tooling material and cut design, lubricant system/type, and part geometry of a production-type broaching operation (Fig. 1). A 2-ton, vertical-surface broach machine was integrated with an automated indexing control table and three-axis dynamometer, allowing for monitoring and capture of the actual loads occurring on the tooling during each broach stroke. A tool was designed with three teeth — each cutting 0.0015" (0.038 mm) during the cut operation for a total of 0.0045" (0.114 mm) taken per stroke. The tool broaches inner-diameter splines inside a steel tube slug — 1.5" (38.1 mm) in length, 40-cuts-per-slot — at ram speeds up to 50-surface-feet-per-minute (sfm) (15.24 smm) (Fig. 2). The tool is inspected periodically during the test until 0.005" (0.127 mm) flank wear is measured on two of the three teeth, at which time the test is considered completed and the number of cuts to reach that limit (average of two tools) then characterizes the broaching characteristics of the steel being tested. Controlled test variables (beyond the steel type and condition) include the ram speed, lubricant type/flow rate and tool material/surface condition. The baseline test conditions utilize an M4 tool steel tool with no surface treatment, a chlorinated/sulfinated blended mineral oil lubricant, and a ram speed of 40 sfm (12.2 smm).

Results and Discussion

A series of steels typical of both carburizing and induction hardening gear applications were selected for testing. The steels were tested in both the typical baseline, ferrite/pearlite, and modified conditions, with the intent to improve upon the baseline broach life results. These steels and the heat chemistries are listed in Table 1 and include low-to-medium carbon grades (0.20–0.60 wt.% C), with varying alloying combinations (Mo; Cr; Cr-Mo; Cr-Ni-Mo; Mn; Mn-V) and hardness levels.

Seamless mechanical tubing of the appropriate broach test size range was acquired for each steel grade. Normalizing each steel prior to testing (fully austenitized and air-cooled) developed a uniform, fine grain size and an equivalent processing method for each grade. In addition, the same or similar grades were processed to achieve a non-pearlitic structure and similar hardness range for comparison with the ferrite/pearlite steels. The hardness, microstructure and broach life results for each steel condition are presented in Table 2, and representative photomicrographs are presented (Fig. 3).

The tool wear results for the baseline ferrite/pearlite condition show a clear difference between grades based on carbon

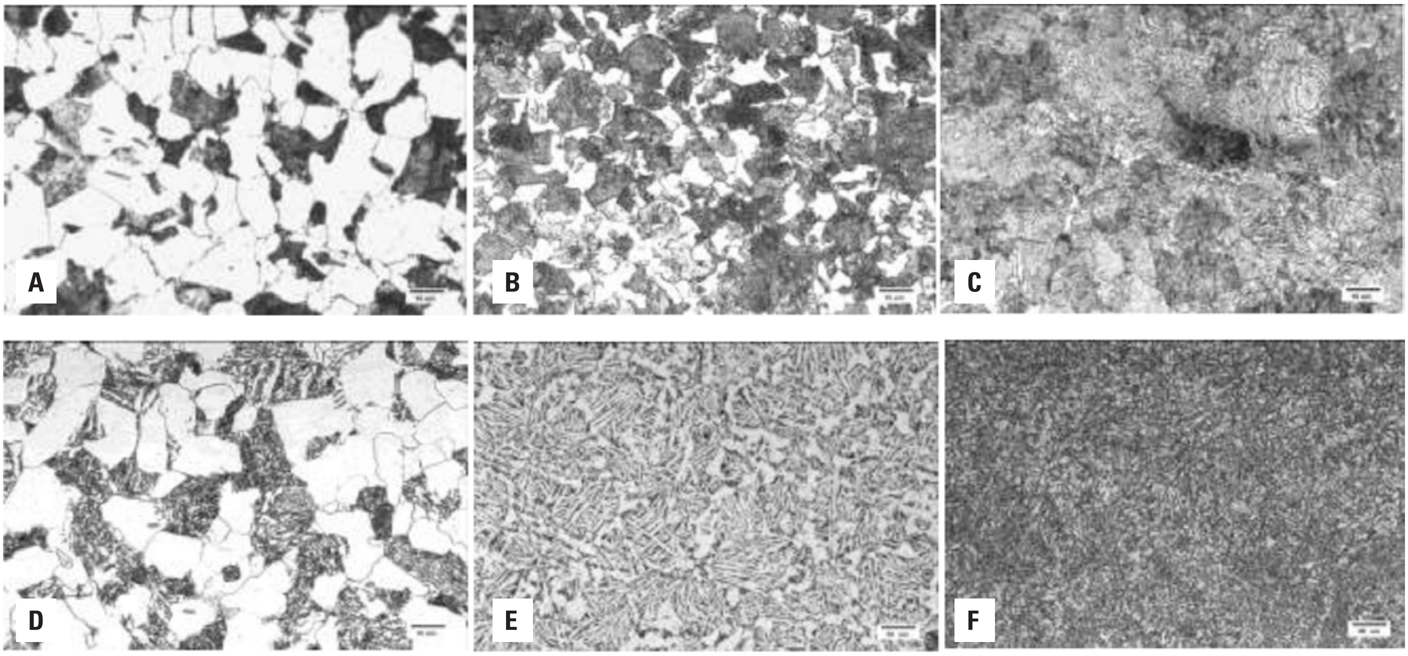

Figure 3 Representative photomicrographs of ferrite/pearlite: a) low-carbon; b) medium-carbon; c) high-carbon steels, and ferrite/bainite; d) low-carbon; e) medium-carbon; f) high-carbon steels.

and hardness level. These trends (Figs. 4 and 5) show the apparent negative effects of carbon level and hardness on broach tool life (exponential trends). Whereas both carbon level and hardness appear to influence tool life, this is not necessarily the case, as carbon level and hardness are significantly correlated to one another (Fig. 6). These results would tend to indicate that lower, carbon carburizing grades would be much less costly for gear broaching, while higher, carbon induction hardening grades could be prohibitively expensive. Further investigation is necessary to determine which of these factors truly influences broach tool life, and if any opportunities exist to improve upon these baseline results.

Whereas these traditional grades and conditions tend to be dominated by ferritic/pearlitic structures (baseline), investigation into alternate material conditions was also explored. The results obtained from numerous internal studies (Refs. 4–5) have shown that non-pearlitic structures provide advantages in many machining operations, and therefore these types of conditions were generated and tested over a similar range of steel types and carbon levels. Creating the non-pearlitic conditions was achieved through a combination of alloying approaches, modifications to prior austenitic grain size (i.e., hardenability approaches), and/or rapid cool-

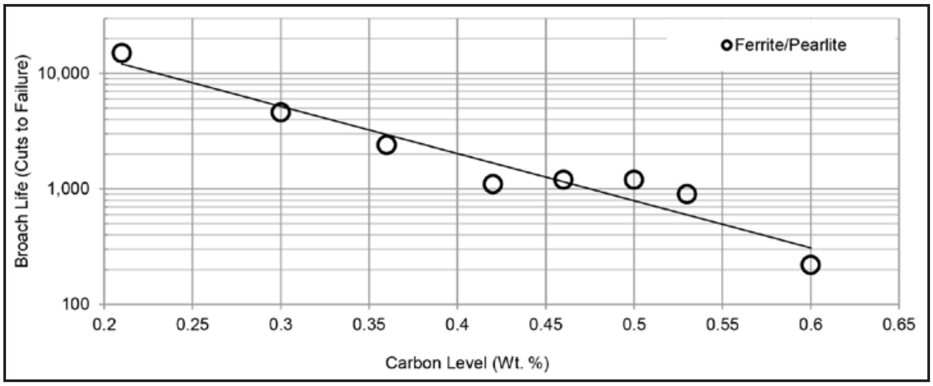

Figure 4 Effect of carbon content on broach tool life for normalized baseline steels composed of ferrite/pearlite microstructure.

Figure 5 Hardness versus broach tool life for normalized baseline steels composed of ferrite/pearlite structure.

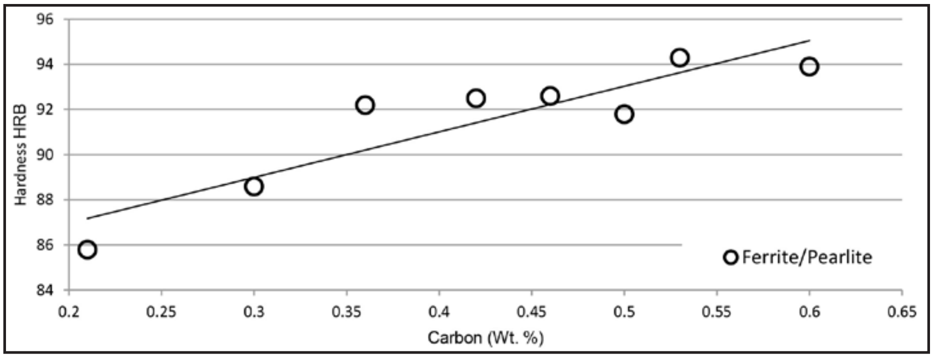

Figure 6 **Correlation between hardness and carbon level for normalized baseline steels composed of ferrite/pearlite structure.**

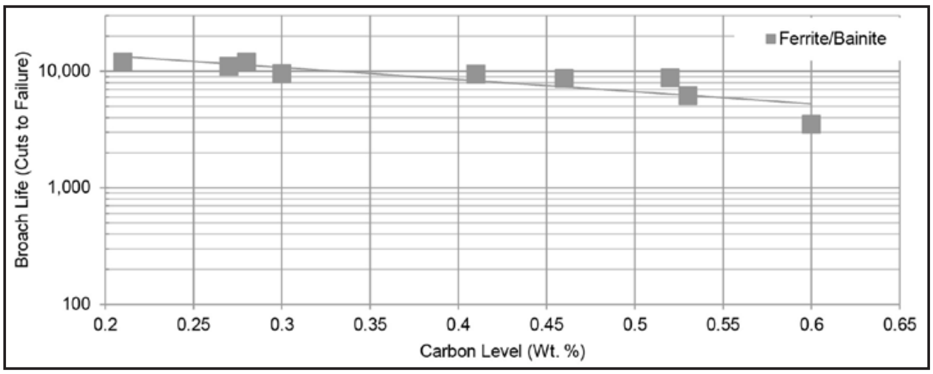

Figure 7 **Effect of carbon level on broach life of steels composed of ferrite/bainite structure.**

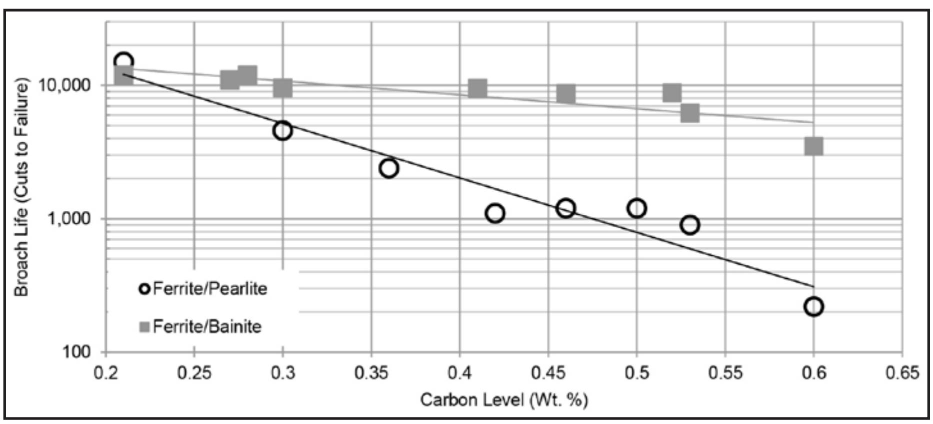

Figure 8 **Comparison of effect of carbon level on broach life for both structure types.**

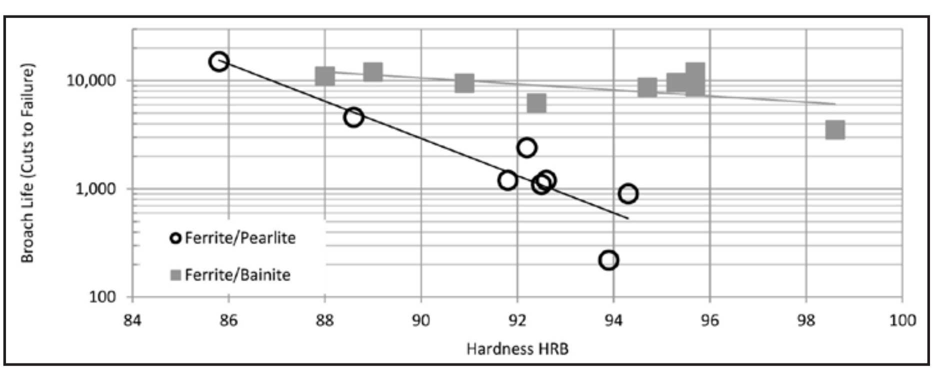

Figure 9 **Comparison of trend between hardness and broach life for both structure types.**

ing to bypass pearlitic transformation. Table 2 compares the results from these approaches with the baseline grades and conditions. A similar range of carbon level is shown for these modified conditions, while the hardness range is somewhat reduced and the hardness level is slightly increased, as compared with the baseline ferrite/pearlite conditions.

The apparent trends from this dataset deviate significantly from what was observed for the ferrite/pearlite baseline conditions. Figure 7 illustrates the same carbon level versus broach life plot as shown for the ferrite/pearlite conditions; however, in this case the effect of carbon level on broach life is much less pronounced. This becomes even more apparent when both conditions are plotted together (Fig. 8). The relative improvement in broach life for the non-pearlitic condition is much more pronounced for the higher-carbon steels, elevating broach life of the higher carbon steel to levels approaching the lower carbon ferrite/pearlite steels. Plotting the non-pearlitic results against hardness levels for these conditions (Fig. 9) also indicates a reduced trend of hardness and broach life for the non-pearlitic conditions. These results suggest that higher carbon induction hardening gear steels can be economically broached in the non-pearlitic condition, with cost structures similar to lower carbon carburizing grades and while maintaining a sufficient level of core hardness for the application.

