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Cover image by David Ropinski

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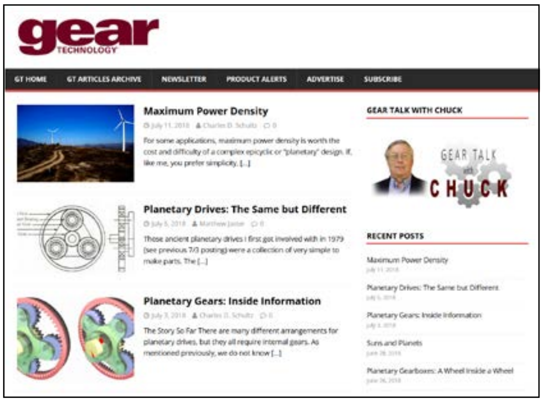
What You've Missed on the Blog

Since the beginning of 2018, resident blogger and *Gear Technology* technical editor Charles D. Schultz, has been busy blogging about the basics. So far this year, he's covered:



- Spur Gears
- Nomenclature
- Measurement over Pins
- Helical Gears
- Worm Gears
- Bevel Gears
- Basic Rules of Thumb
- Tooth form modifications
- Software
- Gear Materials
- Heat Treating
- Planetary Gear Drives

And that's just this year! Chuck has been blogging for us since 2014. If you're not reading "Gear Talk with Chuck," then you're missing out, because the wisdom and insight you find there can't be found anywhere else.

www.geartechnology.com/blog/

Want More Gear Inspection Info? Watch Gear Technology TV!

In this issue, you'll find a number of articles focused on gear inspection, but there's even more great content online. If you head over to *Gear Technology TV*, you'll find great interviews with technical experts as well as our "Ask the Expert Live" sessions from Gear Expo.

www.geartechnology.com/tv/

White Papers and Videos Just for You

Did you know there's an archive of white papers and videos on the *Gear Technology* website? You can read about water-based lubrication, power skiving, powder metal gears, closed-loop gear grinding or gear inspection. Or stop in and see the replay of a webinar on NVH and transmission design.

www.geartechnology.com/sc/

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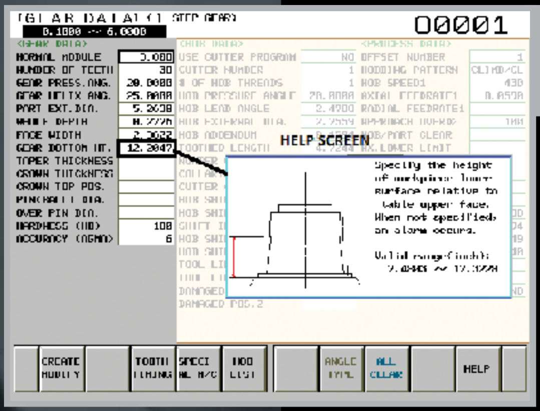

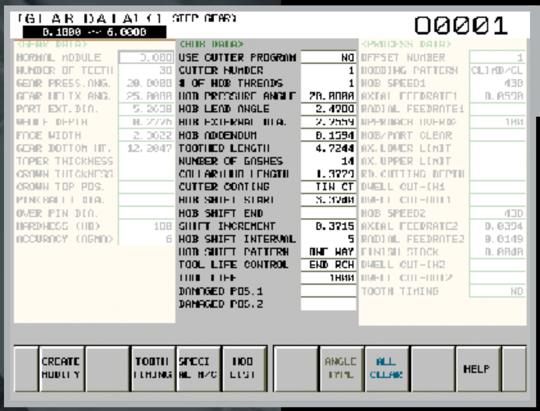

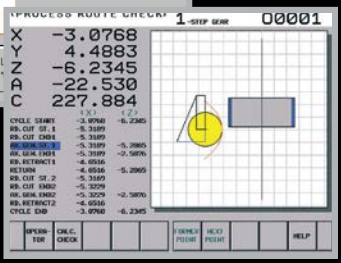


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Steel Yourself

Publisher & Editor-in-Chief
Michael Goldstein

If you've been reading this column for any length of time, you know that I'm a big believer in industry associations like the American Gear Manufacturers Association. AGMA provides great value to industry professionals like you in the form of phenomenal opportunities for professional and personal growth and education, as well as the ability to build a network among your peers. More importantly, associations like AGMA have the ability to tackle problems collectively that would be extremely difficult or even impossible for individual companies to achieve. They can help you look at issues facing the industry from a much larger perspective.

A good example of that was the AGMA Marketing Forecast webinar held in May. The webinar included a presentation on steel tariffs and quotas by John Anton, Senior Principal Economist for IHS Markit. Frankly, what he said scares the living daylights out of me and should be cause for concern for all of us.

You've all heard about the 25% tariff on imported steel and 10% tariff on imported aluminum that the U.S. government has imposed. You've all heard about the retaliations being put in place by the rest of the world. Your steel prices have increased.

It's a full-on trade war, and it's likely to get worse before it gets better.

That in itself is scary enough. But what really scares me is that many of you might be too busy to realize that you could soon be in a situation that could endanger your very company. When I brought up the subject with several industrial gear manufacturers recently, they didn't seem to have given it much thought.

You're already dealing with higher prices. But are you ready for a scarcity of raw materials? What will you do if you can't get the steel you need—at any cost? That's the real danger that Anton warned about. Tariffs are bad, because they mean higher prices, but quotas are potentially catastrophic for a company that relies on raw materials. What happens if the steel you buy comes from a country who has agreed to accept quotas instead of tariffs?

South Korea, the third largest supplier of steel to the United States, already agreed to such quotas. They've promised to reduce their shipments to 70% of their 2015-2017 totals. Each type of steel (different grades of bar, plate, coil, etc.) is treated separately for each country. For certain types of steel, South Korea has already reached its quotas, which means the United States simply won't accept any further shipments. Brazil and Argentina have also agreed to quotas. Pretty soon, it will be hard to get steel of any type from these countries.

Anton didn't mince words about the threat. He went so far as to recommend that gear manufacturers think seriously about buying up as much steel as possible, even if they have to lease additional warehouse space to hold it. It's an expensive, risky proposition, because there's also the very real possibility that if the quotas disappear, prices could fall by the end of the year. But you have to weigh that against the possibility that you just might not be able to ship any product in the third and fourth quarters.

None of this makes for easy decision-making from a long-term strategy standpoint, especially considering that the situation changes daily. More tariffs and more retaliations are on the way. Negotiations between countries will continue, and there's nothing you can do about any of it.

So it's very tempting just to wait and see. Business is great, after all. You can probably weather some higher prices, at least in the short term.

But if more quotas get implemented, you'd better be ready to act quickly. You'd better have a contingency plan in place. If you haven't already done so, you'd better take some time to evaluate your supply chain. At a minimum, find out where your steel is coming from and evaluate the potential risk of extreme shortages later in the year.

If you don't, there's a chance you won't be so busy for too much longer.

Buehler

OBTAINS ISO CERTIFICATION FOR HARDNESS TESTING BLOCKS

The Buehler Wilson Reference Block Laboratory in Binghamton, NY, has achieved accreditation to ISO/IEC 17025 by A2LA (American Association for Laboratory Accreditation) for Rockwell, Knoop, Vickers and Brinell hardness test blocks and indenters. A2LA is in full conformance with the standards of the International Organization for Standardization (ISO) and the International Electro-Technical Commission (IEC), including ISO/IEC 17025. Buehler markets the reference blocks along with the Wilson hardness testers and DiaMet software globally.

Process of Calibration

The testers used in the calibration process undergo a stringent monitoring process using NIST traceable devices and Buehler conducts 100% inspection to ensure that every single test block meets the physical requirements of ASTM (thickness, flatness, parallelism, surface roughness and magnetism). The laboratory then uses specialized hardness testers to calibrate blocks according to Rockwell, Vickers and Brinell scales which comply to ASTM and ISO standards for calibrating test blocks.

According to Matthias Pascher, hardness product manager, "The hardness readings are taken and statistics calculated according to the applicable standards. Each test block will get its own certificate, thus achieving full traceability. In addition to in-house daily verifications, standards also require indirect verifications to be completed periodically by an accredited third-party. After the indent certification, the blocks are engraved with a laser engraver to add a grid (if applicable) and the hardness value with tolerance according to the standards. All hardness test blocks ship with ASTM and ISO certificates. Buehler is the only global supplier in the metallographic solution market that produces and calibrates hardness reference blocks."

Scope of Accreditation

The Buehler Wilson Reference Block Laboratory in Binghamton, New York, is accredited to perform calibrations on hardness reference blocks according to the following standards:

- Calibration of Standardized Rockwell Hardness Test Blocks (ASTM E18 and ISO 6508-3)
- Calibration of Standardized Rockwell Superficial Hardness Test Blocks
- (ASTM E18 and ISO 6508-3)
- Calibration of Standardized Vickers Test Blocks (ASTM E92 and ISO 6507-3)
- Calibration of Standardized Knoop Test Blocks (ASTM E92 and ISO 4545-3)
- Calibration of Standardized Brinell Test Blocks (ASTM E10 and ISO 6506-3)

Buehler Test Blocks Available in Rockwell, Vickers, Knoop and Brinell Hardness Scales

Buehler's hardness reference blocks utilize the highest quality material to insure the most uniform and repeatable test blocks available. Buehler's Test Block Calibration Laboratory has the capability to produce and calibrate test blocks for many different hardness scales.