In addition to this study between various grades and conditions, selected studies concerning the impact of processing on individual grades have also been performed in an attempt to optimize broach life for a particular steel grade. One such grade of interest is the induction hardening grade SAE 5046, where both the ferrite/pearlite condition and bainitic conditions were tested (as previously reported), and where additional tests were performed on the bainitic condition after various tempering conditions. Table 3 summarizes those results for the ferrite/pearlite condition, and the ferrite/bainite condition following tempering within a range of 1,150°F–1,325°F. As seen in the table, while there is a significant improvement in broach life in going from the ferrite/pearlite to the non-pearlitic structure, the broach life of this condition

Table 3 5046 structure, hardness and broach life data			
Tempering Temperature (Deg F)	Microstructure	Hardness (HRB)	Broach Life (Cuts to Failure)
NA	Fenite/Pearlite	92.5	1200
1150	Ferrite/Bainite/ Martensite	98	3100
1200	Ferrite/Bainite/ Martensite	97	3800
1275	Ferrite/Bainite/ Martensite	95	7200
1325	Ferrite/Bainite/ Martensite	94	10000

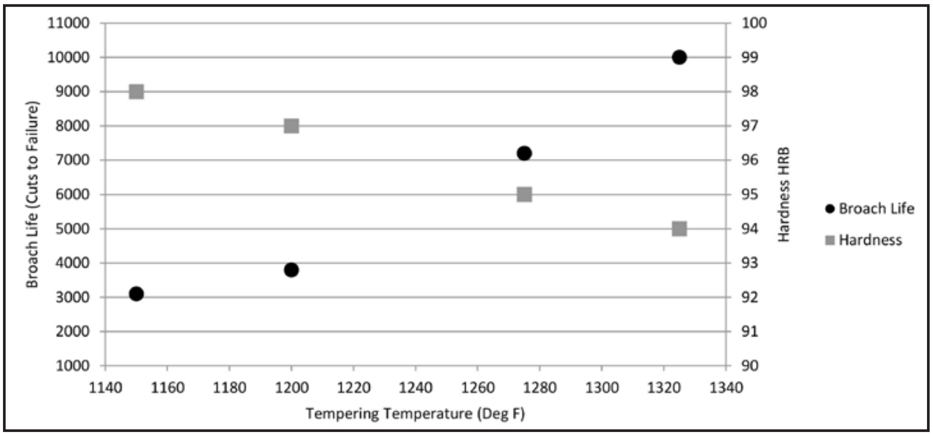

Figure 10 Effect of increasing tempering condition of non-pearlitic 5046 material on both material hardness level and broach tool life.

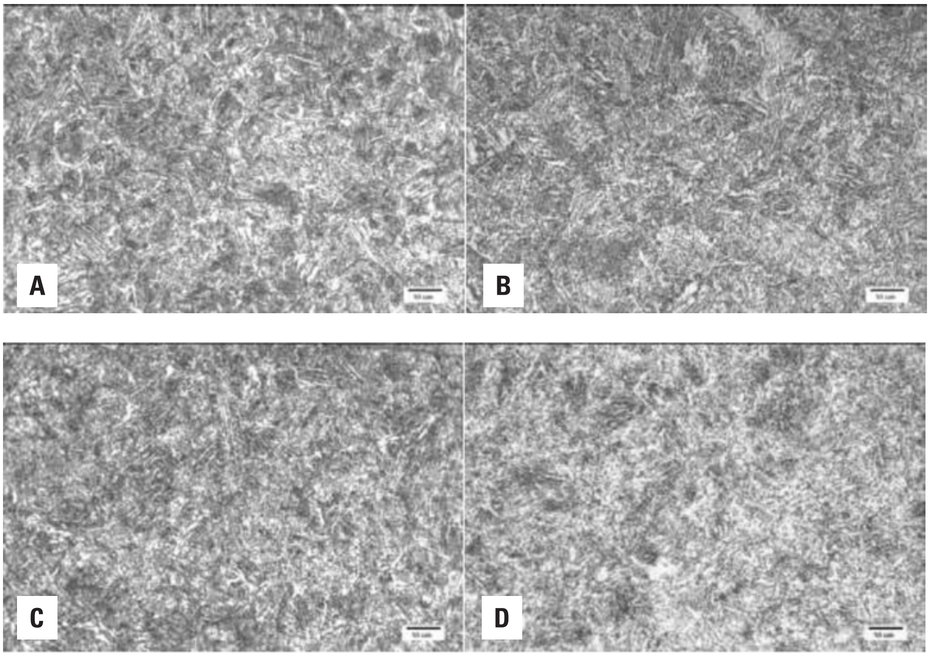

Figure 11 Photomicrographs of 5046 bainite/martensite/ferrite conditions after tempering at a) 1,150°F; b) 1,200°F; c) 1,275°F; and d) 1,325°F, nital etch.

is highly dependent upon the tempering condition employed. As depicted in Figure 10, a significant range in broach tool life results is realized by varying the tempering conditions for the bainitic structure — even over a fairly narrow range of hardness levels. Therefore, as has also been witnessed with other grades that have also been optimized in the non-pearlitic condition, the broach life is more dependent upon the tempering condition than the actual hardness level of the material.

Photomicrographs of the various tempered conditions are shown in Figure 11, and indicate that only subtle changes in the level of spheroidization of the fine carbides is revealed at maximum magnification under the light microscope. Whereas the microstructural changes are subtle under the light microscope, more significant changes to the level of carbide spheroidization are realized at higher magnification, which would account for the more dramatic shift in broach tool life. Figure 12 depicts the level of carbide spheroidization in two of the temper conditions — 1,200°F and 1,275°F — and it is evident that the carbide size has increased while the number of carbides has decreased with this level of increased tempering condition. As noted previously, this progressive carbide spheroidization with increasing tempering condition process appears to impact the tool wear characteristics to a greater extent than the hardness change in the material.

Discussion

The development of a laboratory broach testing machine has enabled a detailed exploration of the impact of workpiece material type and condition on the life of high-speed, steel broach tools, and the subsequent cost impact on profile broaching operations. Ferrite/pearlite steels were tested on this unit to determine the baseline broach tool wear rates. Results indicated that the carbon level of the steel had the primary impact on tool life. This is thought to result from the abrasive wear characteristics of the lamellar-type, pearlitic carbides on the tool cutting surface — and which increase exponentially as the carbon level and pearlite content increases. With decreasing levels of pro-eutectoid ferrite in the structure, the highly pearlitic structure rapidly abrades the tool. However, it has been discovered that these higher-carbon steels can achieve remarkable increases in broach tool life by avoiding the pearlitic structure altogether and developing a non-pearlitic, tempered bainite/martensite structure.

The non-pearlitic structure has been shown to achieve greatly increased broach life conditions over a similar range in hardness levels, as compared to the pearlitic conditions. These results allow for significant flexibility in steel selection and core hardness levels, while maintaining reasonable broach costs throughout. These structures develop an entirely different carbide structure, as compared to the pearlitic carbides. The fine, spheroidal-type carbides present in these tempered and non-tempered steels are much less abrasive to the broach tool and so provide greatly enhanced tool life. This is evident within a single grade in that as the tempering condition is increased, the level of carbide spheroidization progresses and positively impacts upon broach tool life to a much greater extent than the hardness level reduction. As such, utilizing this technology allows for achieving the lower tooth/profile cutting cost structure of the carburizing grades with the core properties and hardening characteristics required for induction hardened gears.

Conclusions

A laboratory broach test unit has been developed enabling the quantification of broach tool wear conditions that occur when cutting gear teeth in a variety of steel types and conditions.

A full characterization of baseline ferrite/pearlite steel conditions has been accomplished with this test, indicating an exponential effect of increasing carbon level on tool wear rates for this structure type.

A characterization of these same steels in an alternate, non-pearlitic condition, composed of ferrite and bainite and/or martensite at the same or higher hardness levels, shows that this material condition is much less abrasive on the broach tool, especially at higher carbon levels.

A study on the impact of tempering condition of a non-pearlitic SAE 5046 grade indicates that significant optimization of broach tool life can be accomplished by increasing the tempering level for this material type and condition.

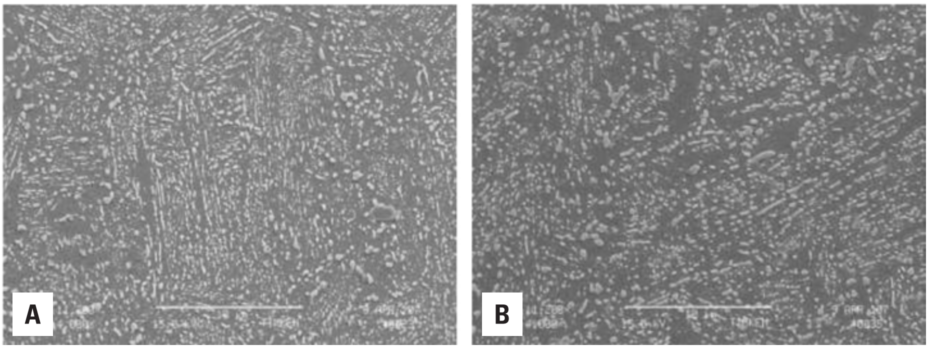

Figure 12 SEM photomicrographs of 5046 steels after tempering at a) 1,200°F temper and b) 1,275°F, picral etch.

The demonstrated improvements in tool wear characteristics for the non-pearlitic conditions allow for the attainment of the higher core properties and hardening response necessary for induction-hardened gears, at a cost level comparable to lower carbon, carburizing grades.

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Mike Burnett, a technologist at TimkenSteel, has been with the company for more than 30 years. He earned a bachelor's degree in metallurgical engineering at Purdue University and a master's in metallurgical engineering at Colorado School of Mines. Just this year, Burnett was awarded an American Iron and Steel Institute finalist medal for his "Improved Broaching Steel Technology" paper.

Influence of Hobbing Tool Generating Scallops on Root Fillet Stress Concentrations

Benjamin S. Sheen and Matt Glass

This paper discusses a specific example regarding parallel-sided splines manufactured with a finish hobbing process and their effects on generating root fillet stress concentrations. To estimate the value of the stress concentrations, finite element analysis (FEA) was conducted on the components for two unique hobbing tool designs. The FE results are compared to actual component field service histories.

Introduction

While designing gear and spline teeth, the root fillet area and the corresponding maximum tensile stress are primary design considerations for the gear designer. Root fillet tensile stress may be calculated using macro-geometry values such as module, minor diameter, effective fillet radius, face width, etc. However, the cutting tool geometry and manufacturing process parameters can create microgeometry features, which can greatly influence the actual tensile stress in the root fillet area.

This paper will discuss a specific example regarding parallel-sided splines manufactured with a finish-hobbing process (Fig. 1). Hobbing is a tooth generating process, and the root fillet geometry is solely determined by the geometry of the hob cutter rack form. Other hob cutter features — such as the number of threads and number of gashes — also influence the generated hob scallops in the fillet area. For this discussion, stress concentrations caused by root fillet generating scallops were observed on shafts.

To estimate the value of these root fillet stress concentrations, two methods were used: an ISO 6336-3 stress correction factor for notches in fillet areas and a finite element analysis method. Both methods for estimating the stress correction factor were performed on components for two unique hob tool designs. FEA results will be used to verify the ISO 6336-3 method can be applied to parallel-sided splines.

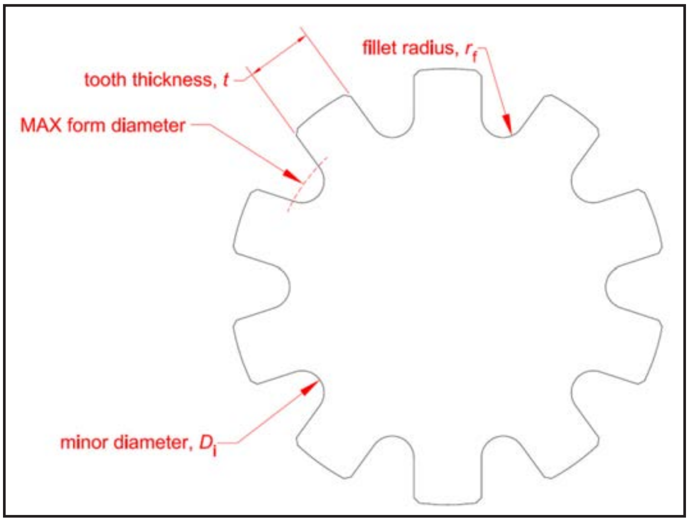

Figure 1 Parallel-sided external spline.

Background

The scope of this study is a parallel-sided spline that is finish-hobbed prior to heat treatment. Multiple applications over a long period of time have proven the spline's design intent and demonstrated reliability. However, there was an observed difference between different suppliers in terms of demonstrated reliabilities within specific vehicle applications. Components from all suppliers met the drawing requirements in terms of specified spline geometry, heat treatment, and other dimensional requirements. To further explain the reliability differences between suppliers, this project was initiated.

For one particular part number that uses this parallel-sided spline specification, multiple samples from different suppliers were obtained. Supporting documentation relative to the cutting tool design for each supplier was obtained as well. After comparing the different samples and looking for differences between the hardware and cutting tool information, it was observed that the generated fillet radius was different between suppliers at the micro-geometry level. All suppliers met the drawing requirement of a minimum fillet radius (*rf*) at a macro-level. In particular, the height and radius of the hob tool generating scallops are unique between the two samples. A comparison of a root fillet area for Supplier A and Supplier B is shown below in Figure 2.

Additional clues for the difference between reliabilities were revealed with metallurgical examination. Crack origination points were found within the fillet area. Furthermore, the initiation points corresponded to small radii related to the hob generating scallops.

Analysis

To quantify the effect of the hob generating scallops, an initial estimation of the increase tensile stress was made per ISO 6336-3:2006, section 7.3 — "Stress correction factor for gears with notches in fillets."

$$Y_{Sg} = \frac{1.3\ Y_S}{1.3 - 0.6\sqrt{\frac{t_g}{\rho_g}}} \tag{1}$$

Where:

t_g defect depth (mm)
ρ_g defect radius (mm)

$Y_S = 1.0$ as the baseline tensile stress
Y_{Sg} stress correction factor

For the supplier comparisons, initial values for stress correction factor Y_{Sg} were calculated based on root scans of multiple hardware samples. The geometric measurement of hardware was taken directly from the printed root scan, and values for defect radius ρ_g and defect depth t_g were drawn. Generating scallops were present and consistent along the entire axial length of the spline. A circle was drawn with a template and overlaid with the defect radius for simplicity, and this circle diameter is considered as $2 \times \rho_g$. An example of the printed root scan and measurement of the geometry is shown in Figure 4.

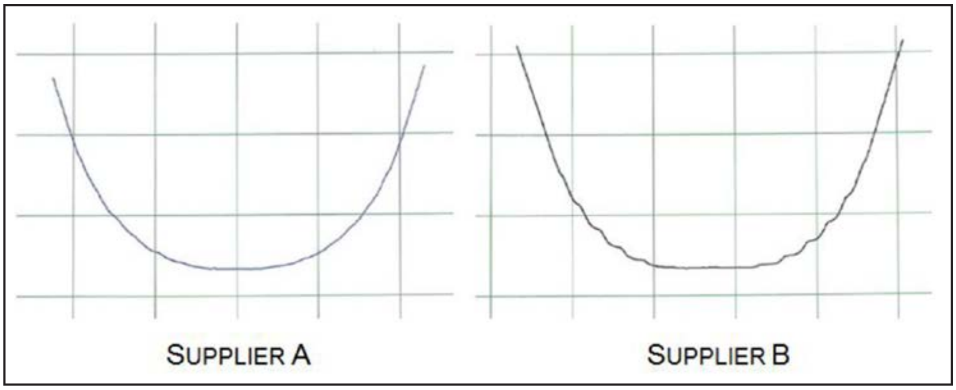

Figure 2 Measured fillet radius comparison.

After proper scaling from the printed output, the values for Y_{Sg} were calculated (Table 1).

Table 1 ISO 6336-3 stress correction factor (Y_{Sg}) from measured hardware.

	Y_{Sg}
Supplier A	1.10
Supplier B	1.31

Initial calculations of the ISO stress concentration factor, calculated from measured hardware, directionally correlate to the experienced reliabilities of known field hardware.

For correlation to each supplier's hob tool design, the ISO 6336 method was used with CAD design data per the hob tool manufacturer's roll-out. The CAD data was assumed as nominal design data for the hobbing tools themselves, and each hob tool vendor directly supplied the appropriate "roll-out" geometry for the workpiece. These CAD roll-outs were then used to estimate values for the defect depth, defect radius, and defect location for each of the suppliers (Fig. 5).

A summary of the stress correction factor calculated by CAD hob roll-out geometry is shown in Table 2.

Table 2 ISO 6336-3 stress correction factor (Y_{Sg}) from hob tool CAD model.

	Y_{Sg}
Supplier A	1.12
Supplier B	1.51

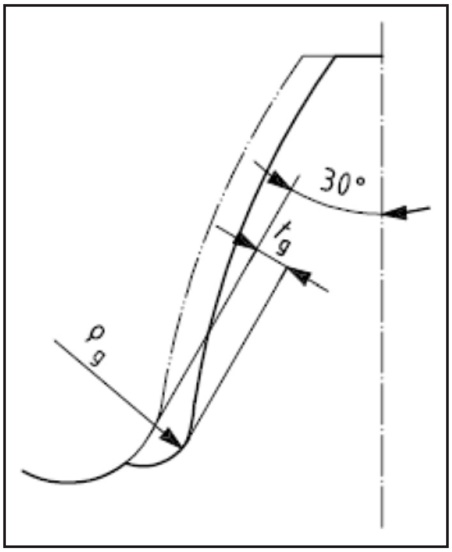

Figure 3 ISO 6336-3 fillet notch geometry details.

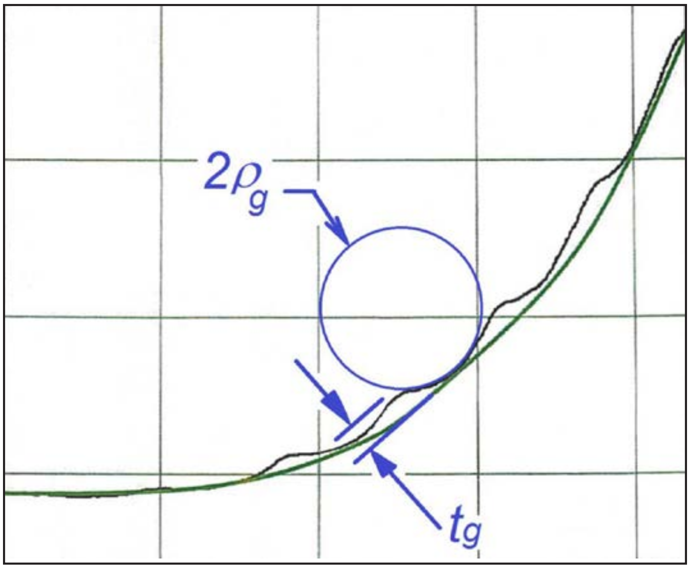

Figure 4 Root scan with defect measurement.

The correlation between actual measured hardware and theoretical CAD geometry leads to similar trends — but not an absolute agreement. For Supplier A, the Y_{Sg} value calculated from the hob tool CAD geometry is slightly higher (+2.2%) than direct hardware measurements. For Supplier B, however, the Y_{Sg} value calculated from the hob tool geometry is much higher (+ 15%) than the direct hardware measurements. Actual measured hardware includes effects of the carburizing process, shot cleaning/blasting, and any manufacturing variation(s) that may explain the difference between theoretical and measured fillet geometry.

The ISO methodology, however, lacks the ability to accurately account for the fillet geometry in the following ways:

Multiple fillet notch features, such as hob generating scallops

Any notch location other than 30 degrees from the tooth centerline

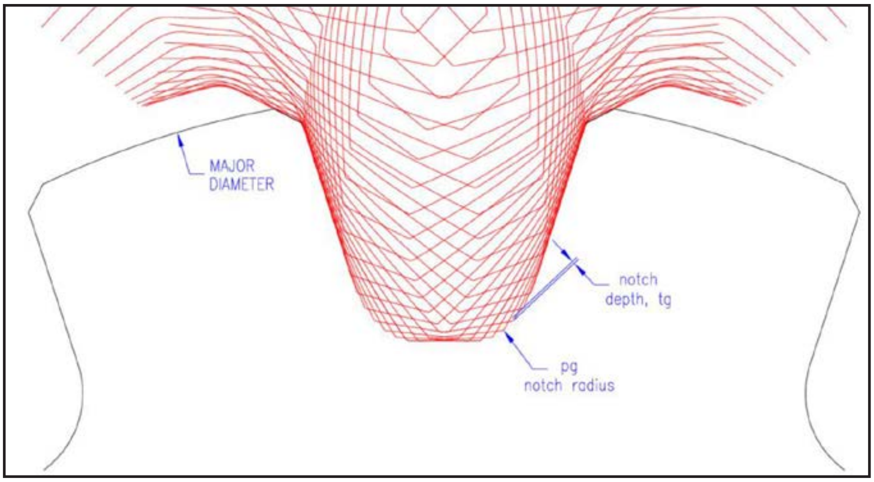

Figure 5 Example: hob cutter rollout, per CAD.

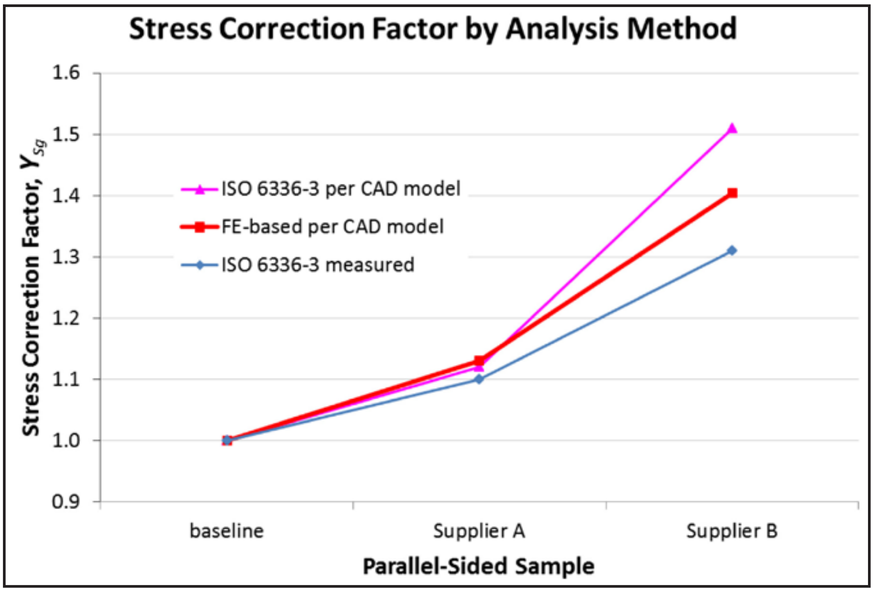

Figure 6 Stress correction factor as function of analysis method.

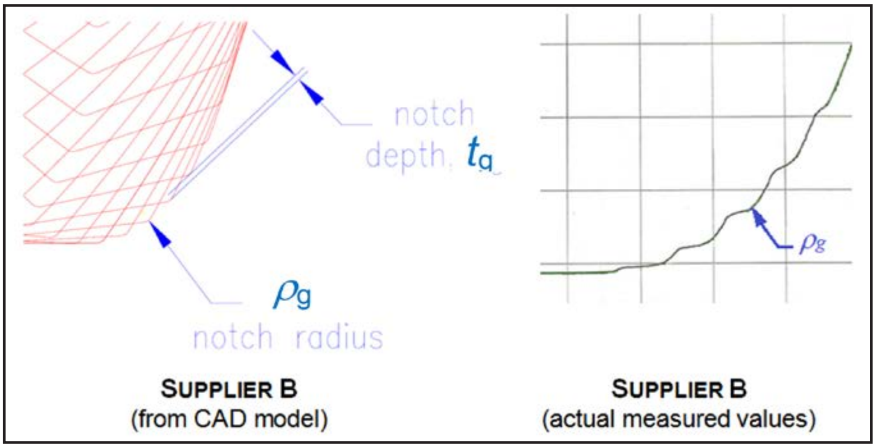

Figure 7 Supplier B fillet details.

To account for these two factors a different approximation methodology is needed. A finite element (FE) method was chosen to represent the geometry for the as-hobbed condition, and the geometry inputs for this FE model were taken directly from the hob tool manufacturer's CAD rollouts. The FE analysis was completed for hob tool designs from Supplier A and Supplier B and compared to a baseline FE model without generating scallops. In this way an FE-based stress correction factor could be calculated as a variation above a baseline tensile stress state. The results of the calculated stress correction factors are shown in Figure 6.

While comparing the three different analysis methods, it can be seen that there is good agreement among stress correction factors for "Supplier A" (within 3%). The stress concentration factors for Supplier A are acceptable in terms of component reliability.

However, for "Supplier B" samples the stress correction factor Y_{Sg} varies when comparing the measured parts and CAD-based geometry. This variation is driven primarily by the defect radius ρ_g, since the defect depth t_g of the measured part correlates within 5% of the CAD model. As stated previously, the actual measured hardware includes effects of the carburizing process, shot cleaning/blasting, and manufacturing variations such as hobbing tool wear, which may influence the measured fillet geometry (Fig. 7).

Stress correction factors calculated with the ISO and FEA methods diverge for the "Supplier B" samples, as Y_{Sg} values increase above 1.13. For Supplier B samples the ISO 6336-3 method over-predicts stress values by 8% when compared to the FE results. Efforts to estimate the stress concentration factor using other methods were evaluated, but found to be overly conservative and did not correlate to observed field service histories (Refs. 2–3). Additionally, the referenced notch geometries and locations were not representative of the specific geometry.

Improved State

To reduce the stress concentration factor due to hob generating scallops, the approach was to re-design the hobbing tool to make the individual generating scallops smaller in height and to increase the radius of the notch. Specifically, the generating scallops can be made shorter by simply having more of them: i.e., increasing the outside diameter and adding more gashes to the hob tool. Reduced tool life can be a concern due to the reduced tooth length, but the added number of gashes adds more teeth to the tool.

Overall, the effect on tool life for the new hob design yields a tool life improvement of approximately 20%. Specifically, the number of gashes of the hob tool was increased 1.5x by increasing diameter and reducing tooth length.

Increasing the tip radius of the hob tool must be done while still preserving the maximum form diameter of the workpiece (Fig. 1). Feasible hob design options were considered by working with a trusted cutting tool supplier, and the end result is a tool radius that reduces the stress concentration factor while still meeting the maximum form diameter requirements of the workpiece (Fig. 8).

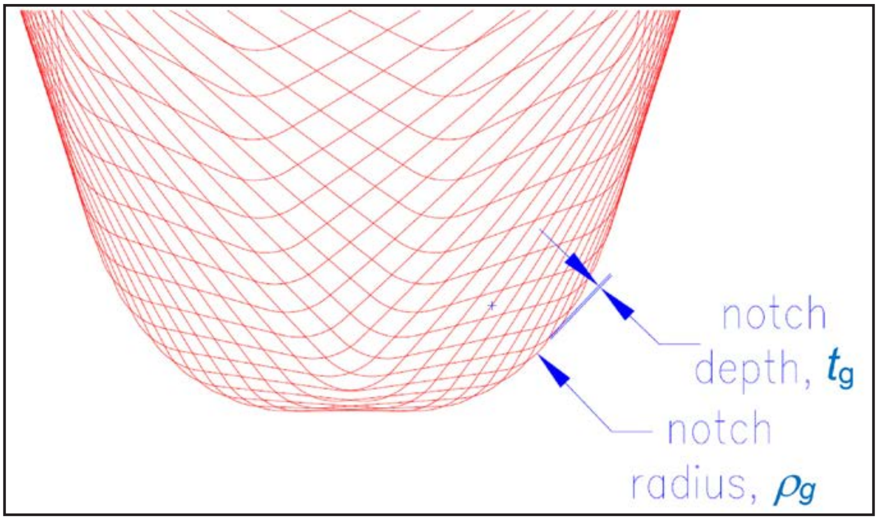

Figure 8 Improved state fillet geometry.

For the improved state, the stress correction factor was re-calculated for Supplier B using both the ISO and FE methods. Overall, the stress correction factor was reduced to the point that it is now equal or superior to the value for Supplier A. For Supplier B, the stress correction factor Y_{Sg} was reduced by solely revising the hob tool design. The Y_{Sg} values displayed in Figure 9 are based on CAD rollouts for each supplier's hob tool design and the FE analysis method.

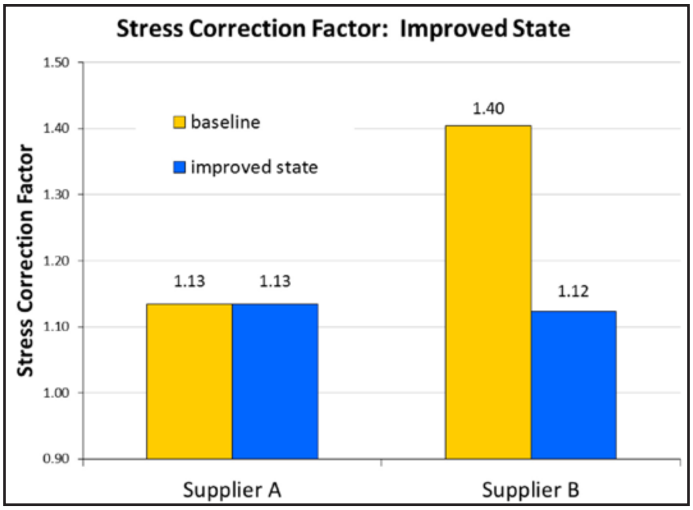

Figure 9 Improved state stress correction factor.

Conclusion

In the design and production of gear and spline teeth, deliberate and clear definition of the root fillet area can prevent unintended variation in component reliabilities. Simply stated, dimensions like minor diameter, maximum form diameter, or equivalent fillet radius may meet the design envelope intent, but it leaves fillet geometry options open for other variations to be produced — some to the benefit and others to the detriment of component reliability.

For this specific case study, the effects have been shown of two different hob cutter designs on the ISO 6336-3:2006 stress correction factor Y_{Sg} for a parallel-sided spline. Furthermore, a stress correction factor was also determined via the use of FE methodology in an attempt to establish correlation between the ISO and FE methods. The FE method further refined the ISO method by including multiple hob generating scallops in their various fillet area locations. It is also shown that for values of Y_{Sg} above 1.15, the predicted stress values using FEA are lower than the ISO predictions.

ISO 6336-3:2006 is conservative when stress correction factor $Y_{Sg} > 1.15$

This conservative result may or may not be the same when applied to an involute spline

In summary, the fillet generating scallops can be optimized by deliberate hob tool design, such that a stress correction factor $Y_{Sg} = 1.12$ can be achieved.