- **Rockwell:** Regular and Superficial scales
- **Vickers Microindentation:** Loads from 10gf to 1kgf
- **Vickers Macroindentation:** Loads from 1kgf to 120kgf
- **Knoop Microindentation:** Loads from 10gf to 1kgf
- **Brinell:** Loads from HBW5/750, HBW5/250, HBW10/1000, HBW10/3000, HBW2.5/62.5, HBW2.5/187.5

The complete line of Wilson Rockwell, Wilson Brinell and Wilson Vickers/Knoop Test Blocks for hardness testing is available within the hardness section of the Buehler website. To assist customers in the selection, process Buehler has also released a Test Block Application Guide with valuable information about the Wilson line of test blocks and important information about proper usage of test blocks.

For more information:

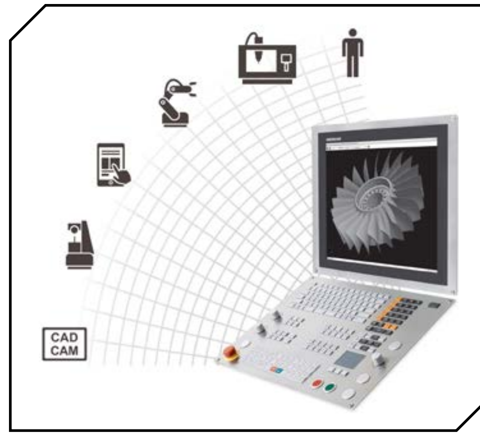
Buehler (an ITW Company)
Phone: (847) 295-6500
www.buehler.com

Heidenhain

PLANS TO DIGITALLY CONNECT MACHINES THROUGHOUT IMTS 2018

In order to truly showcase the new age of digital manufacturing, Heidenhain will use its control systems during IMTS to connect equipment from many machine tool builders throughout the massive exhibition at Chicago's McCormick Place back to the Heidenhain booth. The list of connected manufacturers is to be announced closer to show time.

"Connecting Systems for Intelligent Production" has been Heidenhain's motto at many trade shows over the past year as the manufacturing trend of digitization and networking have become the goal for many in order to increase competitiveness. To this end, Heidenhain offers Connected Machining, a package of components and systems to support end users introducing digital order management in their production processes.



At IMTS 2018, this will be demonstrated in a live presentation at its Connected Machining booth area, including the use of a TNC 640 control on a high precision 5-axis machine tool. Heidenhain's new *StateMonitor* software focuses on the evaluation of machine data — that was acquired during the operation of machine tools — by the Heidenhain TNC or other CNC controls with the MTConnect protocol interface. This can also be monitored online utilizing mobile devices via a secure IT structure.

At the show, it will be shown that the use of these systems results in concrete solutions for analyzing and reducing downtimes so that end users can significantly increase competitiveness. Heidenhain will put special emphasis on metal removal rates, productivity and accuracy while supporting the machine operator through full access to manufacturing IT. Five-axis application engineers will be on site explaining the new TNC features and cutting a high precision 5-axis part.

IMTS will be held September 10-15. Heidenhain's main booth will be located at the Lakeside Center (#135226). Heidenhain will also have a booth at the Student Summit (#215108), allowing students to program on the new TNC 640

For more information:
Heidenhain
Phone: (847) 490-1191
www.heidenhain.us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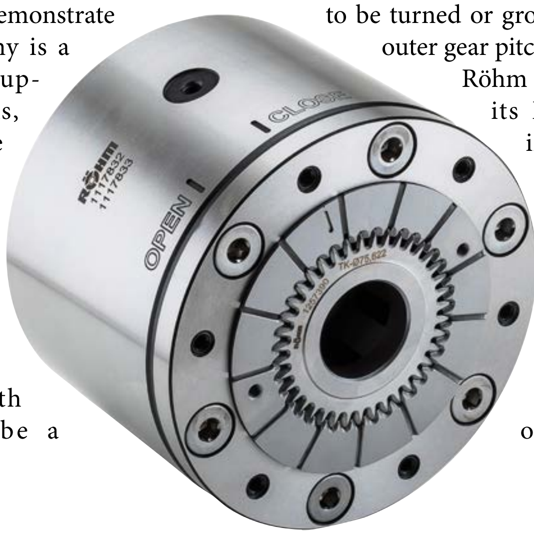
Röhm Products of America

WILL FEATURE CHUCKS FOR GEAR SURFACE FACE GRINDING DURING IMTS 2018

At IMTS 2018, Röhm Products of America will present a wide range of workholding solutions that lead to higher levels of efficiency in turning, milling, grinding and drilling applications as well as enable lights-out manufacturing. The workholding specialist will also demonstrate how the company is a single source supplier for chucks, centers, face drivers, rotating workholding, fixtures, palletizing and robot gripping solutions.

A must-see for visitors to Booth #432528 will be a powered external clamping chuck for gear surface face grinding. The KZF-S collet chuck is especially well suited for clamping gears/workpieces that have an external plane or gear teeth geometries accessible from the outside. Additionally, the chuck allows face and ID diameters to be turned or ground concentric to outer gear pitch diameters.



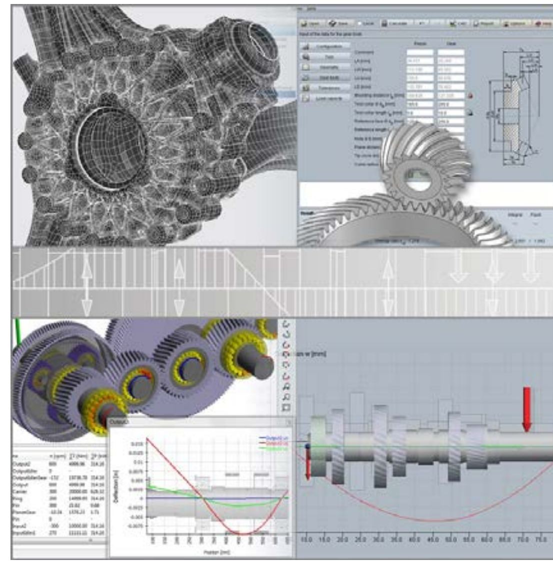
Röhm will also showcase its Easylock clamping system, a zero point palletization solution that reduces setup times by up to 90 percent. With a standardized interface and level of precision and repeat accuracy of less than 0.005 mm, Easylock can be outfitted with a large range of Röhm's collet chucks, lathe chucks and vises for full flexibility via its modular design. The clamping system is equally well suited for vertical, horizontal or multi-axis machining.

IMTS attendees interested in learning more about the company's comprehensive range of clamping and gripping solutions should visit the website below to schedule a meeting with an application specialist in Röhm's booth during the show.

For more information:
Röhm Products of America
Phone: (770) 963-8440
www.rohmdonein60.com

GWJ Technology

OFFERS SOFTWARE SOLUTIONS FOR AUTOMOTIVE INDUSTRY



The International VDI Dritev Congress was held June 27-28 in Bonn, Germany. The exhibition at the Dritev congress featured a unique mix of over 100 national and international companies and has become a central marketplace of the industry. Dritev gives an efficient overview of the most important providers across all sectors of development, simulation and production of gearboxes and drive components.

GWJ was part of this congress as exhibitor and welcomed visitors at Booth #109. GWJ presented the latest version of *TBK*. For more than 30 years, *TBK* software is widely accepted calculation software and is used by many companies around the globe in different industries.

The GWJ product range of innovative calculation software is wide- from standard software for classical machine elements to the determination of whole systems up to a complex special software. There are common features that all GWJ solutions share — intuitive design, sleek interface, easy to use and suitable applications for all users from beginner to very advanced.

GWJ´s extensive product portfolio covers many different applications - the web-based calculation software *eAssistant* and the classical software *TBK* for gearboxes including 3D CAD integration modules, system calculation for multi-stage gearboxes and *GearEngineer* to determine and generate the real 3D geometry of complex gearings. This geometry provides the basis to manufacture cylindrical and bevel gears in conjunction with multi-axis machining centers.

GWJ considers itself an ideal partner for the automotive branch from prototype manufacturer to supplier of components and systems in the drive technology business to the development of complex transmission systems for vehicle manufacturers.

For more information:

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

Tectorius

EXPANDS LUBRICANT AND COATINGS PORTFOLIO

Maelstrom Chemical/Tectorius has expanded its portfolio of synthetic lubricants and coatings. The Tec-Flon family of products now contains a wide range of non-silicone, synthetic oils, greases and pre-applied coatings for automotive, aerospace and special service application. Key features include high temperature performance, ultra-low volatility and compatibility with plastics and paint shops. Many Tec-Flon grades are lower cost, direct replacements for major brands. Example applications include automotive sub-assemblies, optical components, electrical contacts/electronics, gas handling, vacuum systems, oven/furnace components and corrugated processing equipment.