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3. Ristić, Daniela. "Numerical Stress Concentration Analysis of a Driven Gear Tooth Root with Two Fillet Radius," *Scientific Technical Review*, Vol. LIX, No. 3–4, 2009.


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Hybrid Hertzian and FE-Based Helical Gear-Loaded Tooth Contact Analysis and Comparison with FE

Paul Langlois, Baydu Al and Owen Harris

A loaded tooth contact analysis model for helical gears combining an FE representation of bending and base rotation stiffness of teeth with a Hertzian contact formalism for contact stiffness is presented. Comparison with full 3-D FE contact analysis and the tooth contact analysis program LDP is made. Correlation with the 3-D FE contact analysis is good. For the low-helix angle gear pair under consideration, it is shown that it is important to include the phenomenon of extended contact at the tips of the gear teeth in such hybrid tooth contact models for correlation with the FE analysis at high loads. It is further shown that LDP underestimates the mean transmission error for helical gears when compared to the FE analysis results. A possible cause of this underestimation is presented. A second helical gear example is presented with comparison with results available in the literature.

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 have been discussed in the literature for many years. A number of early review articles include (Refs. 1–3). A number of commercial tools are available that perform such calculations. These specialized tools are used extensively within the industry due to their fast setup and analysis times. While similarities between tools are significant, they differ in implementation and significant differences in results can be found. The most important 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.

Performing loaded tooth contact analysis in a general FE package requires a very fine mesh in order to accurately capture the Hertzian deflections local to the contact, and therefore are 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 as a benchmark analysis providing a means of validation of the assumptions made within specialized gear tooth contact analysis models.

In this paper we present a hybrid FE and Hertzian-based loaded tooth contact model — with particular emphasis on the requirements for helical gears — and discuss its relation to other models presented in the literature. We perform an extensive comparison with a loaded tooth contact calculation using a commercial FE package showing good correlation for TE results. Further comparison is made with another well-known specialized loaded tooth contact analysis tool — *LDP* (Ref. 4).

Methodology

Specialized loaded tooth contact analysis model. The following assumptions are made within all calculations in this study:

- The effect of friction is neglected
- The effect of the lubricant is not considered
- Dynamic effects are not considered

A further common assumption is made in the specialized gear tooth contact analysis discussed here:

- Deflections are sufficiently small that the contact points and normals do not move from their theoretical no-load locations

Where the effect of extended tip contact is being considered, potential contact points along the tips of the teeth are included that are not in contact under no-load conditions. This fourth 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.

The model presented is based on that outlined in (Ref. 5). Inputs include torque, gear macro and microgeometry (flank modifications) and misalignment at the gear mesh. The analysis is quasi-static, performed at a specified number of steps through the mesh cycle. At each step, unloaded potential contact lines are calculated from the gear macro geometries, relative locations and rotations. Potential contact lines are divided into strips (Fig. 1) and contact points expressed in a 2-D coordinate system as distance along face width and roll angle.

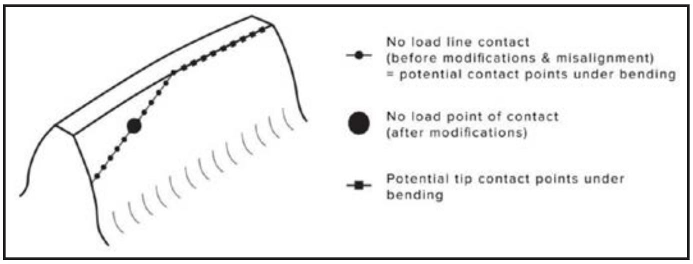

Figure 1 Potential contact line for helical gear tooth with flank modifications and extended contact along gear tip.

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

At any point, k, in the proposed contact zone, the sum of elastic deformations and initial separations must be greater than or equal to the rigid body approach.

$$U_k^1 + U_k^2 + \varepsilon_k - \alpha \geq 0 \qquad (1)$$

Where:

1, 2 label the pinion and wheel respectively

U_k^i Is the elastic deformation of gear i at point k
$\mathcal{E}_k$ Is the initial separation at point k
α Is the rigid body approach

The sum of all the forces acting on the discrete points of contact must balance with the applied load normal to the surface.

$$\Sigma_k F_k = F \quad (2)$$

Where:
F_k Is the normal force at strip k
F Is the total applied normal force due to the applied torque

The formulation of the elastic deformations used in this study is discussed later in this paper. Equations 1 and 2 are solved for F_k, U_k^i, and α, giving the load distribution across the contact lines the elastic deformations at each contact point pair and the rigid body approach.

Helical gear-specific considerations. Some care needs to be taken when formulating the contact problem for helical gears. For spur gears the transverse and normal planes coincide and the components of Equations 1 and 2 are all expressed in the transverse plane normal to the flank profile.

Transmission error is usually expressed as a linear dimension in the transverse line of action

$$TE = r_b^1\theta^1 - r_b^2\theta^2 \quad (3)$$

Where:
r_b^i Is the base radius of gear i
θ^i Is the rotation of gear i

For spur gears the rigid body approach α in Equation 1 is equal to the linear transmission error (TE) in Equation 3.

For helical gears the forces at the contact lie normal to the helix. Care must be taken in which direction the elastic deformations, initial separations and rigid body approach are expressed in and the relationship between the rigid body approach and transmission error. Each component in Equations 1 and 2 can be expressed and solved in a direction normal to the flank and normal to the helix. The rigid body approach, defined in the normal plane, is related to the transmission error, defined in the transverse plane (Fig. 2).

$$\alpha = TE\cos\beta_b \quad (4)$$

Where:
β_b Is the base helix angle

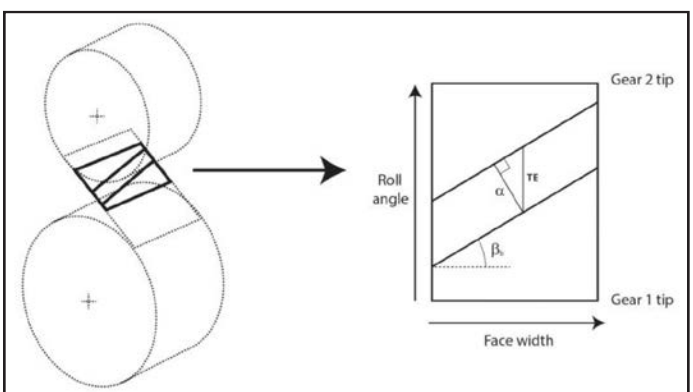

Figure 2 Relationship between TE and normal rigid body approach (α) shown in the plane of action extended off line-of-action contact at gear tips.

Extended off-line-of-action-contact at gear tips. For specialized gear tooth contact models the potential contact points are often limited to the no-load contact points for the corresponding conjugate gears before microgeometry and misalignment are applied (Fig. 1). However, due to the deflections under load (and manufacturing errors), the tips of the teeth may come into contact at points which nominally would not be in contact (those indicated by a square in Fig. 1). Such contact is known in the literature as "off-line of action contact," "corner contact" or "contact outside the normal path of contact." The effect is to increase the operating contact ratio, but also to significantly raise contact stresses due to non-involute contact; this is the main motivation for applying tip relief modifications to gear flanks.

Saeger (Ref. 6) discussed the separation of gear teeth at approach and recess and the possibility of corner contact. Steward (Refs. 7–8) provides a calculation of the off-line-of-action transmission error, together with the corresponding meshing points. Lin et al (Ref. 9) and Singh (Ref. 10) provide equivalent expressions to those of Steward. Munro (Ref. 11) discusses a reformulation of the expressions of Lin et al, together with a number of approximations. The focus of all of these studies is spur gears. Although some mention is given to helical gears, there is little demonstration of the effect of extended tip contact for helical gears on transmission error.

In order to include the effect of extended tip contact in our model, we calculate the potential points of contact in face width and roll angle space and include them in the contact zone points of Equations 1 and 2. The gap between the contacting flanks at these points is calculated according to (Ref. 10) and included in the initial separations of (Eq. 1). The expressions are relatively lengthy and are thus omitted here for brevity.

Hybrid Hertzian and FE-based tooth contact analysis. In the class of models considered here the elastic deformations in Equation 1 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.

$$U_k^1 + U_k^2 = (C^1F)_k + (C^2F)_k + h_k(F_k) \quad (5)$$

Where:
C^i Is the FE compliance matrix relating the contact points on gear i in the direction normal to the flank
F Is the vector of forces normal to the flank
$h_k(F_k)$ Is the Hertzian deflection normal to the flank at point pair k as a function of the normal load F_k at k

One of the earliest hybrid FE and Hertzian based gear tooth contact models was developed by Vedmar (Ref. 12). Steward (Refs. 7–8) developed such a method for wide face width spur gears, which was subsequently developed further for helical gears. Prabhu (Refs. 13–14) developed a similar method that was the basis of the thin-rimmed option in *LDP*. This option can also be used for solid gears. It is this option that is the focus of comparison here, as it can be considered the most comparable to our models and FE.

In order to calculate the compliances C^i an FE model of each gear is used. The FE model needs to represent the gear geometry in sufficient detail to capture the bending stiffness and base rotation of the teeth. Out of necessity, and given the computing power at the time, Vedmar (Ref. 12) and Steward (Ref. 7) ran a discrete set of FE models and performed extensive curve fitting on the displacement results in order to calculate equations for the bending compliance for utilization in their tooth contact models. Both used the accurate gear geometry for their FE models; however, both were based on gears using a standard basic rack with no addendum modification. Their methods may be less applicable to non-standard gears. Vedmar considered only a single tooth model and therefore did not include the compliance due to loads on adjacent teeth. Steward included multiple teeth and this compliance was included. Vedmar considered the rim grounded approximately two modules below the root; therefore the gear body deflection was mostly omitted. Steward performed a study of the effect of the gear body compliance with different grounding diameters at the gear bore.

LDP uses an FE model with multiple teeth — but with a tapered straight flank tooth and no fillet radii (Ref. 13). A different FE model is used for each geometry, and so no curve fitting is performed. Compliance with respect to contact points that do not coincide with the finite element mesh are calculated via interpolation using the element shape functions.

In our implementation, the FE mesh for each gear is generated from the exact gear macrogeometry, with no curve fitting of FE results. The FE mesh for the gear is generated using the same code that generates the full FE tooth contact analysis meshes to be discussed later. Via this FE representation, using multiple teeth, the compliance due to loads on adjacent teeth is naturally considered.

One important consideration with the compliance calculated from the FE model is the removal of any "near field" displacements local to the applied loads. When a point load is applied to an FE model node, a local spiked displacement is seen at the node of application. Further, the contact stiffness in these models is represented by an analytical Hertzian model and so these local displacements must be removed from the compliance. Steward and *LDP* (Refs. 7, 13) take the deflection at a corresponding point on the centerline of the tooth, when calculating the FE compliance, via projection of the point normal to the flank in the transverse plane. Vedmar (Ref. 12), in contrast, calculates the compliance with a second FE model where a datum surface a certain distance within the tooth is grounded. The compliance is then calculated by taking the compliance of the original FE model and subtracting the compliance from this model with datum surface grounded. We use this method within our model with the tooth centerline as the datum.

In our model 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. It is this stiffness with respect to the discretized contact points C^i that is used in Equation 5.

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 tooth contact analysis re-run without having to recalculate the bending stiffness.

The local contact between potential contact points $h_k(F_k)$ in Equation 5 is considered as a line contact between cylinders. The compression of each tooth between the point of load and the centerline is also included, as this is removed from the stiffness represented by the FE model. In our implementation the approach of Weber (Refs. 15–16) was chosen due to the conclusions of Cornell (Ref. 17) that the Weber method is almost universally used for gear contact and was found to give more consistent results than two other methods investigated by Cornell. Steward (Ref. 7), Vedmar (Ref. 12) and *LDP* (Ref. 13) all use variations of Weber's expression.

If the gears have the same Young's modulus and Poisson's ratio, Weber's expression for the Hertzian deflection normal to the flank at point pair k is given by:

$$h_k(F_k) = \frac{4F_k(1-\nu^2)}{\pi l_k E}\left[\ln\left(\frac{2\sqrt{h_{1k}h_{2k}}}{b_k}\right) - \frac{\nu}{2(1-\nu)}\right] \tag{6}$$

Where:

l_k Length of strip k
ν Poisson ratio
E Young's modulus
h_{ik} Sear length for gear i at strip k; given by the length of a line normal to the gears profile at point k from the centerline of the gear
b_k Half of the Hertzian contact length at strip k

$$b_k(F_k) = \sqrt{\frac{8F_k(1-\nu^2)\,r_{1k}r_{2k}}{\pi l_k E\,(r_{1k}+r_{2k})}} \tag{7}$$

Where:

r_{ik} Radius of curvature on gear i at point k

Figure 3 gives a flow diagram illustrating the main steps in our model.

Loaded Tooth Contact Analysis Model in FE

For validation of our hybrid model, loaded tooth contact analysis was performed in *ANSYS*. Code was written to set up the analysis automatically via a script using the *ANSYS Parametric Design Language* (*APDL*). The geometry was specified in SMT's *MASTA* software (Ref. 18). An algorithm was written to define the FE mesh node locations in the *APDL* script directly from the geometry, avoiding issues which can arise if the geometry is constructed via a CAD model and meshed using automatic meshing tools. Microgeometry flank modifications were included by modifying the node positions before writing them to the script. The algorithm generates a 3-D mesh for a single tooth section first. This mesh 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/transforming the node positions.

An algorithm was written to associate the node numbers to element definitions in the script. Solid linear, 8-node hex elements were used for the mesh using *SOLID45* elements. Although *SOLID45* elements are now considered legacy elements, the accuracy of results was checked against models with the now recommended *SOLID185* elements. Further commands

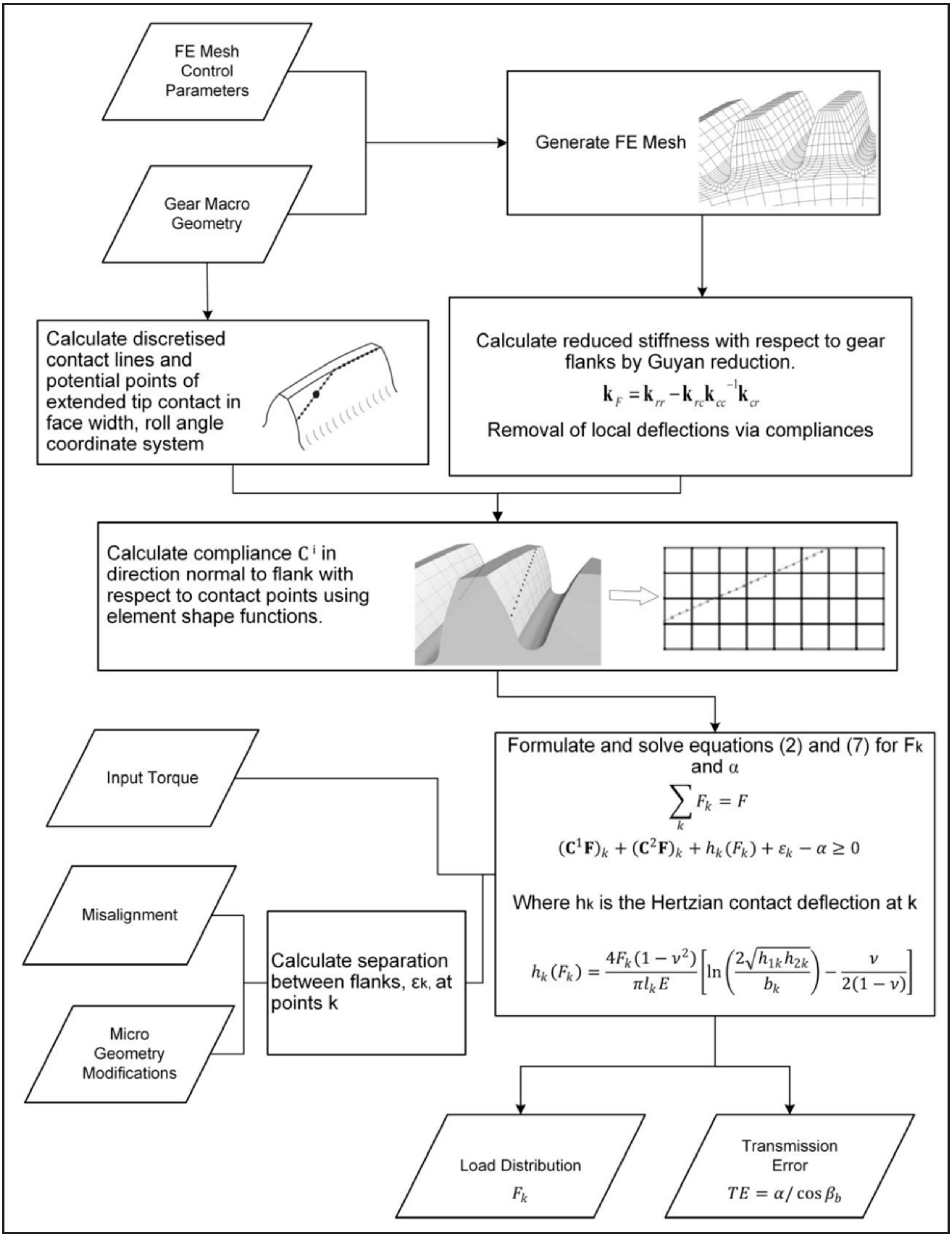

Figure 3 Flow diagram showing main steps in authors gear tooth contact analysis.

were included in the script to translate the wheel and rotate both gears to a meshing position. Backlash was removed by a further rotation of the pinion, as it is not included in the specialized gear tooth contact calculations used.

In order to define the surface to surface contacts between teeth, all nodes on a flank were associated with a named component within the *APDL* script. The potential contacting teeth were calculated given the phase of mesh and the contact ratio. General surface-to-surface contact elements — *TARGE170* and *CONTA173* — were defined between them directly within the script, using the nodal components for these teeth. The Lagrange method was used to maintain the contact constraints purely via Lagrange multipliers; as such, no penetration between contacts was allowed.

Figure 4 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 — *TARGE170* and *CONTA175*. Zero displacement boundary conditions were applied to all degrees of freedom, except rotation about the pinion axis, at the pilot node.

Commands were included within the *APDL* script to rotate

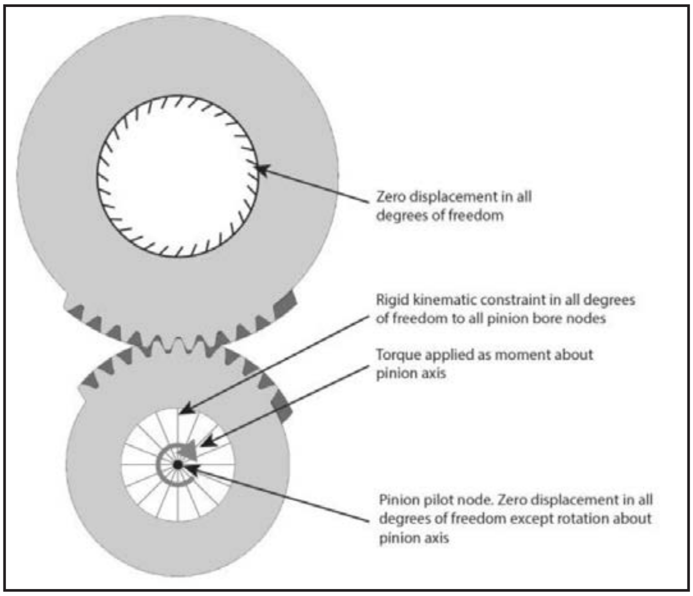

Figure 4 A schematic diagram showing displacement and force boundary conditions applied to FE model.

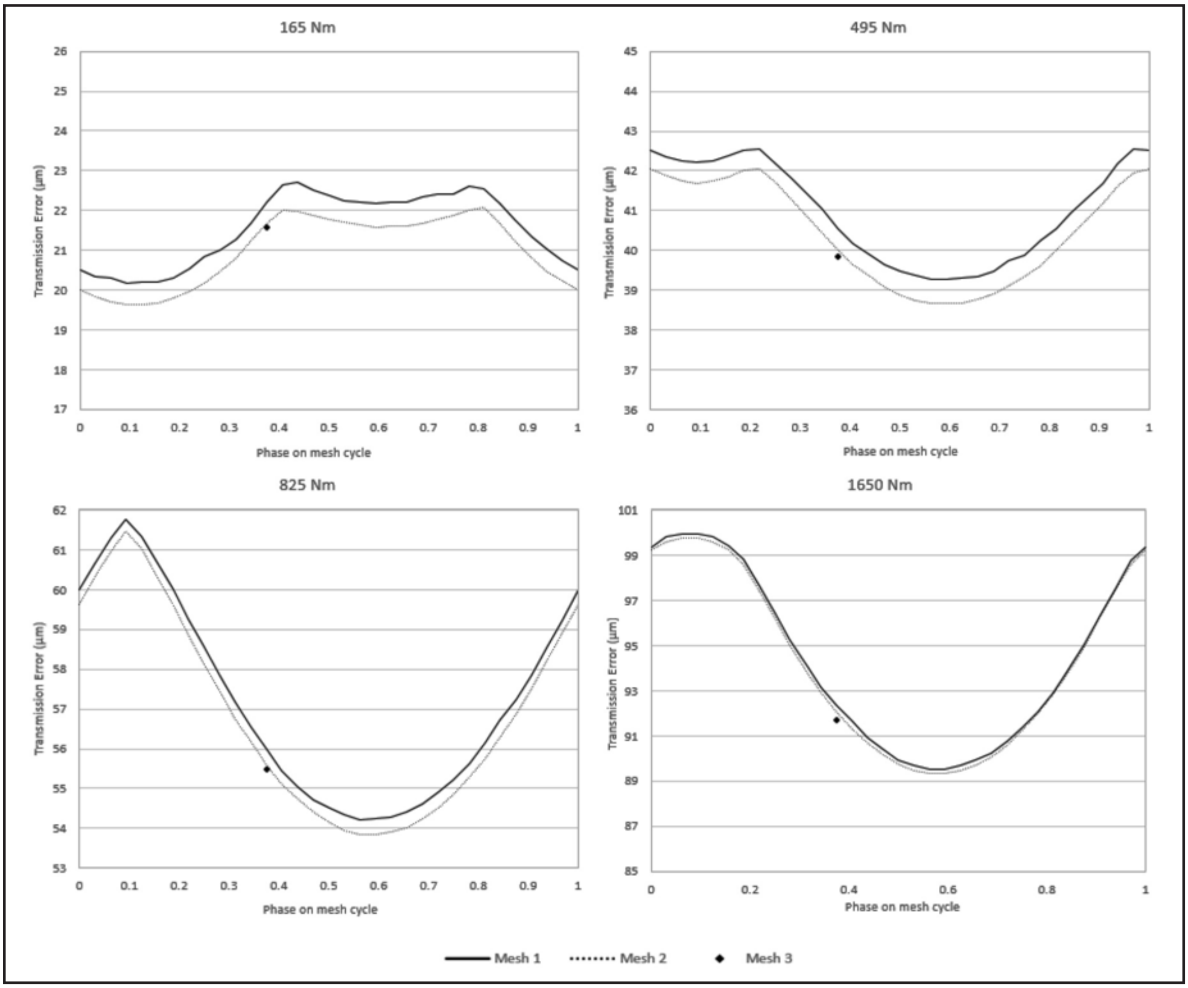

Figure 5 Transmission error results for input torques of 165 Nm; 495 Nm; 825 Nm; and 1650 Nm for Meshes 1, 2 and 3.

the mesh through one base pitch rotation in 32 equal steps. An *ANSYS* model file was saved at each mesh position.

Finally, a static analysis was run at all 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. Geometric non linearity was included in the analysis. Force convergence was checked.

A mesh refinement study was performed for all results. Figure 5 displays results for the transmission error calculated by *ANSYS* for a range of loads for the example introduced later.

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 shown in Figure 5, the mesh was refined in all areas with more refinement at the contacts. Figure 6 shows the contact results for a single phase of the mesh cycle, for the 3 meshes used, at the 1,650 Nm load.

The results in Figure 5 show that the original mesh, Mesh 1, actually captures the deflections and therefore the TE to a sufficient level of accuracy for torques 825 Nm and higher. For lower torques, Mesh 2 results are presented throughout the rest of this study.

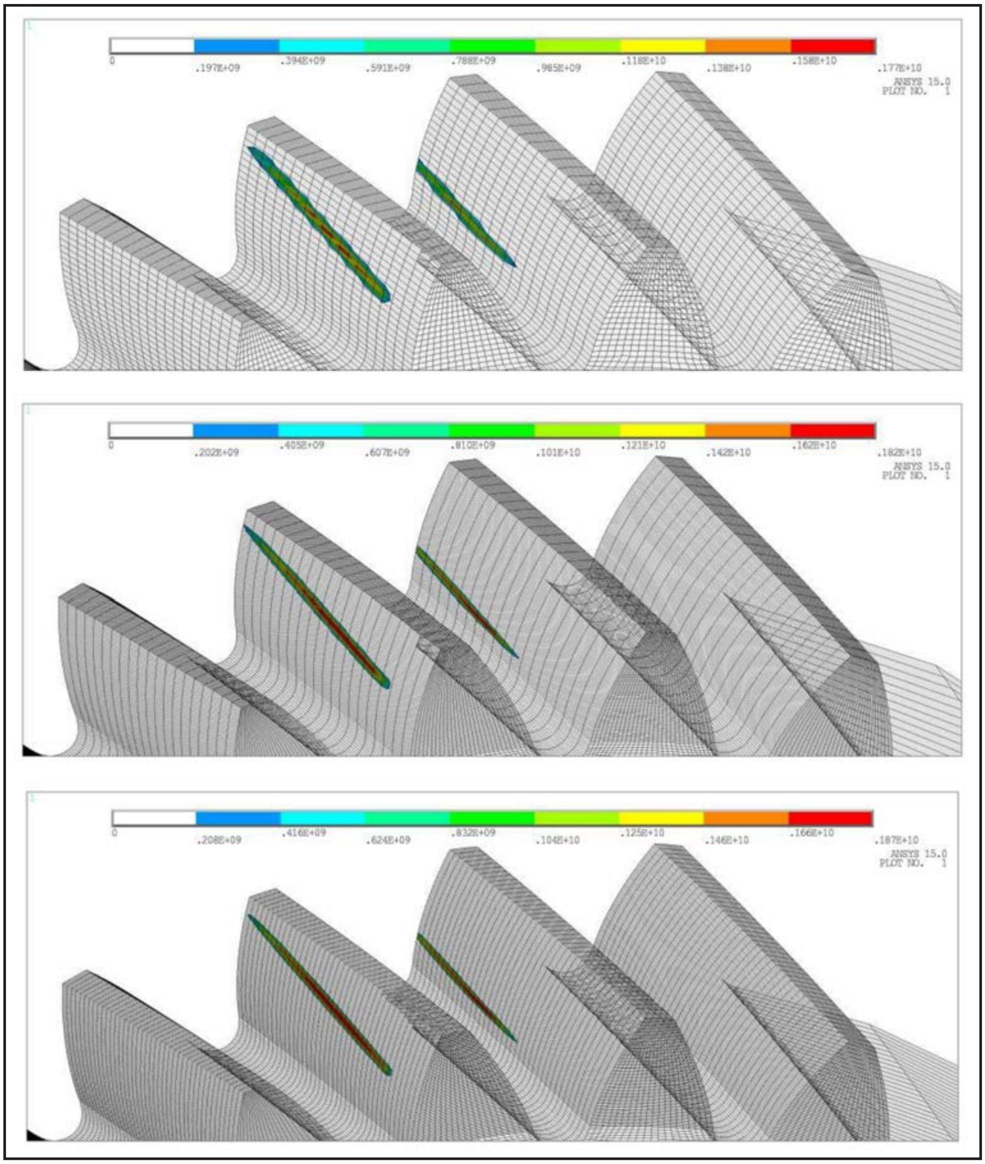

Figure 6 Contact results showing contact stress for 3 meshes considered at single roll angle of 1,650 Nm load case; from top to bottom — Mesh 1, Mesh 2, Mesh 3.

Although dependent on the computing resources available, it is interesting to note the relative run times for the 3 meshes considered. Using a 64-bit system with Intel Xeon Processor E5-2667 @ 2.90 GHz, utilizing 4 of the 6 cores and 128 GB of RAM for 32 mesh positions, the analysis for Mesh 1 ran in approximately 15 hours. Mesh 2 ran in approximately 96 hours, while Mesh 3 took approximately 20 hours to run a single step. This shows why such FE analyses cannot be used as design tools, and why specialized, gear tooth contact models are used extensively in industry.

Results

Helical Gear Pair

Example 1. An example helical gear mesh from a truck application was chosen as our test case. The geometry details for the gear set are given in Table 1.

The microgeometry design, as measured, was considered in all models and analyses. In all analysis models, it was checked

Table 1 Helical gear pair data for example 1.