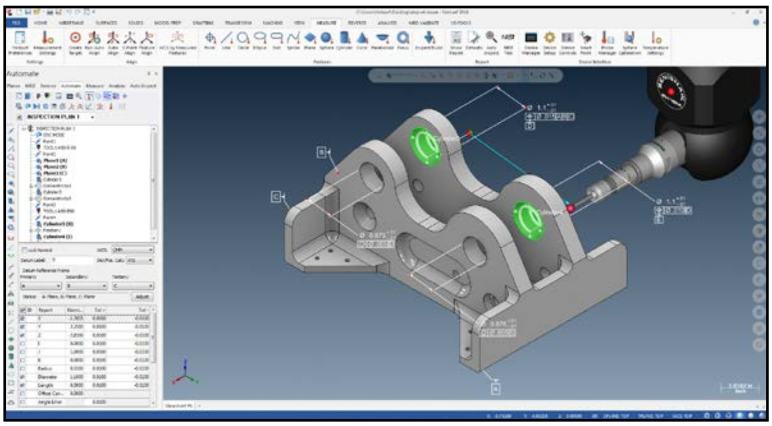
For more information:
Maelstrom Chemical/Tectorius
Phone: (586) 232-3999
www.tectorius.com

Verisurf

PRESENTS VERISURF 2018 SOFTWARE AT CONTROL 2018

Verisurf Software, Inc. recently presented *Verisurf 2018* at Control 2018, Stuttgart, Germany. *Verisurf 2018* is the latest release of the measurement software for automated quality inspection, reporting, scanning, reverse engineering, tool building and assembly guidance. Universal CMM is a key option to the new software as it insures software compatibility with virtually all CNC CMMs.

All CMMs, including previously closed legacy systems, are now open to *Verisurf* users streamlining productivity, training and ensuring compatibility. A universal CMM does not require controller upgrades or added software, the legacy CMM data is translated allowing the operator to take full advantage of the *Verisurf* user interface, data management and reporting functionality. This allows legacy CMMs to immediately become relevant once again as part of an overall measurement strategy.



Universal CMM communicates between *Verisurf's* standards-based I++ protocol and CMM controllers, enabling seamless interoperability between hardware and software. CMM operators avoid any risk associated with adopting new technology because with Universal CMM, they can continue to use legacy inspection programs if needed yet still enjoy the benefits of using Verisurf. Inspection programs created in *Verisurf* for a CNC CMM can also be used on portable systems. Human and technology resource utilization improves substantially when all measuring devices can be operated with the same metrology software and skill sets; the result is a manufacturing 'enterprise-wide' measurement solution.

A complete list of *Verisurf 2018* features is available on the company's website.

For more information:
Verisurf Software, Inc.
Phone: (888) 713-7201
www.verisurf.com

Schunk

DESIGNER JAWS INCREASE EFFICIENCY IN FINISH MACHINING

The intelligent jaw design of the Schunk UVB-HS soft chuck jaws defines a new class of efficiency in lathe chuck technology. With a combination of overheight and angle cutting, it achieves a whole bundle of efficiency effects during finish machining of workpieces. The unusual jaw height allows for a larger clamping surface on the workpiece, which reduces deformations. Alternatively, the distance between the workpiece to the chuck face can be increased and thus accessibility can be optimized. In comparison to conventional monoblock jaws, Schunk UVB-HS reduces the jaw weight by up at least 20% depending on the size. This increases energy efficiency and shortens the processing time, since the lathe chuck can be accelerated and braked faster. At the same time, the reduced jaw centrifugal force allows for higher holding forces on the workpiece, which means increased process reliability.

But it doesn't stop there: Angle cutting minimizes the danger of collisions with the turret and improves the fluid dynamics during machining. At high speeds, Schunk UVB-HS chuck jaws lower noise emissions by up to 10 dB, which halves the level of the perceived noise. Since significantly lower cooling lubricant is swirled around the machining area, it is easier to see the machining process. This also lowers the amount of aerosols in the air when the machine is opened. The highly efficient monoblock jaws with angle cutting are part of the over 1,200 jaw types in the world's largest standard program of chuck jaws from Schunk. They are available immediately for wedge bar lathe chucks with straight serration in the sizes 200, 250/260 and 315 and can be turned individually to the desired diameter.

For more information:
Schunk
Phone: (919) 572-2705
www.schunk.com

Overlapping Pursuits

More than any other field, IIoT overlaps directly with metrology's mission to analyze and measure as much of the manufacturing process as possible, and it's no surprise that the latter is utilizing the former.

Alex Cannella, Associate Editor

Metrology experts have been in the business of analyzing and measuring tools and gears for a long time. It's just one step of the gear manufacturing process, but also an established, essential one. With demands for manufacturing accuracy and process repeatability growing increasingly exacting, the need to make sure your products are up to specifications down to the micrometer is ever more pressing, and metrology experts are always there to step up and meet those demands.

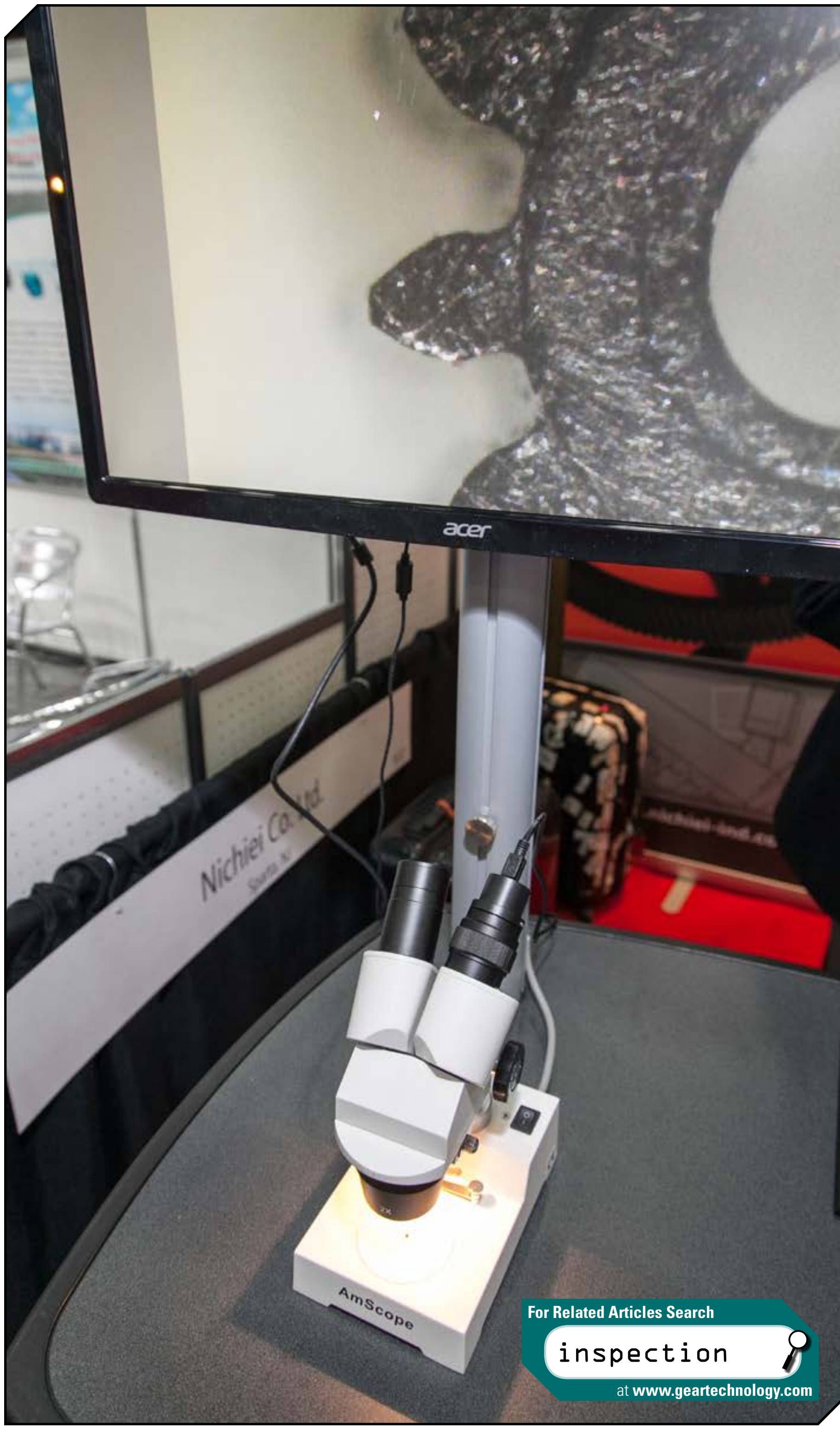
The Industrial Internet of Things, or Industry 4.0 as some in Europe call it, is all about that. From RFID tags to big data operations capable of analyzing heaps of digital information orders of magnitude vaster than ever before, IoT technology is a colossal leap forward, the largest we've seen since the advent of computers, in how we study and understand our own production processes.

Is it any surprise that these two fields would go hand in hand?

There isn't merely overlap between metrology and IoT technology — metrology stands squarely in the epicenter of innovation. By virtue of a common goal, metrology systems may stand to grow and improve more than any other field of manufacturing from the "Fourth Industrial Revolution," and we're already seeing the field being revolutionized by its pioneers.

"Metrology tools are in the business of providing data and the Internet of Things is a way to handle that data," Pat Nugent, vice president of product management at Mahr, said.

Take, for example, all the new doors the Internet of Things has opened for Klingelnberg. Closed loop systems, accurate digital twins, smart tooling systems, and uniform digital design data sets are just a few of the many new directions Klingelnberg's digital efforts are exploding out in.



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Our customers say it best!

Nick Schmelzer
Gear Lead Machinist

"The most decisive aspect when buying our 2nd ZP15 KAPP NILES machine is the advantage of a kinematic capability that allows us to work much bigger diameters than having to purchase a larger and higher priced machine. Since we're already running on a ZP15, we knew that we can count on the KAPP Technologies team for support whenever needed. The KAPP applications engineers are particularly responsive to our needs and their knowledgeable service team keeps our machines in top shape with their annual maintenance."