	Pinion	Wheel
Number of Teeth	29	45
Normal Module (mm)	3.566	
Normal Pressure Angle (degrees)	22.5	
Helix Angle (degrees)	15.778	
Face Width (mm)	30.1	28
Face Width Offset (mm)	2.481	
Centre Distance (mm)	136 501	
Tip Diameter (mm)	116.17	170.97
Root Diameter (mm)	99	154
Cutter Edge Radius (mm)	1.394	0.937
Bore Diameter (mm)	51	78.7
Transverse Tooth Thickness at Reference Diameter (mm)	6.06755	4.86105
Transverse Contact Ratio	1.4915	
Overlap Ratio	0.6195	

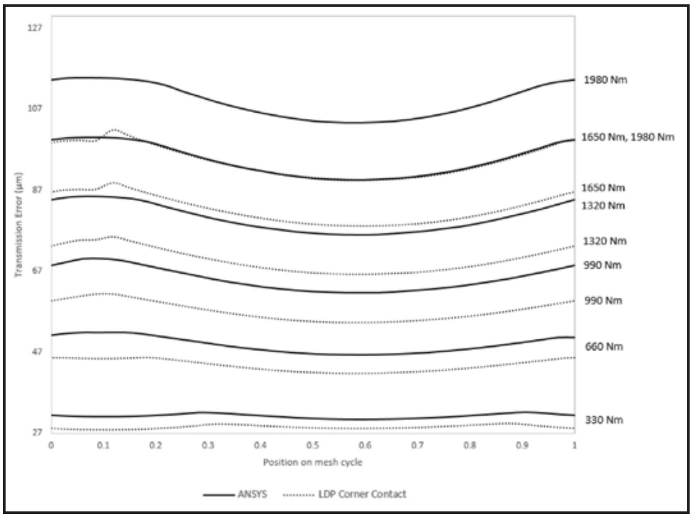

Figure 7 **Harris map of calculated transmission errors (TEs) from ANSYS and LDP.**

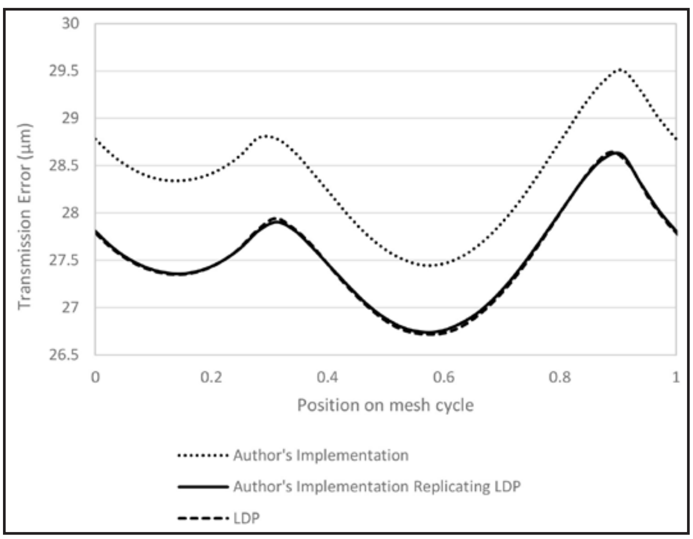

Figure 8 **Calculated TE at 1,650 Nm load considering only the Hertzian contact deflection from LDP and the authors' model.**

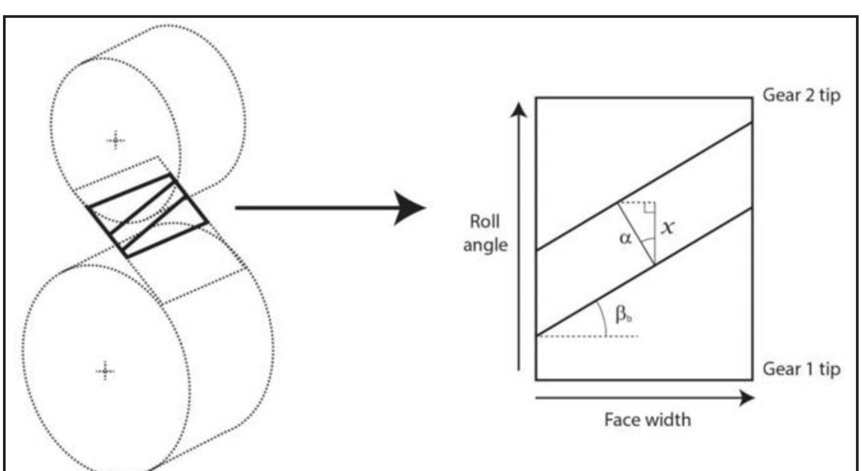

Figure 9 **Tangential component of normal rigid body approach shown in the plane of action.**

that the relative starting location of the gears was the same. This was done by running the analysis at low load. It was seen that at very low load, as expected given the analysis set up, the minimum transmission error was given by the minimum combined microgeometry modifications within the meshing regions of the flanks, 2.8 μm. This confirmation means that the results of mean transmission errors for all loads should be comparable.

Comparison of LDP and FE. We begin by presenting the FE results as compared to those of a corresponding *LDP* model (*LDP Version 4.6.1* was used for all results within this study). The *LDP* calculations were done using a mesh close to their default values. Unfortunately, a mesh refinement study was not feasible due to limitations of the program. Results from *LDP* are presented with the option for including extended tip contact. Figure 7 presents a Harris map of TE for a range of loads.

It is clear from the results that there is a difference in mean TE between *LDP* and *ANSYS* for all loads, suggesting that *LDP* may be overestimating the mesh stiffness. A possible explanation for this difference is given in the following section.

Comparison of LDP and our hybrid FE and Hertzian models. In order to understand the difference seen in results between *LDP* and FE, we aimed to implement a method that could reproduce the *LDP* results.

To simplify the problem we first considered the calculation ignoring the effect of the bending deflection, i.e. only including deflection due to Hertzian contact. The contact deflections can be isolated in *LDP* by running their tapered plate analysis setting factors for the influence of the tapered plate to 0.

Figure 8 shows the transmission error for the 1650 Nm load case considering the effect of contact deflections only. It is observed from the figure that there is again a significant difference in mean TE between *LDP* and our models. The same behavior was seen at all loads. Figure 8 also shows the results where we do the calculation, as we believe *LDP* is. It is clear that the results are almost identical.

The modifications made in the model "Authors' implementation replicating *LDP*" were made after further investigation of the differences seen. It was identified that a possible explanation lies in the way in which the conversion from normal to transverse plane is done.

In particular, it appears that *LDP* uses the tangential component of the normal rigid body approach as the TE (Fig. 9) i.e.:

$$x = \alpha \cos \beta_b \tag{8}$$

From Figures 2 and 9 this does not appear physically justified and as a result there is a factor of $(\cos \beta_b)^2$ difference between the tangential rigid body approach x (which *LDP* appears to use for the TE) and the TE given by Equation 4.

$$TE = \frac{x}{(\cos \beta_b)^2} \tag{9}$$

Figure 10 shows a comparison of *LDP* with our method replicating *LDP*, including both bending and contact stiffness. Comparison is good. The mean TE is almost identical. A slight difference is seen in the peak-to-peak TE. Peak-

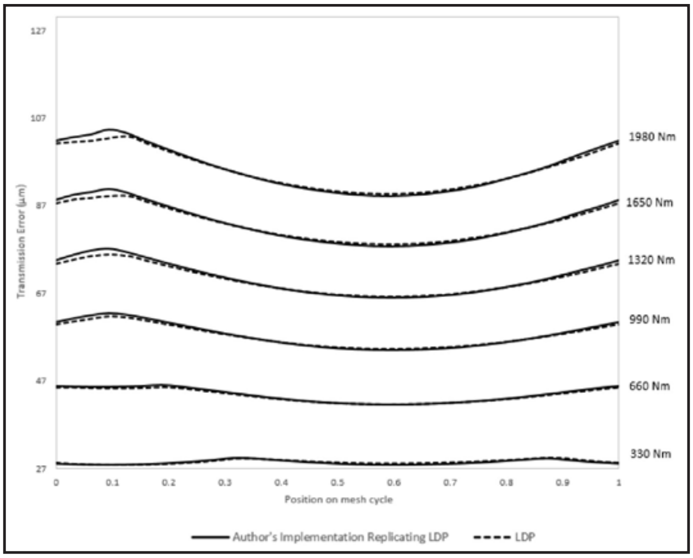

Figure 10 **Comparison of calculated TE from LDP and the authors' model replicating LDP.**

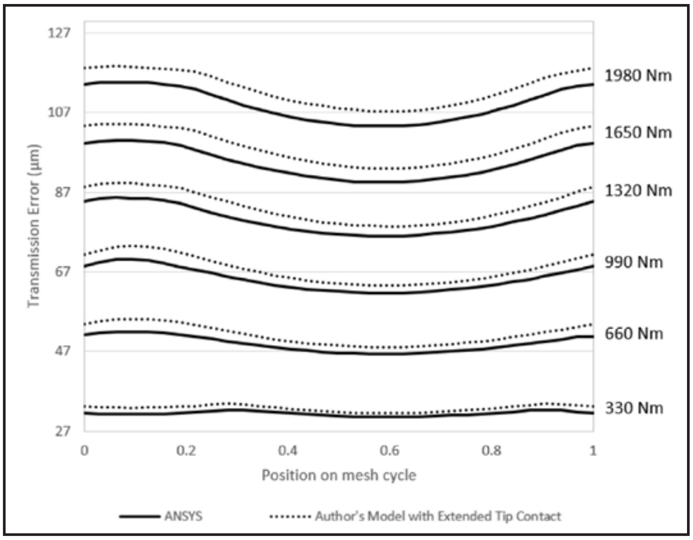

Figure 11 **Harris map of calculated TEs from ANSYS and the authors' model with extended tip contact.**

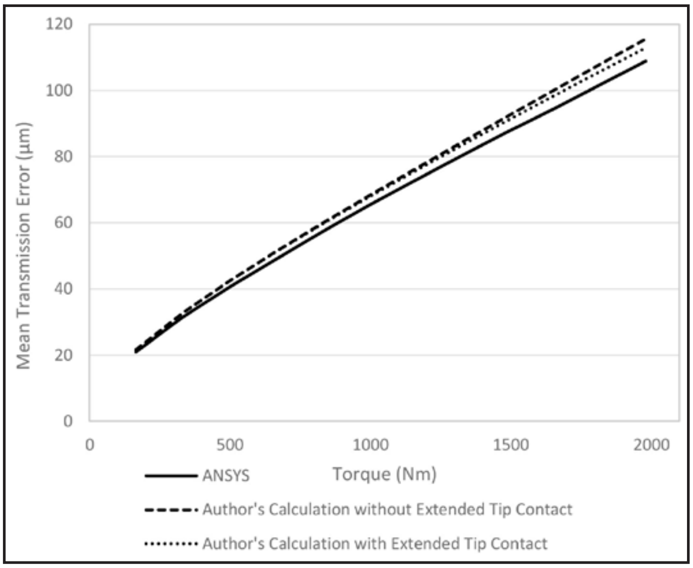

Figure 12 **Mean TE from ANSYS and the authors' models against load.**

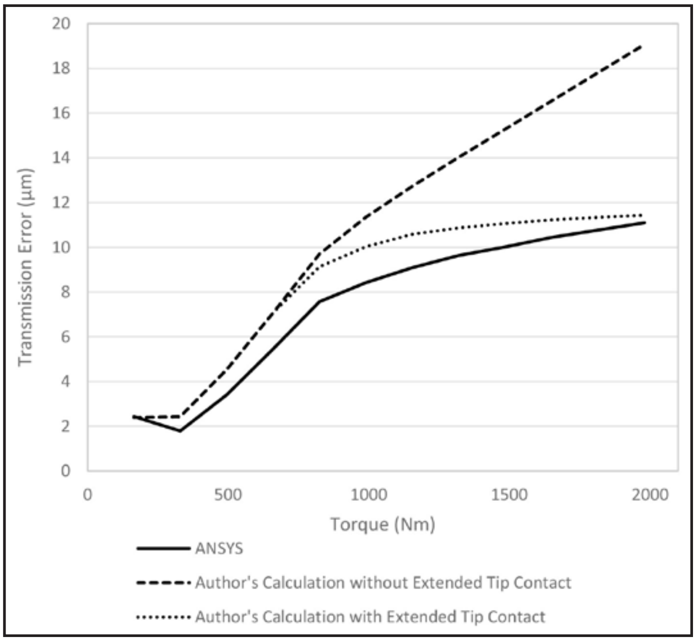

Figure 13 **Peak-to-peak TE from ANSYS and the authors' models against load.**

to-peak TE is very sensitive to the change in stiffness from tip to root. One possible source of this difference is the use of a straight sided tapered tooth in the *LDP* FE model, as compared to the accurate macro geometry used in our implementation.

Given these results, we have potentially identified why the *LDP* results differ from the FE results.

Comparison of hybrid FE and full FE models. In this section we present a comparison between our model, including the relation between TE and rigid body approach according to Equation 4 and FE results. As with the FE results, a mesh refinement study was performed for our models to ensure convergence.

Figure 11 shows a Harris map of the Transmission Error, Figure 12 shows mean TE and Figure 13 the peak-to-peak TE against load.

We see good correlation between our models and the FE analysis. From Figure 13 it is clear that the effect of extended tip contact becomes significant for the peak-to-peak transmission error at loads greater than around 825 Nm. At higher loads, if this effect is not considered, the peak-to-peak transmission error starts to diverge from the FE results and is overestimated.

One possible reason for the slight differences seen between our models and the FE may be the assumption that the contact, except for extended tip contact, lies in the plane of action. In reality gears with profile modifications and deflections under load would contact slightly outside the plane of action (Ref. 19) leading to slightly different gaps being taken up and therefore slightly different transmission errors. Recently, Mahr and Kissling (Ref. 20) suggested applying a correction factor of 0.5 to Weber's formula in such models, this was investigated but no evidence was found in our results to suggest that such a factor should be applied. For our models this factor of 0.5 lead to TE significantly lower than those calculated from FE — especially at the lower loads.

Figure 14 shows the calculated contact ratio, against load together with the theoretical contact ratio.

It is seen that for the model including extended tip contact the calculated contact ratio increases under load, due to tooth deflections, and passes the theoretical at around 825 Nm. From Figure 13 we can see that this is the load at which the TE with extended tip contact starts to differ from that without. This is where the additional contact points at the tips of the teeth begin to take significant load. For the model without extended tip contact the calculated contact ratio increases up to the theoretical value but can never exceed it.

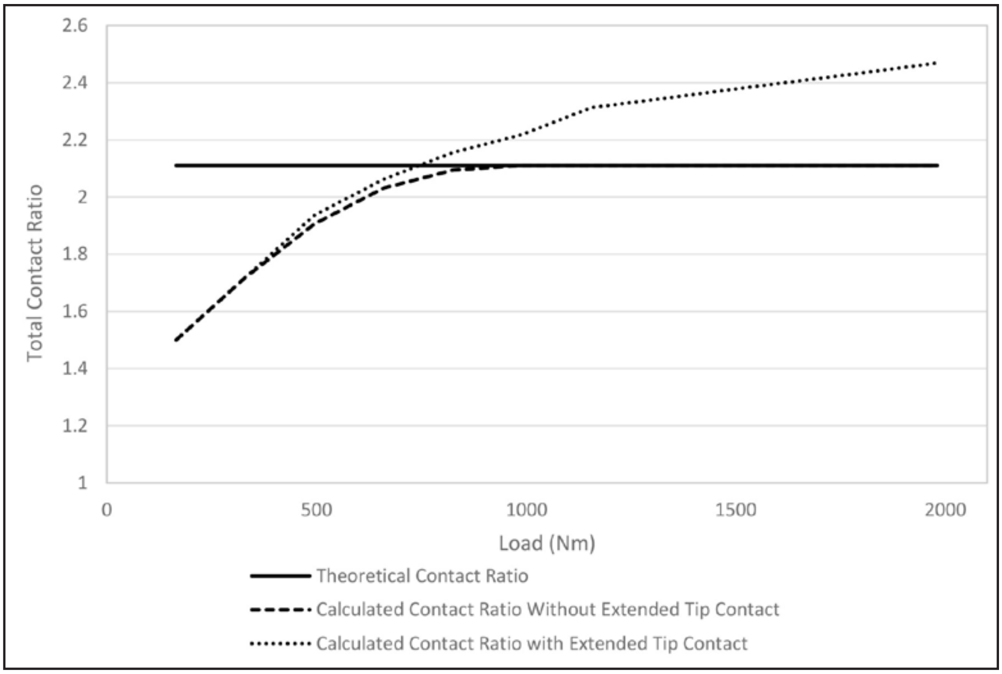

Figure 14 **Calculated total contact ratio against load for the authors' models.**

Example 2. In this section we consider a second example using some data available in the literature (Ref. 21). Rigaud et al (Ref. 21) develop two hybrid Hertzian and FE-based tooth contact analysis models and compare the results between the two for a gear pair from a truck application. The two models presented include Method 1, using quadratic elements, but only considering coupling between single adjacent teeth, and Method 2, which uses linear elements with curve fitting of displacements and considers the cross-coupling of deflections between all adjacent teeth. We consider comparison of the results shown in Figure 4 (Ref. 21) for the full-bodied example, Model 2, with no misalignment and no microgeometry modifications and under a 1,300 Nm pinion torque.

The details of the gear pair geometry are given in Table 2.

Figure 15 shows a comparison of the transmission error results.

Table 2 **Helical gear pair data for example (Ref. 21)**

	Pinion	Wheel
Number of Teeth	35	49
Normal Module (mm)	3.5	
Normal Pressure Angle (degrees)	22.5	
Helix Angle (degrees)	21.539	
Face Width (mm)	36.5	
Centre Distance (mm)	158	
Tip Diameter (mm)	138.297	190.897
Root Diameter (mm)	122.247	175.903
Cutter Edge Radius (mm)	0.875	1.225
Bore Diameter (mm)	77	95
Transverse Tooth Thickness at Reference Diameter (mm)	5.911	5.878
Transverse Contact Ratio	1.373	
Overlap Ratio	1.219	

The results confirm the conclusions made in the previous section. The *LDP* results exhibit the same behavior for helical gears as seen in the previous section, i.e. — that the mean TE is lower as compared to the FE results. The authors' model replicating *LDP* agrees well with the *LDP* results.

The Rigaud results appear to be closer to those of *LDP* than to those of *ANSYS*. Further, the difference between *LDP* and Rigaud results appears to be within the range of mesh refinement. We have similarly reproduced close to the results of Rigaud with a change of mesh. This suggests that Rigaud may have used the same conversion of deflections in the normal plane to those in the

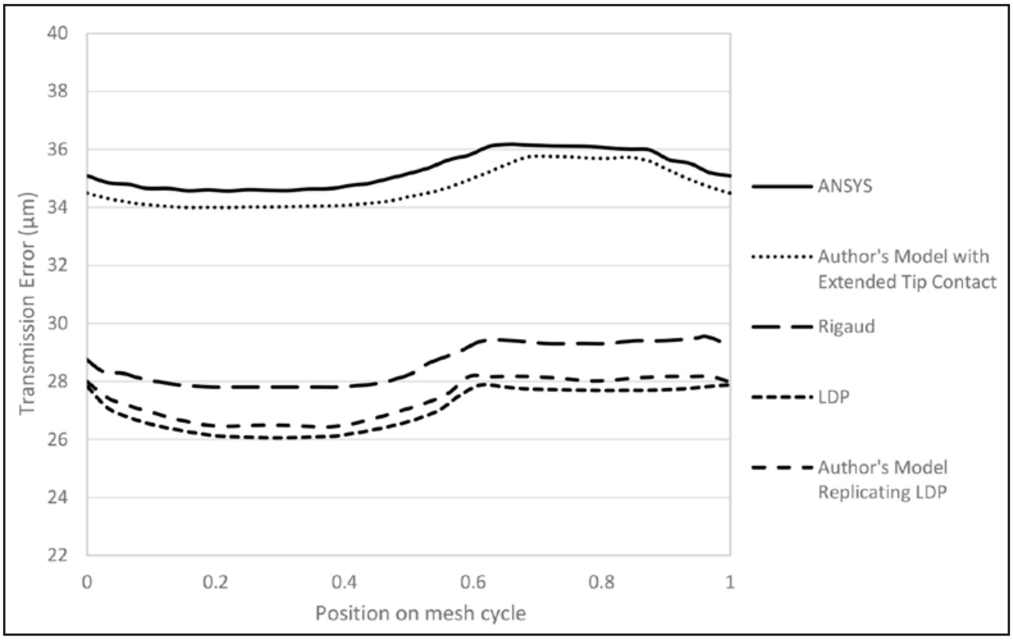

Figure 15 **Comparison of TE between ANSYS, LDP, Rigaud and the authors' models for the 1,300 Nm load.**

transverse plane as *LDP*.

The *ANSYS* results match our hybrid implementation including the effect of extended tip contact closely.

Conclusion

- A specialized gear tooth contact analysis model based on hybrid FE and Hertzian contact formalism has been presented, with particular focus on helical gears.
- An extensive comparison was presented between the results of this model and a 3-D FE tooth contact analysis using *ANSYS* showing good correlation in TE. These results reinforce the use of such models as efficient design tools that can be run in time scales orders of magnitude quicker than FE tooth contact analyses, while retaining similar accuracy. The presented solution has been implemented in SMT's *MASTA (MASTA Version 7.0* was used for the results in this study*)* software (Ref. 18).
- It was shown that, particularly for the case of low helix angle helical gears under consideration, the extended off line of action tooth contact at the gear tips plays a critical role in the transmission error at higher loads.
- Further comparison has also been made with the results of the well-known tooth contact analysis program, *LDP*. It was observed that *LDP* appears to underestimate the mean transmission error as compared to the FE. A possible explanation for this difference, as a difference in the conversion from normal to transverse plane, was proposed. It was shown, via modifications to the authors' models, that this proposed difference could lead to the results observed.

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Dr. Paul Langlois is the CAE products development department manager at SMT. Having worked for SMT for 10 years, he has extensive knowledge of transmission analysis methods and their software implementation. He manages the development of SMT's software products and is a main contributor to many aspects of the technical software development. As a member of the BSI MCE/005 committee, Langlois contributes to ISO standards development for gears.

Baydu Al has worked since October 2014 as an analyst/software engineer at Smart Manufacturing Technology Ltd. (SMT). He previously worked as a researcher at Nottingham University in gas turbine and transmission systems, specializing in efficiency and oil management. Upon joining SMT, Al has been contributing to MASTA's loaded tooth contact analysis as well as the analysis of tooth interior fatigue fracture.

Dr. Owen Harris, a graduate of Trinity College Cambridge, has worked in the analysis of transmissions and geared systems for over fifteen years. He was instrumental in writing some of the first commercial software codes for housing influence, system modal analysis and gear whine and planetary load sharing. Harris has filled many roles in over ten years working at Smart Manufacturing Technology Ltd. (SMT). He has worked on SMT's state-of-the-art MASTA software, while at the same time being heavily involved in many engineering projects. Harris's current focus is to lead SMT's research department.

Ron Bullock, Bison Gear

1942-2016

It is with great sadness that we announce the passing of Bison Gear owner, chairman, mentor and friend, **Ronald D. Bullock**. Bullock's life not only impacted everyone he directly worked with at Bison over his 30+ years of service and leadership, but also the lives of countless people pursuing a career in the manufacturing industry.

Bullock began his career with Bison in 1981. He served in key R&D, engineering, marketing, operations and general management roles before acquiring Bison in 1987. Since then, he led Bison through unprecedented growth while simultaneously expanding the company's product line, distribution channels and introduction into the European market. He championed Bison's customer focused approach, while also driving a culture of continuous improvement. His strong leadership will be continued by his associates, guided by the principals and the knowledge he shared.

In addition to his work at Bison, Bullock was a dedicated proponent for American manufacturing. He recently completed a two-year term as chairman of the Manufacturing Institute, a 501c3 think tank affiliated with the National Association of Manufacturers - for which he also served on the board of directors. His dedication to improving the manufacturing industry also includes serving as chairman of the Illinois Manufacturing Association, the IMA Education Foundation and founder of the Illinois P-20 council.

He also concentrated on the importance of continuing education and community outreach. BisonCares, (a 501c3 charity organization operated through Bison Gear and Engineering) recently celebrated its 10-year anniversary of providing services and support to local charities. He funded several scholarship programs through the IMA Education Foundation and also offered financial support to children of Bison associates attending college through the Bullock Family Scholarship.

Bullock was a dynamic, charitable human being and a true American innovator at heart. His contributions to his family, community and country will be felt for years to come. He is survived by his daughter, Laurel Novak, daughter-in-law, Kelly Burch, brother-in-law, John Stewart, seven grandchildren and his friends and family at Bison. He will be missed.

Marc Bours, who has 30+ years' experience in the industry and who is the lead director on Bison's board of directors, has been appointed interim CEO of Bison effective immediately.

Koepfer America Gear Tour

COVERS HOBBING, SHAPING AND GRINDING TECHNOLOGIES IN GERMANY AND ITALY

Following the 2014 tour, Koepfer America has sponsored a group of North American gear manufacturers for the 2016 Gear Technology Tour. This trip, which took place April 11 through April 19, 2016, focused on the latest technologies for gear hobbing, shaping and grinding that are developing in Germany and Italy. The group comprised key members from the industry's leading gear manufacturers who benefited from personally visiting several original equipment manufacturers, tool manufacturers, as well as gear manufacturers.

In Germany, the tour visited the Koepfer machine tool factory in Villingen-Schwenningen where attendees observed the assembly of fine-pitch horizontal hobbing machines rated up to 6 DP. This stop also included technical presentations covering topics such as Koepfer's flexible automation systems, dry hobbing, multi-thread skiving, Conikron bevel gear hobbing, and non-circular gear hobbing. Finally, nearby gear manufacturers opened their doors for the group to see the latest European manufacturing processes. Armin Wacker, vice president sales and service of EMAG Koepfer GmbH said, "We always welcome American gear manufacturers to our factories, so we can share the latest information on our machine tools. I feel this group learned much to improve their own factories back home."

The tour continued with a stop at Saazor, one of Germany's premier manufacturers of high-speed steel and carbide hobs, in Pforzheim. Next up: Kapp Niles, a top-tier manufacturer of gear grinding machines for small to very large parts. This world leader in grinding technology shared the latest advancements in continuous generating and discontinuous profile grinding.

The tour was not all work. Between technical presentations and factory visits, the group enjoyed cultural stops to the Veste Coburg (a hilltop fortress that once served to protect Martin Luther in 1530), Neuschwanstein (a Romanesque Revival palace that inspired Disneyland's Sleeping Beauty Castle), and the BMW Museum in Munich.

The final featured stop for the tour was at the CLC gear cutting machine tool plant in Italy. The local mayor greeted the group and expressed thanks and excitement for the collaboration and business between the group's American gear manufacturers and the CLC factory. Claudio Montanari, general manager for CLC, said, "The Koepfer America Gear Technology Tour is a perfect way for gear manufacturers to see the latest hobbing and shaping machines built by CLC, such as the new model 100-SZ gear shaping machine." The group was impressed by this machine's robust set of features, such as 2,000 strokes-per-minute up to 4-inch stroke length and a dual-spindle table for maximum machine productivity.

ITAMCO's Joel Neidig

RECEIVES AGMA 2016 NEXT GENERATION AWARD

Joel Neidig, an engineer and lead technology developer with ITAMCO, has received the 2016 Next Generation Award from the American Gear Manufacturers Association (AGMA). This award, presented annually since 2011, recognizes innovative work by an individual responsible for one or more significant achievements through his or her effort and work that has enhanced or strengthened the gear industry and/or AGMA. This award honors individuals who are emerging as contributors, innovators and leaders in the gear industry and serves as an incentive for others in the next generation of gear industry talent. The award was presented May 13th at AGMA's Centennial Annual Meeting in Amelia Island, Florida.

The award is the latest in a series of milestones for Neidig and ITAMCO to acknowledge their efforts to transform their precision machining facilities into "smart factories." ITAMCO is part of a research group that recently received an Applied Research and Development award from the Digital Manufacturing and Design Innovation Institute. The group is developing a platform that will integrate every piece of software, hardware and equipment from its accounting program to its machine tools. ITAMCO was chosen as the implementation site because many of their machine tools are already connected to the Internet and each other through MTConnect. "We are only 12 to 15 months away from a totally integrated shop floor. A job will be entered into our ERP system and then every piece of the job, from allocating materials, to manufacturing, to shipping and invoicing, will be routed through the entire facility. Machines will be chosen based on the type of work and availability. And the platform is dynamic — if a machine goes down, the job will be automatically rerouted," said Neidig.

ITAMCO is also part of a team awarded a Research and Development fund by America Makes, a division of the National Additive Manufacturing Innovation Institute. The team is working on a project that will improve the building of support structures with Direct Metal Laser Sintering, an additive manufacturing technique. In addition, the technology team at ITAMCO, led by Neidig, is implementing the "Strategic Technology Initiative for Additive Manufacturing." They have released over 65 apps for mobile devices; designed iBlue, the first industrial Bluetooth transmitter; and developed an award-winning Google Glass application.

Interestingly, despite its innovative approach to gear manufacturing, ITAMCO is not a new company. ITAMCO has provided open gearing and precision machining services since 1955. They specialize in servicing many heavy-duty industries including mining, off-highway vehicles, marine, and aviation. The "next generation" staff members like Neidig are part of a rich history of thinking outside the gearbox. "I was honored to receive this award from AGMA on behalf of ITAMCO. What made it especially meaningful was that Tom Pellette with Caterpillar gave a keynote address on the Internet of Things before the award presentation. Our first purchase order was from Caterpillar in 1956. It was one of those moments where I saw the past, present and future of our company coming together so perfectly," said Neidig.

Bodycote
OPENS HEAT TREATMENT PLANT IN MEXICO

Bodycote announced that the company will open a new, state-of-the-art heat treatment plant in San Luis Potosi, Mexico. Mexico is one of the largest automotive manufacturing countries in the western hemisphere, with many of the world's leading car manufacturers investing in manufacturing and assembly plants.

Bodycote's latest investment, a 100,000-square-foot facility, established to serve the country's extensive and growing automotive supply chain, will be capable of supporting large automotive projects and providing the necessary heat treatment ser-

vices for technologically advanced components, such as complicated transmissions.

The plant, which will be TS 16949 certified as well as holding all required OEM quality approvals, will offer a wide range of heat treatment processes, including low pressure carburizing, ferritic nitrocarburizing, and Bodycote's proprietary Corr-I-Dur process.

In addition to the existing Silao and Empalme plants, the San Luis Potosi facility will be Bodycote's third plant in Mexico and will be able to provide customers with complementary services and qualified backup to the existing sites, if needed. It is scheduled to be fully operational by fourth quarter.