- Jerry Capone
Shop Operations Manager with Umbra Group

UMBRAGROUP

Umbra Group provides motion solutions and components or systems for Aerospace, Power, and Industrial high-tech markets.
They just purchased their 2nd ZP15 machine from KAPP NILES.

KAPP NILES

KAPP Technologies

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"All measuring- and production-machines do produce and collect huge amounts of data," Dr. Christof Gorgels, director of the measuring machines division at Klingelnberg, said. "Systematic evaluation of this data helps our customers to improve their processes, to decrease process times and to increase their profitableness and reliability."

One pillar of Industry 4.0's many advances in particular that has been most critical for Klingelnberg is interconnectivity. Many of Klingelnberg's most recent IoT-related advances come back to this one critical concept, most notably their closed loop system. At its absolute core, the Internet of Things is all about making machines communicate more effectively with each other, and more than any other new product or system coming out of Klingelnberg, the closed loop system takes advantage of this fact.

This closed loop system connects every machine in the manufacturing process together into a single system. Technically, closed loop systems are much bigger than just metrology machines. Design programs, grinding, cutting and finishing machines, and digital tooling are all connected alongside them. But inspection systems are one of the most critical elements in that chain.

Klingelnberg's closed loop system starts with a digital design of a workpiece, including digital recreations of the tooling and manufacturing processes utilized to make it. According to Gorgels, this digital design is the "expected outcome in a perfect manufacturing world," what the workpiece should look like without any outside forces or unexpected complications arising during the process.

Metrology machines come into the closed loop process after the workpiece has been ground down. Their job is to check each workpiece against that digital ideal, note any inconsistencies or imperfections, and if they find any, send that workpiece back to the grinders complete with information on what corrections need to be made to fix the piece.

And according to Gorgels, metrology machines in Klingelnberg's closed loop system can execute their tasks automatically, even on more complex workpieces.

In order to make this process possible, Klingelnberg has not only needed to know the parameters of their workpieces, but also of the tools used with them, and to that end, they've developed their most recent new release: smart tooling products. Many of Klingelnberg's tools now come with a data matrix code that identifies the tool. The tool's information is already part of the database, but scanning the code brings up that information, along with additional

details such as the tool's accuracy or how many workpieces it has cut. All this combines to create a digital twin for your manufacturing machines to utilize.

A digital twin is exactly what the name suggests: a digital recreation of a physical object that exists alongside it throughout the entirety of its lifecycle and often reflects not just its basic parameters, but also how that object changes over time. If set up to do so, digital twins can even make note of changing parameters such as when a gear is reground or how a tool is being worn down as its performance shifts over time.

In many cases, digital twins are used to follow individual workpieces from their inception all the way until they're eventually discarded by whoever purchases them. This gives manufacturers unprecedented and increasingly granular insight into the typical lifecycle of their products. In automotives, for example, the information from multiple digital twins can be collated and studied to inform a manufacturer about trends such as how often an individual part needs to be replaced, which in turn can identify weak points in a product's design that can be iterated upon.

Klingelnberg's smart tooling technology, however, creates digital twins of the tools and their associated workholding equipment, not the workpiece, which gives entirely different benefits that tie back into the closed loop system. It's no secret that your tool can affect the finished product and introduce variance into the process, so in order to create a fully digital design of the entire process before ever putting a gear to the grinder, Klingelnberg needs to understand how the tool will interact with the workpiece.

By having all of that tool's digital information available already in the system, Klingelnberg can understand exactly how every individual tool in the system should theoretically interact with a workpiece and incorporate that into the design process.

"If the process is known and the tool (e. g. a hob) is measured a simulation can show which errors on the workpiece are coming from the tool inaccuracy," Gorgels said.

Metrology machines are intrinsically tied to this step of the process, as well. In addition to their role of scanning workpieces for imperfections, they can also be used to scan tagged tools during setup to double check that they've been properly set up as initially programmed and reduce the risk of incorrect machining or an outright crash of the machine.

"By tagging the tools and scanning them before each use a lot of data is generated in order to improve efficiency, productivity and thus profitability of manufacturing processes," Gorgels said.

"The measuring machine is in this case the nucleus, where a tool and a data set are combined."

Currently, this smart tooling system is only available in Klingelnberg's bevel product line, but the company is working to expand it across their processes and is currently implementing it into their cylindrical gearing line, as well.

Data consistency is another challenge systems like Klingelnberg's closed loop can solve. Here again, the Internet of Things' focus on interconnectivity lubricates the process. By keeping each machine perpetually interconnected, every machine can draw on the same single digital data set, as opposed to being manually updated separately, removing the risk of errors arising from old data floating around in one machine or operator error.

"Connecting machines using exactly the same data ensures the consistency of data over multiple machines," Gorgels said. "This improves the quality and reliability of measuring results especially for companies with manufacturing sites distributed throughout the world. When measured data can be accessed via network, communication with machine tools can be established easily. This enables the closed loop in manufacturing around the whole manufacturing chain and thus the creation of a digital twin of each manufactured part."

According to Gorgels, this singular digital design data set is still rare in the gear world, but Klingelnberg utilizes modern techniques such as their KIMoS (Klingelnberg Integrated Manufacturing of Spiral Bevel Gears) software package to generate that data.

Gleason has seen similar advances brought about by IoT technology. Everything from closed loop systems to predictive analysis back through the gear design itself have been improving gear design, manufacturing and measurement processes there, as well. Douglas Beerck, vice president and general manager at Gleason Metrology Systems, has watched these innovations be implemented and has a few ideas on what might be next in the future.

"With the expansion of closed loop capability between the inspection machine and the machine tool, the predictive capability goes beyond the state of each machine individually and is being developed into a predictive capability of the gear manufacturing process itself," Beerck said. "With identification and part recognition technology, the machine, part, tool, operator, workholding, etc. can all be tracked and monitored and performance trends analyzed automatically in a lot of cases. The IIoT adds to the seamlessness and speed of the transfer of the data...Industry is really just beginning to tap into the capability IIoT tools have to enhance the manufacturing process, but the results are already driving significant throughout, uptime and quality improvements beyond what was thought possible just a few years ago."

Beerck also has a few ideas on how the industry might dig deeper into the Internet of Things' possibilities. In particular, he pointed to artificial intelligence as a future possibility. Perhaps not necessarily a full on AI as we might imagine one in a science fiction story, but a machine capable of learning and developing decision trees from the data we give it. As we continue to make data easier and faster to pass between machines than ever before, Beerck believes that machines will only grow smarter.

Of course, the Internet of Things may be providing massive benefits to both manufacturers and metrology experts alike, but its not without its challenges. As Nugent noted, a lot of manufacturers have been tempted by IoT networks such as those being developed by Amazon, but are cautious due to those networks' open nature. Wanting to keep one's cards close to the chest is a natural instinct in a competitive business environment, and Nugent's found that the prospect of having to show those cards intimidates many manufacturers.

"I think there's a lot of concern in the world of manufacturers about sharing this big data that would be created by really leveraging the Industrial Internet of Things somewhere outside of their walls," Nugent said. "While we all love the idea of working in the cloud, I think having the product data on every part you make be out there on some Amazon server out there makes a lot of customers of ours nervous."

And that's why Mahr has been working with an open source platform, ADAMOS (Adaptive Manufacturing Open Solutions). The main advantage Nugent has found with ADAMOS is that even though it's open source and cloud-based, individual companies can use the platform on their own private servers, thus keeping their data only in their own system instead of intermingling with everyone else.

ADAMOS is a joint venture being undertaken by DMG Mori, Zeiss and several other German manufacturing and software experts, but companies like Mahr have been adapting to incorporate the system. Mahr, for example, has been retooling their interfaces to work with the platform.

Mahr has also been bringing IoT to hand metrology tools, implementing wireless transmission capabilities across an increasing number of calipers and micrometers. Mahr is using the ANT+ protocol as the basis for connecting their hand tools to a single network. Nugent cited the protocol's low power consumption as a primary factor in choosing to use the protocol, as battery life is a concern with hand tools.

"We think that making it easy to collect that data is critically important," Nugent said. "The old days of — even with simple hand tools — measuring and writing down data on paper is gone."

The old days of a lot of things are fading in the manufacturing sector. As ever, the Internet of Things has already started changing how we do our jobs, and as Beerck noted, it still stands to potentially change everything a lot more. And metrology is not only being transformed by it, but also being made an an ever more indispensable part of the manufacturing process.

And just as it's no surprise that metrology and the Internet of Things go so well together, it won't be a surprise when both continue to rapidly evolve in tandem.

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Plastic Gear Design Remains a Work in Progress

Jack McGuinn, Senior Editor

Despite the development and availability of a number of newly engineered, rugged materials intended for plastic gear applications, some engineers/designers continue to believe metal is better. But there now exists a long list of simple poly materials (nylon and acetal, for example) that can now be mixed with other materials such as fiberglass and then reinforced with a carbon steel core.

However, designers may also be put off by the cost of certain plastic-in-place-of-metal gear applications. The cost occurs when the mentioned reinforcements are added to the mix — which can add hundreds of dollars to the cost of a simple spur gear, for example.

And while there are any number of websites available that present lists of plastic gears' positives and negatives, we include the following Good/Bad lists intended to provide some context for what follows.