Solar Atmospheres and Solar Manufacturing

WRAP UP PRODUCTION OF WORLD'S LARGEST FURNACE

Solar Atmospheres and Solar Manufacturing, Inc. have been building the largest vacuum furnace in the world and are counting down the days to its completion. The working hot zone of this high vacuum (three 35" Varian diffusion pumps) furnace is 80 inches in diameter by 48 feet in length with a maximum operating temperature of 2400 degrees Fahrenheit. 35 points of temperature will be surveyed to within ±10 degrees Fahrenheit per the stringent AMS 2750E specification. The robust dual load car design will have the capacity to transfer up to 150,000 pounds of material in and out of the furnace. For dimensionally critical, near net shaped jobs, the dual load car design will also have the capability to maintain the critical support needed at elevated temperatures to keep parts flat to within .030-inches.

All of the major components have been delivered and installed. The gas and water systems are in place. The remaining installation of all the electrical components and wiring will occur over the next several weeks. This multi-million dollar project is expected to be completed in June with the commissioning of the furnace into production in July of 2016. This unique piece of equipment will not only open up new production opportunities within the North American vacuum heat treating markets, but also internationally.

GMTA

APPOINTS DAN THOMAS PROJECT MANAGER

German Machine Tools of America (GMTA) today announces the appointment of **Dan Thomas** as Project Manager for this major supplier of various machine tools, lasers and parts washers to the North American automotive, off-highway, heavy equipment and other power transmission markets.

GMTA Vice President Scott Knoy comments, "We welcome Dan to our team. His role will be a vital part of our ongoing efforts to be more customer-centric, as we expand our machine offerings, penetrate new markets and expand existing ones."

Thomas will be responsible for the end-to-end coordination of the project flow at GMTA, from initial contact through commissioning of machines and systems onsite.

July 19–20—AWEA Regional Wind Energy Conference – Northeast Portland, Maine. AWEA's next regional conference will focus on the critical issues that will help advance wind power's growth issues in the northeastern U.S. The event will also provide attendees with a comprehensive view of both land-based wind power development and the nascent efforts to develop offshore wind power off the region's coast. Attendees will analyze where wind power stands today in the northeast and the critical issues specific to the region, evaluate the market and policy in the region, specifically the various growth strategies and demand drivers, detail the critical issues affecting offshore wind development, siting and wildlife and transmission infrastructure needs, as well as manufacturing and supply chain opportunities in the region and examine the utility issues that can secure cost-effective wind energy supply, jobs growth, and economic development opportunities. For more information, visit *www.awea.org*.

July 25–29—CMSC 2016 Nashville, Tennessee. The Coordinate Metrology Society Conference (CMSC) provides a professional venue where ideas, concepts and theory flow freely among participants. The educational atmosphere encourages attendees to network and learn about the latest innovations in the field of portable 3D industrial measurement technologies. The event includes technical presentations by industry experts, advanced workshops and seminars along with an exhibition hall filled with the world's leading providers of metrology systems. The keynote speaker at the event will be Dr. Ed Morse, professor at UNC Charlotte, discussing the work of the PrecisionPath Consortium for Large Scale Manufacturing. CMSC 2016 includes two scheduled tours one of Nissan's Smyma Vehicle Assembly Plant as well as Oaklands Mansion, the plantation home of the Maney family that reflects the history of Murfreesboro, Tennessee. For more information, visit *www.cmsc.org*.

August 2–4—Ipsen 2016 U Classes Cherry Valley, Illinois. These three-day courses provide attendees with a broad overview of furnace equipment, processes and maintenance, as well as a hands-on approach to learning while receiving qualified tips directly from the experts. Throughout the course, attendees are able to learn about an extensive range of topics - from an introduction to vacuum and atmosphere furnaces to heat treating, furnace controls, subsystems, maintenance and more. They will also be able to view the different furnace components first-hand while learning how they affect other parts of the furnace and/or specific processes, take part in one-on-one discussions with Ipsen experts, participate in a leak detection demonstration and tour Ipsen's facility. For more information, visit *www.ipsenusa.com/aftermarket-support/ipsen-u*.

August 9–11—PC Applications in Parallel Axis Gear System Design and Analysis UWM School of Continuing Education, Milwaukee, Wisconsin. Attendees will gain an understanding of parallel axis gear design, and learn to use the software tool, *PowerGear*, to analyze the main parameters involved (a student version of the software is included in the price of the course). This course covers the basics of gear load capacity evaluation from a theoretical viewpoint and uses the PC as a tool to apply these theoretical concepts. Attendees will understand durability, strength and scoring concepts, discuss typical sets of problematic design parameters and experience hands-on design perspectives through group projects. For more information, visit *http://uwm.edu/sce/courses/pc-applications-in-parallel-axis-gear-system-design-and-analysis/*.

September 12–17—IMTS 2016 McCormick Place, Chicago, Illinois. The International Manufacturing Technology Show is one of the largest industrial trade shows in the world, featuring more than 2,000 exhibiting companies and 114,147 registrants. This year's show is expected to be one of the largest IMTS events at 1.3 million net square feet with a full line up of exhibitors showcasing the latest technology. Co-located shows include Motion, Drive & Automation North America, Industrial Automation North America, Surface Technology North America, Comvac North America and Industrial Supply North America. For more information, visit *www.imts.com*.

September 13–17—AMB 2016 Stuttgart, Germany. AMB 2016 has posted record figures for the previous event in 2014. The promotional supporters - the German Machine Tool Builders' Association (VDW) and the German Machine Tool and Plant Builders' Association (VDMA) with the Associations for Precision Tools and Software - contribute to this success. The exhibition areas of AMB Stuttgart comprise metal-cutting and metal-removing machine tools, precision tools, measuring systems and quality assurance, workpiece and tool handling technology, robots, industrial software & engineering, components and accessories. The exhibitors includes Chiron-Werke, DMG Mori Seiki, EMCO, GF Machining Solutions, Gühring, Hahn+Kolb, Ilg + Sulzberger, Index-Werke, Iscar Germany, KASTO Maschinenbau, Komet Group, LMT Tool Systems, MAPAL Präzisionswerkzeuge, Nagel Werkzeug-Maschinen, Paul Horn, Sandvik Tooling Deutschland and Yamazaki Mazak Deutschland, to name just a few. For more information, visit *www.messe-stuttgart.de*.

September 19–21—2016 Gear Failure Analysis Big Sky, Montana. The Gear Failure Analysis seminar provides participants the skills necessary to diagnose gear failures and prescribe remedies. This presentation covers six classes of gear tooth failure: overload, bending fatigue, hertzian fatigue, wear, scuffing and cracking. Each failure mode is illustrated by color slides and field samples because of the magnification inherent in slide projection. However, it is important to examine the field samples because there is no substitute for hands-on experience that students experience. Working in small groups, students participate in a hands-on practical exam using field samples and a case study. Instructors include Robert Errichello and Jane Muller. For more information, visit *www.agma.org*.

September 19–23—2016 Basic Training for Gear Manufacturing Students learn the fundamentals of gear manufacturing in this classroom and hands-on course. In the classroom this course offers training in gearing and nomenclature, principles of inspection, gear manufacturing methods, and hobbing and shaping. In the hands-on gear lab, using manual machines, students can see the interaction between the cutting tool and the workpiece. They understand the process and the physics of making a gear and can apply this knowledge in working with CNC equipment commonly in use. Although the Basic Course is designed primarily for newer employees with at least six months experience in setup or machine operation, it has proved beneficial to quality control managers, sales representatives, management, and executives. Instructors include Dwight Smith, Pete Grossi and Allen Bird. For more information, visit *www.agma.org*.


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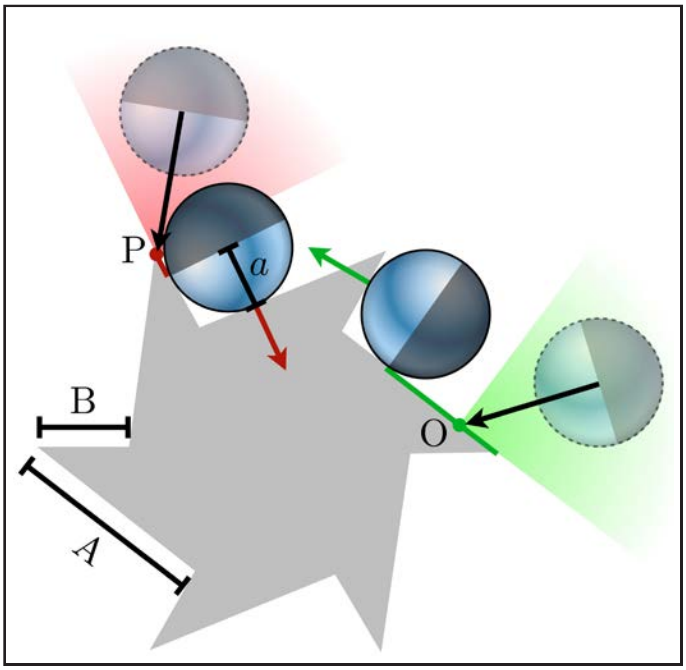
UNDER PRESSURE TO BE FIRST IN AUTOMOTIVE INNOVATION—PRESSURE WE WELCOME! IMTS FUELS GENERAL MOTORS WITH INSPIRATION & IDEAS, DRIVING OUR CURIOSITY TO NEW DESTINATIONS.
WE ARE

MOBILIZING MICROGEARS

We can make gears thinner than a hair. The hard part is getting them to move.

Alex Cannella, News Editor



We've been in the business of making things small and portable for a long time. But when it comes to shrinking things down, a team of scientists from Germany, Italy and Spain led by Roberto Di Leonardo decided to go big. They're working with microgears, gears the size of a red blood cell. Specifically, they're looking at ways to make fully functioning, autonomous micromachines, but before they can get there, they need to develop the parts that will compose the whole.

While microscopic gears are a mind-bogglingly cool and useful idea, the gears themselves aren't that revolutionary. Microgears have been manufactured before, but there's one problem that keeps them from being commercially viable: we still need to figure out a reliable way to keep them turning.

"In our group we study efficient strategies to build fully autonomous micromachines," Claudio Maggi, one of the team members at the University of Rome Sapienza, said. "In this context we have demonstrated that fully autonomous self-assembly and propulsion of the gears can be achieved by using Janus particles."

The generally established way to power a microgear is with an electrical or magnetic field, but that requires large, expensive equipment, which limits the number of applications you can use them for. In a static setting such as research laboratories, portability and cost aren't as much of a concern but it's hard to justify using microgears in many applications when you're still going to need a big, expensive machine to make them work. Microgears need an equally diminutive source of energy if they're to see more widespread use.

"What we wanted to demonstrate is that these particles do not only self-propel but can also self-assemble to autonomously rotate a microgear," Maggi said. "Which makes it quite a 'smart material.'"

The idea the team has hit on is to use Janus particles. Named after the two-faced Roman god, Janus particles similarly feature two halves composed of different materials. In the microgears' case, the particles are made of silica, but one half is thinly plated in platinum. The gears are placed in a solution of Janus particles and hydrogen peroxide (H_2O_2).

Now we start getting into some chemistry. Platinum is a catalyst that causes hydrogen peroxide to deteriorate into water and oxygen. But because a Janus particle is only half coated in platinum, this means that the hydrogen peroxide around the other half isn't deteriorating. So for a brief moment the particle is suspended in between two different solutions, one of hydrogen peroxide, and the other of water and oxygen.

While obviously this state doesn't last very long, it still puts two different levels of pressure on the Janus particle, which propels it forward—into more hydrogen peroxide, where the process repeats. Technically, the Janus particles are freely floating in the solution, meaning they aren't sitting between a gear's teeth just waiting to turn it, but the team has found they can still get the particles to make contact and rotate the gear.

That said, the science behind this particular application of Janus particles is still coming together. Though scientists generally agree on how the process works, there's less of a consensus as to why, and more study needs to be done, both by this team and by other researchers, before we start seeing Janus particle-driven microgears on the market.

"I would say we are still quite far [from commercial use]!" Maggi said. "However many potential applications for these self-propelled particles have been already envisioned (such as micro-cargo transport and drug delivery)."

While their current studies show promise, the research team hasn't ruled out other possibilities, including Janus particles with different compositions. According to Maggi, Janus particles that start catalyzing when illuminated are also promising. They're also investigating microfluidic systems to cycle the hydrogen peroxide, as the Janus particles eventually run out of solution to break down.

Maggi's team has published their findings in the January 2016 volume of Small, a scientific journal focused on all things micro- and nanoscale. If you're interested in the full nitty gritty report, you can purchase it at *onlinelibrary.wiley.com/wol1/doi/10.1002/smll.201502391/full*. The research was funded by two ERC Grants and combines recent advances in catalytic propulsion (Grant n. 311529) and statistical mechanics of active matter (Grant n. 307940).

For more information:
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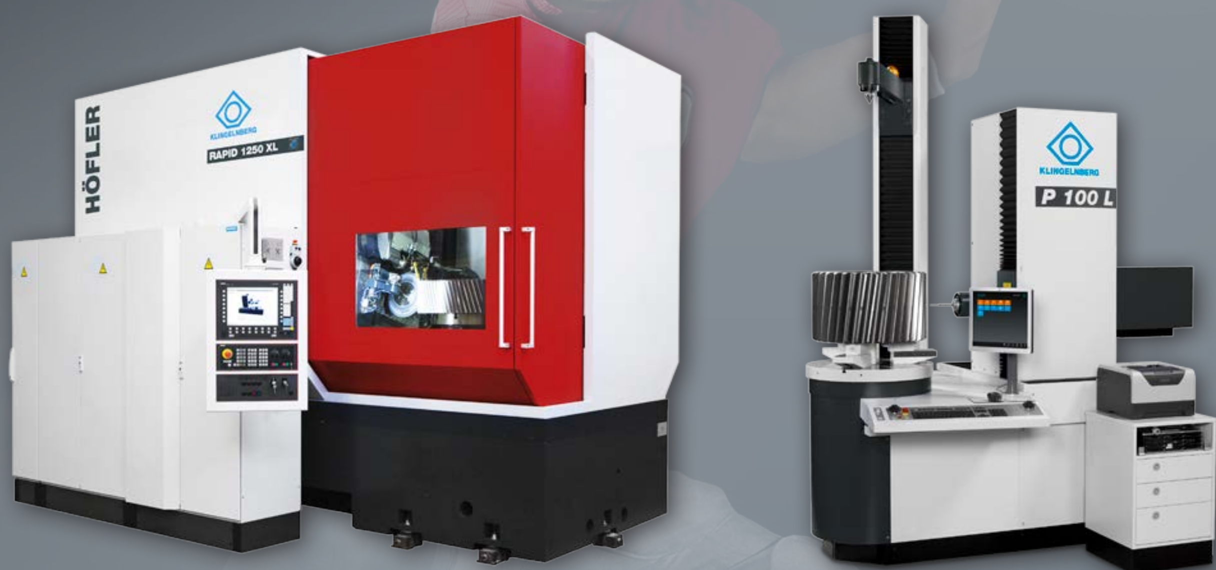
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