Plastic gear attributes:

- Elimination of machining operations; capability of fabrication with inserts and integral designs
- Lightweight
- Reduction in shock, noise and vibration
- Parts uniformity
- In many applications, no or very little lubrication; self-lubricating in some cases (nylon)
- Corrosion-resistance.
- More forgiving tolerances than with metal gears
- Relatively simple production, with no pre- or post-production

A not-so-positive list of plastic gearing negatives includes:

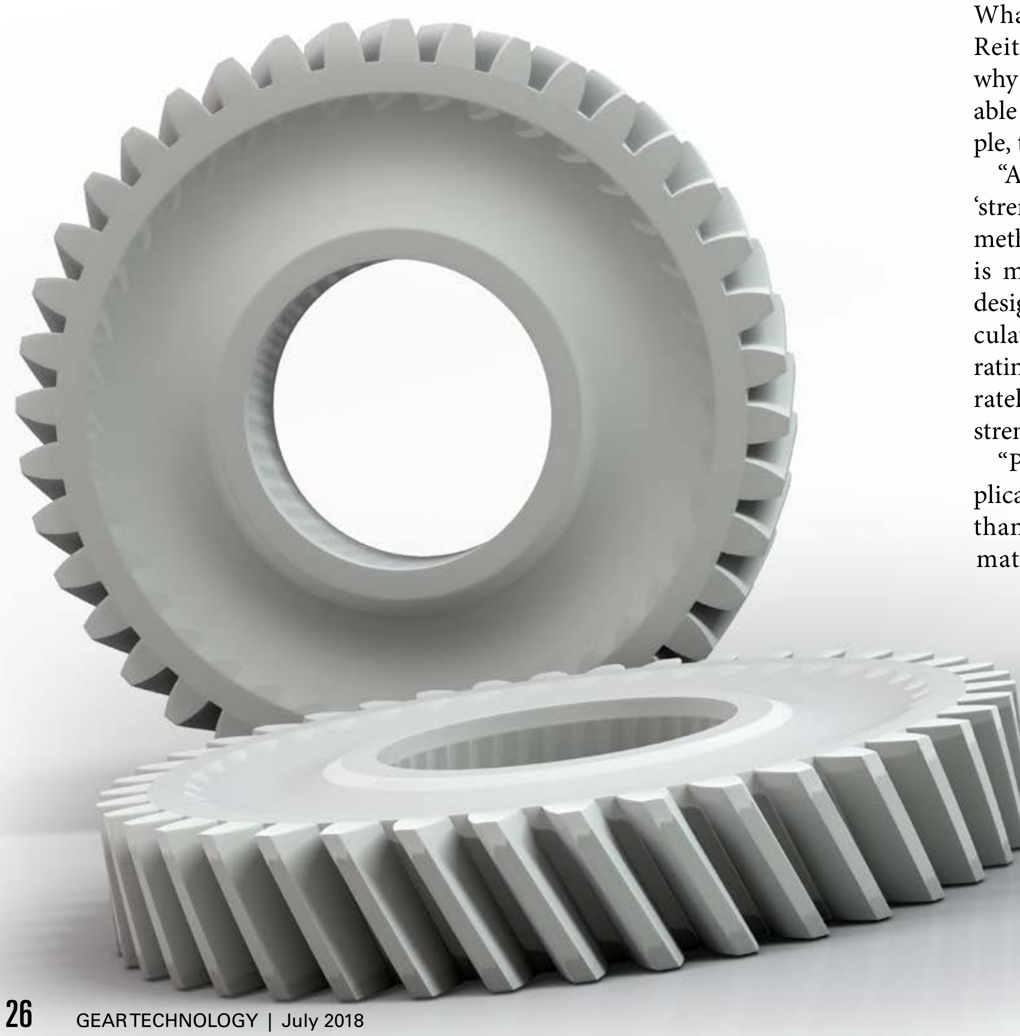
- Material cost can be markedly higher than basic metal gears, especially if custom poly materials are used
- Difficulty in wedding plastic gears with metal shafts
- Often less strength than similar metal gears
- Problems with high tolerances vs. metal gears
- Not as dimensionally stable as metal gears in that plastic gears are adversely affected by temperature and humidity conditions

Understand, however, that this is not an article on the specifics of plastic gear design. Rather, what follows presents some of the ongoing big-picture issues that affect plastic gear designers and end-users alike.

Take, for example, the continued lack of published standards for plastic gears (although some *rating* methods exist). What's up with that? We asked Ernie Reiter, who runs Web Gear Services, why he thinks that there is still no available standard for estimating, for example, the strength of plastic gears.

"AGMA and ISO do not estimate the 'strength of gears' but instead provide a method of rating gears. A rating method is merely a means of comparing one design to another using a common calculation method. The AGMA and ISO rating methods do not necessarily accurately predict a particular gear's actual strength.

"Plastic gears are much more complicated in developing a rating method than metal gears. This is because the material properties vary widely with temperature coming both from ambient conditions and frictional heat. The materials are also strain rate sensitive and, and depending on the grade may allow for larger elastic and plastic tooth deflections under load that may promote load sharing."



"ISO in its standards has not focused on plastic gears at all. AGMA's Plastic Gearing Committee has focused on writing documents related to specification, measurement, materials and testing of plastic gears. Creating a standard for rating plastic gears has been discussed as a work project, but the priorities have first been put onto other topics."

Brian Stringer, Manager KISSsoft Sales and Application Engineering, USA/Canada, says "There are currently some guidelines (not official standards) that can be used for calculation of the load carrying capacity for plastic gears. VDI 2736 part 2 (cylindrical gears) and VD2736 part 3 (crossed helical gears) are two examples. These calculation methods are available in gear software such as *KISSsoft*. AGMA also has a plastics gearing committee that is working towards some of their own new standards and guidelines for plastic gears."

For Glenn Ellis, Senior Gear Engineer, ABA-PGT Inc., "It does not seem that there is a standard system of testing plastic materials. Some gear software has estimating calculations but only for a limited amount of materials."

We asked if FEA (finite element analysis) — the long-established method for verifying the strength of metal gears — could work for plastic gears as well.

"I would disagree," Stringer says. "Plastics are viscoelastic materials, and therefore experience both viscous and elastic characteristics when undergoing deformation. With that being said, plastics are non-isotropic, and cannot be treated as such during FEA. This is complicated even further when you are looking at plastics with fillers such as glass fiber, where you have to take into account the stiffness and alignment of the fibers."

Meanwhile, today's designers of plastic gears have more material choices than ever before in developing new applications. But is there sufficient test data available for all of these materials?

Ellis declares that, "There is strength data for most materials. However there is limited data in regard to wear between different material types."

"Not even close," says Stringer. "This is the largest hurdle to currently overcome when designing plastic gears. It is very hard to design anything without sufficient material data. While there is plenty of data available for plastics that have been around for a long time (POM, PA66, etc.), there is limited data available for newer, high-temperature, engineering grade resins. Most of these materials have basic mechanical data available, like modulus and tensile strength, but most do not have fatigue data to help predict flank and root bending safety factors. This data is expensive and time-consuming to collect, as it requires expensive equipment, lots of time/money, and also the ability to control the temperature of the plastic gears during cycling in order to create S-N curves at many different temperatures. All this data must be collected at different temperatures since the mechanical properties of plastics degrade with

Photo courtesy ABA-PGT.

increase in temperature."

It has been reported that plastic gear designers are also hampered by a lack of available material characterization guidelines for plastic gear calculation.

"This is true on some of the newer materials, Says Ellis.

Also in agreement, Stringer says that, "As stated in the answer to the previous question, it is very difficult to design without having enough material data. Multiple calculation methods must be used if possible, and also experience and educated guessing. It is critical to get your material suppliers involved in the process, as they can speak on experience and past projects to compare stress values, and they may have additional internal data to share that they may have not released to the public."

Further researching plastic gear manufacture, we determine, not surprisingly, suppliers are tasked with designing and manufacturing plastic gears and gear components for applications in which there is no international standard available for gear predictive engineering.

Ellis offers the possibility that, "The end user may not be aware of this situation. They rely on the gear molder to produce an adequate gear."

To that end Stringer explains that, "It is certainly tough to sell a plastic gear solution to companies whose applications are pushing the limits of the current materials. Most companies will not take the risk if they don't have the data and calculations to show confidence in the plastic. What is also challenging is that there are a lot of molding companies out there, and many of them mold gears like they would any other component. It is important to work with an actual gear molder who specializes in this. You cannot mold a gear correctly if you do not understand how to design gears, the gear materials themselves, or if you cannot inspect molded plastic gear using the appropriate methods. This includes at least double flank composite inspection using a master gear, to report Total Composite Error (TCE), Tooth-to-Tooth Composite Error (TTCE), and Test Radius (TR)."

Reiter states that, "Plastic gears are designed by benchmarking — so this is not an issue. They are necessary to use in order to achieve low cost designs. We evaluate an existing plastic gear design using some calculating method of our choosing. Most plastics people have their own methods for stress analysis that they have developed; none of these methods is exactly correct, but they get you a comparative result.

"We then evaluate a new design relative to the same calculating method as what was used in the benchmark to project ahead what is likely to happen. As long as the temperature of the application, materials, and loading is generally similar (even though magnitudes may be different) the benchmarking should lead to a good working solution."

In recent years simulation software development and increases in computing power have led to more reliable gear simulations, but often their full capacity cannot be exploited due, once again, to a dearth of gear material data. To what do you attribute the shortage in gear material data?

"The knowledge of what data is needed," Reiter says. "Also, plastic gears represent a fraction of the material volumes that granulate suppliers sell of the grades used in gears. Testing is expensive

and granulate suppliers may have a difficult time in justifying the expense to do the testing relative to the size of the granulate market they can achieve."

Gleason's Stringer says "Time/cost to actually collect this data. Also, material suppliers may be hesitant to release all their internal data due to liability and uncertainty in the data collection process. There is also the topic of how this data is collected, and if all material suppliers are using the same methods/standards (if available), to collect this data. Without a unified method to collect plastic gear data, we can never be certain that the data is accurate."

"This (lack of data) is true," says ABA's Ellis. "It appears that only a few material manufactures have gotten together with the software designers to fill the information data archives."

Research indicates that the most common plastic gear failure modes are wear, fatigue, and plastic flow due to material creep or elevated temperature exposure. We asked our contributors for comment.

"Yes," Stringer agrees. "Wear would be mostly seen on high RPM, unlubricated, continuously running applications (sometimes if the material has a filler such as glass fiber, this can increase the wear as well). Fatigue can occur from root bending stress over a number of cycles on higher loaded applications. Sometimes a gear pair will see a peak torque that simply breaks the teeth in a stall condition, which isn't due to fatigue at all, but more so due to the tensile strength of the material at a specific temperature. High temperature is the enemy of plastics, so it is important to not only understand what you're operating and ambient temperatures are, but what your actual temperature at the tooth flank and tooth root are during operation."

Reiter has a different take. "I disagree that wear is one of the most common plastic gear failure modes. It does happen but most plastic gears that I see are used intermittently and wear is not an issue. Fatigue fractures and plastic flow


Photo courtesy ABA-PGT.

Photo courtesy ABA-PGT.

are significant failure modes. In crossed axis helical gear applications where hard stop exists in a gearbox, shear of the gear teeth is a significant failure mode at stall."

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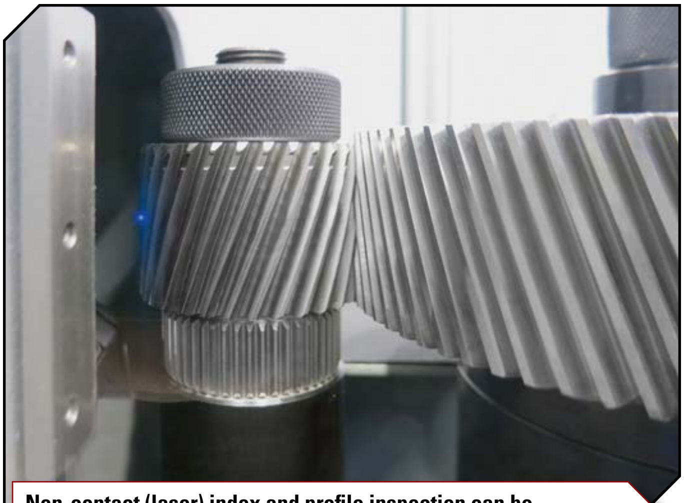
In-Process, Complete Gear Inspection at Light Speeds

New GRSL technology adds value to high-volume transmission gear inspection by combining non-contact laser inspection with tried-and-true composite roll testing.

Douglas Beerck, Vice President and General Manager, Gleason Metrology Systems

Driven by recent advances in power transmission design and manufacturing technologies, unprecedented improvements in gearbox quality, reliability, noise reduction and overall performance are now within reach. At Gleason Metrology Systems, we're racing to keep pace with the inspection challenges that now exist for today's gear manufacturers and, ultimately, to add value with new technologies that improve accuracies, cycle times, capabilities and ease of use.

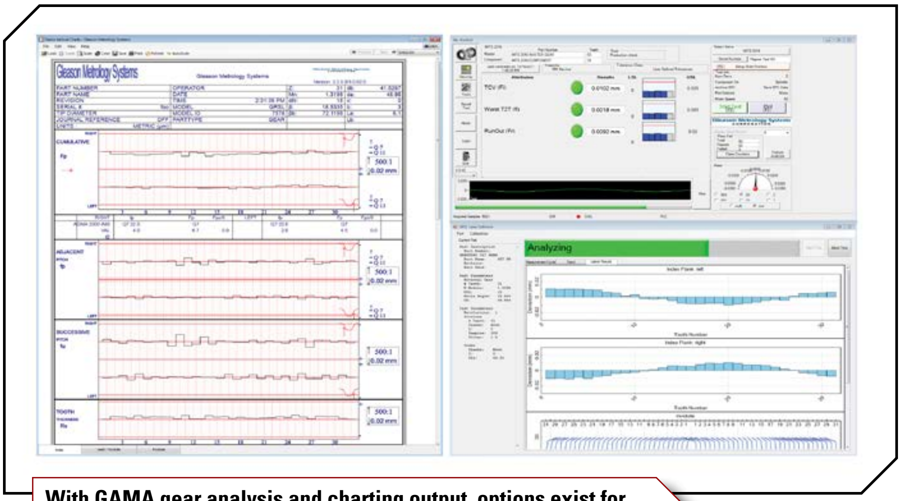


Non-contact (laser) index and profile inspection can be performed on all the gear teeth in a matter of just 10 to 15 seconds, as compared to several minutes when done conventionally.

GRSL: Bringing Non-Contact to High Volume

The most recent example of where all of these 'added value' user benefits have converged in a single technology: the new Gleason GRSL Gear Rolling System with non-contact laser inspection. GRSL combines the latest non-contact gear analytical measurement innovation with the double-flank roll test gear inspection process used today in most high-volume gear production where 100% inspection is required. This new product follows the strategy of the recently introduced multi-purpose GMSL non-contact inspection system from Gleason. Where the GMSL was developed to exceed the requirements of today's most stringent gear processing research, development and reverse engineering needs, the GRSL brings high accuracy, high speed, non-contact measurement of gears in-process to the high-volume production environment, where performance expectations have never been higher.

The GRSL product stays true to the strategy our partner customers continue to ask us to follow. It adds value by adding measuring capability with multiple sensors on a common platform to reduce cost of ownership, the number of operators required and the footprint. In addition, it adds throughput by measuring both the composite, functional error and the individual part characteristics of both involute and index simultaneously during the same revolution of the gear during the test cycle.



With GAMA gear analysis and charting output, options exist for AGMA, DIN, ISO as well as OEM specific analysis for the involute and index measurements, with common charting as seen on the popular GMS series of analytical machines.

Single Platform, Exciting Possibilities

This patent-pending, dual-purpose inspection system provides additional value by offering the GRSL platform in three different configurations for use as a stand-alone manual gauge, a semi-automatic gauge or even as a fully automated gauge where high-volume throughput is the priority. Tests for full analytical results of both involute and index are performed on all teeth for most external, cylindrical gears up to 250 mm diameter in a matter of seconds along with the composite double-flank roll test, again with both tests taking place simultaneously.

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inspection
at www.geartechnology.com

With the new GRSL, the power of high-speed involute and index measurements also comes with the ability to integrate with Gleason Metrology's *GAMA* gear analysis and charting output. This means options for AGMA, DIN, ISO as well as OEM specific analysis are available for the involute and index measurements, with common charting as seen on the GMS line of analytical machines throughout the gear industry today.

Consider the possibilities of full, high speed involute and index measurement in process, inline. Add to that the ability to network this data in a closed-loop configuration directly to the machine tool using *Gleason Connect* to communicate results that can assist in determining necessary changes to the machine tool, the cutting tool, part setup, etc. All of this is now available, fully integrated with the traditional double-flank roll composite testing still called for on most part prints today in high-volume gear production.

GRSL combines the latest non-contact gear analytical measurement innovation with double-flank roll test gear inspection process to deliver unprecedented in-process inspection speed and flexibility for cylindrical gears up to 250 mm in diameter.

Faster Cycle Times, Greater Throughput.

Measurements of analytical characteristics are typically taken on a dedicated, stand-alone analytical machine in a lab or on the shop floor, but not inline. This typically takes several minutes for a sampling of teeth, say every 90 degrees, for involute measurement and all teeth for index. The GRSL offers analytical measurement of all teeth in a matter of seconds, depending on the gear size, with many tests completed in 10 to 15 seconds, and provides the double-flank composite test data simultaneously, thus delivering significant throughput value for our end users. The GRSL also offers the flexibility of operating the analytical and composite, double flank tests independent of one another if desired. This can offer advantages such as extending the life of the master gear if , for example, it is determined that not all parts require double-flank composite testing as more is learned over time from the involute and index measurements provided by the non-contact laser inspection.

Finally, by combining Gleason 4.0 technology with the high-speed, analytical inspection capability now available with the new GRSL, gear manufacturers can 'close the loop' between inspection system and machine tool to make machine corrections fast, error-free and in a fully automated process.

Get In Touch With Non-Contact

Interested customers can *get in touch with non-contact* at the Gleason booth at this year's International Machine Tool Exhibition (IMTS) in Chicago September 10–15.

For more information
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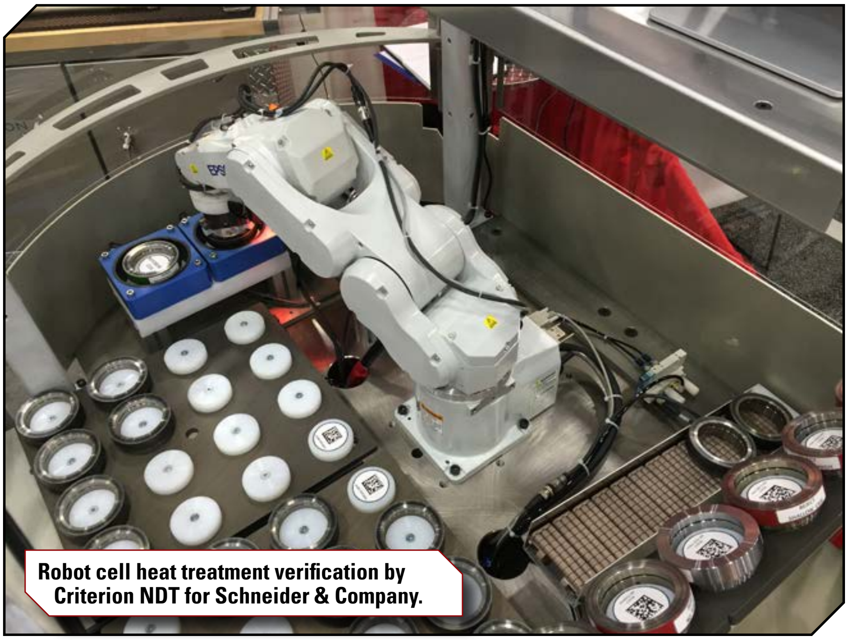
Douglas Beerck is a veteran of 25 years in the gear metrology industry and has been Vice President and General Manager of Gleason Metrology Systems since 2005.

Facing the Future

A Look at Emerging Technologies in Heat Treating

Matthew Jaster, Senior Editor

The following article highlights some of the recent heat treat products, technologies and industry news articles for gear manufacturing. Topics include a technical article on induction heat treat advancements, a developing story on augmented reality on the shop floor and the use of automation and IIoT to liven-up eddy current inspection solutions. Just like general manufacturing, heat treatment is going through a variety of noteworthy changes and developments aimed at making it easier to manufacture and improve gear production. Learn more at *www.geartechnology.com*.



Robot cell heat treatment verification by Criterion NDT for Schneider & Company.

Criterion NDT

LOOKS TO AUTOMATION TO MEET THE CHANGING NEEDS OF GEAR MANUFACTURERS

Criterion NDT specializes in engineered eddy current inspection solutions for the non-destructive testing of critical or essential components. The company serves major automotive OEMs, tier suppliers, industrial products manufacturers, and medical device companies.

Criterion NDT offers single-channel and single-frequency instruments in addition to multi-channel, multi-frequency inspection instruments for more complex inspections. These eddy current instruments and probes have been developed specifically for the component test market, and are simple to incorporate into semi- or fully-automated systems.

Gear Technology recently caught up with Joe Jessop, president at Criterion NDT, Inc., to discuss the role automation plays in the inspection process for heat treating.

Meeting the Challenges of Gear Manufacturing Today

Jessop said there is a lot to consider when designing gears. A mechanical engineer will evaluate a multitude of application aspects, in order to ensure they provide an optimum designed solution. The dimensional calculations must be precise and should be expected when produced on CNC machines. The end goal is that each part manufactured will be physically identical, within some very small tolerance margin.

"Heat treating is one of the final key steps to ensuring a manufactured product will provide its end user the intended function, service life and potential safety requirements," Jessop said. "Automation of heat treating processes provides manufacturers and design engineers with the confidence that each of the manufactured products will result in a correct and consistent uniformity of every manufactured part, which meet the needs of the application as the engineer intended."

This is where Criterion NDT comes into play. Advanced eddy current (electromagnetic test) instrumentation is a key component of an automated heat treatment inspection system. The instruments provide intuitive user interfaces and essential industrial I/O to support automated testing of manufactured materials.

"Modern instrumentation features provide automated adjustments of product inspection limits, minimizing operator interfacing and human subjectivity in order to provide consistent, repeatable and impartial evaluation of each manufactured part. Proper implementation of this automated inspection technology can non-destructively test every part for correct heat treatment results, thereby reducing the number of parts that are destroyed in the lab," Jessop said.

This saves gear manufactures money by minimizing employee time gathering and cutting parts, reducing scrap and consumable materials expense, while ensuring improperly heat treat parts are quarantined before exiting the factory.

Improving Technologies

Jessop believes that leveraging advancements in robotics and the ever increasing power of computer processing, provides gear manufacturers with a range of faster and more precise automation system components. Continued improvements to ancillary devices also help to reduce the time and expense to manufacture a given part. Coupling the key system devices with advanced subordinate controls contribute to automation stations production speed improvements, while reducing manual operations previously required for system setup/training and production.

"For example, an automotive transmission gear can be evaluated for heat treatment in less than 200ms after eddy current sensor engagement. The use of robotics for system setup (loading and unloading of gear components) removes operator interaction, thereby increasing setup time with real world operational conditions," Jessop added.

The end goal is ensuring that the eddy current instrumentation Criterion NDT develops provides thoughtful and flexible communication methods and protocol solutions. Working closely with regional machine builders ensures gear/component manufacturers have a responsive local source for any systems support needed. Jessop said that accessibility, application customization and responsiveness provide Criterion's customers with a unique and welcomed systems solutions partnership.

Bridging the Skills Gap

The skills gap is still a hot topic across every facet of manufacturing and automation is no exception. So how are manufacturers filling the void left by employees that have been running these shops for 25 to 35 years?

"What I've witness during my system installations & training at manufacturing companies is that younger engineers are assigned to one or more of production lines, consisting of one or more high-end automation systems. While this new generation demonstrates the ability to easily comprehend new concepts and complex systems, the rate of employee turnover has appeared to increase due to workload burnout," Jessop said.

Recognizing this new normal of high turnover, Criterion NDT has made a decision to take an often misunderstood technology with overly complicated instruments and make them more intuitive. "This makes the training and operation much easier for the newer individuals as well as their occasional interaction with the instruments during regular production," he added.

The company is also looking into IIoT solutions that can provide additional benefits when it comes to productivity and training. "This is an area that is providing some exciting opportunities for manufacturers, which we are anxious to explore," Jessop said. "We will remain open and adaptable to our customer's needs as they arise."

Competition continuously drives innovation, Jessop said. "Evolution specifics are hard to pin down, but I think it's a safe bet saying that there will always be incremental changes providing the end users with something a little faster, more reliable and cheaper to operate."

For more information:
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Criterionndt.com

Gears and test coils that were part of an automated water pump assembly station. Eddy current test instrumentation and coils then confirmed heat treatment in advance of pressing the gears onto the water pump shaft.

Experience Pays Off

Criterion NDT's team of applications engineers has the know-how to develop solutions to meet inspection requirements. One example was a transmission gear supplier that was shipping gears that were too soft, resulting in transmission failures. The gear supplier was forced to pay the automobile manufacturer for the entire cost of the failed transmission.

The solution was for the gear supplier to install an InSite HT eddy current test instrument and encircling coil downstream from their induction hardening system. The InSite HT simultaneously tests components at eight unique frequencies, helping it to capture multiple failure modes.

The InSite HT is very easy to set up. Known good components are used to develop the heat treat testing standards. The data captured from the good components automatically creates acceptance thresholds for all eight frequencies. The components under test are compared to these acceptance thresholds. Testing times of less than 1 second per part are achievable, making it easy to install in a production line.

The InSite HT has full industrial I/O capabilities, enabling it to interface with material handling systems. The system can be set up to send alarms on consecutive rejects, indicating that there is a process issue on the production line. These could include power failures or bent/damaged induction heating coils. Plugged cooling nozzles can also cause an improper quench which, depending on the severity of the reduced flow, could result in improperly heat treated parts.

Another example was a powder metal fuel pump manufacturer required an in-line hardness test to provide results comparable with those from Rockwell hardness testers. The system had to inspect 100% of the parts and run two lines simultaneously. Parts to be tested included 15 star sizes, 10 ring sizes and three lobe geometries for each size. The test had to be easy to configure with minimal set-up changes. The goal was to reduce production scrap and warranty costs.

The manufacturer installed a multi-frequency eddy current test system downstream of the heat-treat furnace. The system included a multi-channel, multi-frequency eddy current instrument, two eddy current hardness testing coils (one for stars and one for rings), and two sorting stations (one per lane). This provided 100% component testing up to 60 parts per minute, with the ability to physically reject out-of-tolerance components.

While eddy current testing is typically used as a go/no-go test, we were able to develop a close correlation between a measured Rockwell hardness (HrB) and the eddy current results. In an initial sample test, the eddy current test results and actual Rockwell hardness readings are compared.

From this initial test the correlation between Rockwell hardness and eddy current was very good, showing only about 1~3 HrB points variation. Eddy current readings (solid blue line) tended to show a more consistent value when compared to the Rockwell readings. During a subsequent production test, the Rockwell hardness readings were accurate to ±1.0 HrB while the eddy current test provided more consistent results.

For these and other case studies visit *criterionndt.com*

Inductoheat's Dr. Valery Rudnev received two awards at the ASM International Thermal Processing in Motion conference.

Dr. Valery Rudnev

RECEIVES TWO PRESTIGIOUS HEAT TREATING AWARDS

Dr. Valery Rudnev was recognized during the opening ceremony of the American Society for Materials (ASM International) *Thermal Processing in Motion* conference. Dr. Rudnev, director of science and technology at Inductoheat Inc., an Inductotherm Group Company, received two prestigious awards for his contributions in the field of induction heating and heat-treating.

Dr. Rudnev was elected as a Fellow to The International Federation for Heat Treatment and Surface Engineering (IFHTSE), "*For his preeminence in induction heat treating and modeling of the induction heat treating process*" (IFTSE, 2018). IFHTSE is a nonprofit group of scientific/technological societies and associations, groups and companies and individuals whose primary interest is heat treatment and surface engineering. Dr. Valery Rudnev is also Fellow of ASM International and considered by many to be one of the leading global figures in the induction heating and heat-treating industry. He has more than 30 years of experience and is known among induction heating professionals as "*Professor Induction*." His credits include a great deal of "*know-how*", more than *50 patents and inventions* (U.S. and International) and more than 250 engineering/scientific publications.

Dr. Rudnev was also presented with the ASM International "Best-Paper in Heat Treating" award for co-authoring an article entitled "*Revolution — Not Evolution — Necessary to Advance Induction Heat Treating*." The article was published in the September 2017 issue of *Advanced Materials & Processes Magazine* (HTPro quarterly newsletter), and co-authored by Gary Doyon, Collin Russell, and John Maher. The ASM International Heat Treating Society, Research and Development Committee, established this award to recognize the best papers in the heat treat industry each year. To be considered, papers must appear in either the HTPro quarterly newsletter or be published in ASM's Heat Treat conference proceedings. Papers are judged on several criteria including production readiness and breadth of potential applications.

Over the years, Dr. Rudnev has contributed a number of publications for ***Gear Technology*** magazine.

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Seco/Warwick

DEVELOPS AUGMENTED REALITY TECHNOLOGIES FOR HEAT TREATING

Augmented reality (AR) and virtual reality (VR) are two technologies that are often mentioned simultaneously and often confused. VR and AR are approaches of different but similar formats. What is the difference between them? Virtual reality (VR) replaces the real one, cutting off the user from the environment. AR is a technology that enriches its experience, supporting the real world with artificial images, sounds or other stimuli, and Seco/Lens is based on this technology.

Seco/Lens is an application that, based on Microsoft holographic computer—HoloLens, introduces heavy industry into the world of augmented reality. Slawomir Wachowski, director of the automation department at Seco/Warwick created the solution as a way to blend digital components—sensors, displays and data processors—to real manufacturing environments.

Slawomir Wachowski created the Seco/Lens technology at Seco/Warwick.

Seco/Lens can superimpose previously developed 3D models of the device for heat treatment of metals enabling its monitoring, diagnostics, maintenance of the production process, remote repair and planning the most optimal layout of the production line on the hall.

Seco/Lens will allow for a very accurate visualization of Seco/Warwick solutions, as well as for conducting training on the operation of the device without the need for expensive and time-consuming travel. With this technology, a service engineer can check and verify equipment from his desk across the globe. Seco/Lens presents an efficient and accurate means to conduct remote repairs and equipment monitoring.

This is just one of many R&D projects that Seco/Warwick is investing on a national and global level to promote new heat treat technologies.

In 2016, the company launched Seco/Lab, a state-of-the-art metallographic laboratory to conduct its own, unique research and carry out full metallographic tests and develop the acquired or purchased technology, as well as expansively invest in new production undertakings around the world.

The metallographic laboratory at Seco/Warwick is divided into two areas. The first one conducts preliminary work, i.e. prepares material for studies. The research area, on the other hand, conducts analyses of the prepared samples. The Seco/Warwick R&D department is not just about technological trials or the metallography laboratory; it also provides design support using specialized computer software. The new office space serves to carry out computer simulations using the *ANSYS* application, which is based on the finite element method (FEM).

Using the *ANSYS* software the company is able to model the distribution of temperatures, flow speeds, pressures, as well as distribution of stress, deformation, etc. Numerical analyses contribute to significant reduction in design times, as well as costs. They are an excellent tool which enables to develop and optimize the construction of their equipment, without the need to build expensive and complex physical models. The use of CFX and Mechanical modules significantly extends the range of research capabilities of the Seco/Warwick R&D department.

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Inspection System Upgrades Meet EV Gear Challenges

Delta Research upgrades its Gleason Metrology 'Workhorses' to meet the development requirements of the latest electrical drive vehicles.

With upwards of 70 million Electric and Hybrid Vehicles (EVs) predicted to be in operation by year 2030, automotive OEMs and their suppliers are racing to develop the next generation of more efficient and affordable electric cars, trucks and buses. Delta Research, a leading Livonia, Michigan producer of high-precision gears, gearboxes and transmission components, is deeply immersed in the efforts of many of the world's leading OEMs to develop EV transmission gears that improve overall efficiency and, most importantly, optimize acoustics. It's the quest for quieter gears that's driving development of a new class of very high quality transmission gears with mirror-like finishes that reduce wear and vibration — and adding greatly to the workload of a very busy Delta Quality Lab, says Delta Research Vice President of Operations Tony Werschky. "Prototype gear development relies heavily on metrology equipment, and never more so than with these new gears requiring very high precision, mirrored flanks," he says. "As we were planning our actions for expanding capacity of advanced inspection capabilities for gears, we found a practical and cost effective solution from Gleason Metrology Systems."

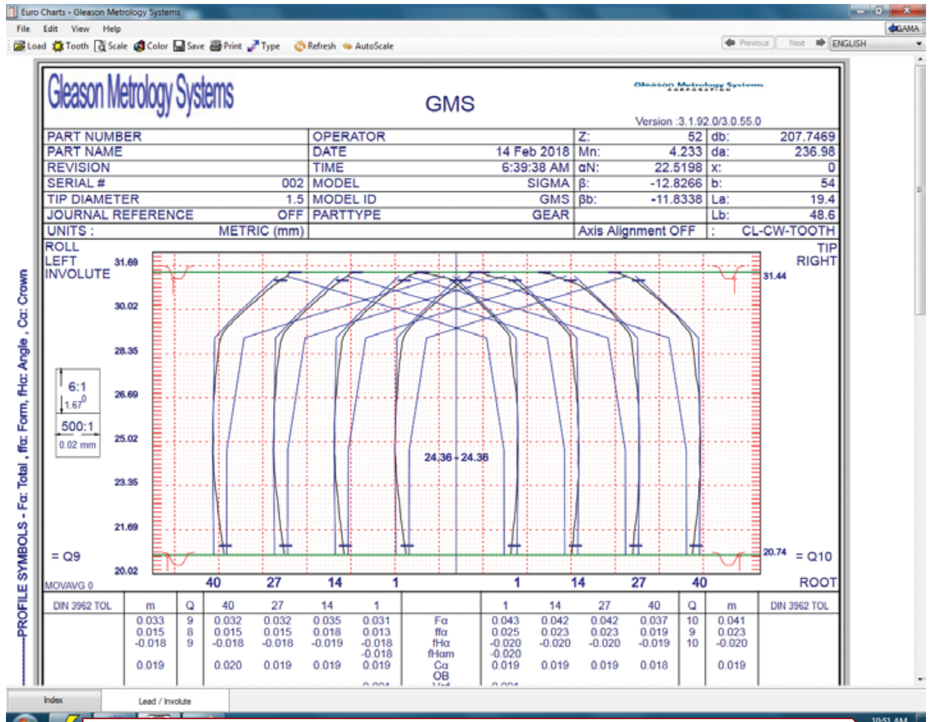

Refurbishing existing inspection equipment has resulted in increased capability and productivity at Delta Research.

Inspection 'Workhorses' Running Like New. Gleason Regional Sales Manager Metrology Products Americas Dave Taylor proposed that Delta could save significantly on new equipment costs, and add capabilities more quickly to its Quality Lab, by simply upgrading Delta's existing two SIGMA 3 gear inspection systems to like-new condition. These Gleason machines, built in 2005, were still in everyday use but limited primarily to the routine inspection requirements of production parts. "In fact, one of the SIGMA machines had been dedicated for years to inspecting just a single part that's produced in high volumes," recalls Taylor. "This short, highly repetitive motion had begun to produce some wear and tear on the X (radial) and Z (vertical) axes after years of heavy use, further limiting its effectiveness. Nonetheless, these two machines were prime candidates for an upgrade program that would add important capabilities and functionality on par with our current generation GMS systems. Delta saw the potential, and gave us the green light."


Delta Research's Tony Werschky (left) and Gleason's Dave Taylor (right) shown here with one of two Gleason SIGMA 3 upgrades.

Over the course of about four weeks, Gleason service personnel completed the upgrade program. For the SIGMA machines, this meant installing an SP80H Renishaw fully digital 3-D

scanning probe system and all associated hardware, combined with installation of Gleason's latest *GAMA* suite of applications software and Windows system, thus bringing the SIGMA machines to the current level of applications software and probing system found on the latest generation of Gleason GMS machines. Additionally, the guideways for the X and Z axes for the one SIGMA described previously were returned to Gleason Metrology Systems' facility in Dayton, OH, where they were re-ground, inspected in-house and returned in like-new condition. The existing machine base, sub-assemblies, mechanical components, drives and motors on both SIGMA machines were inspected, determined to be in good working order and did not require replacement or major refurbishment. The controllers were upgraded in order to run the new *GAMA* suite of software, and a flat screen monitor was added.



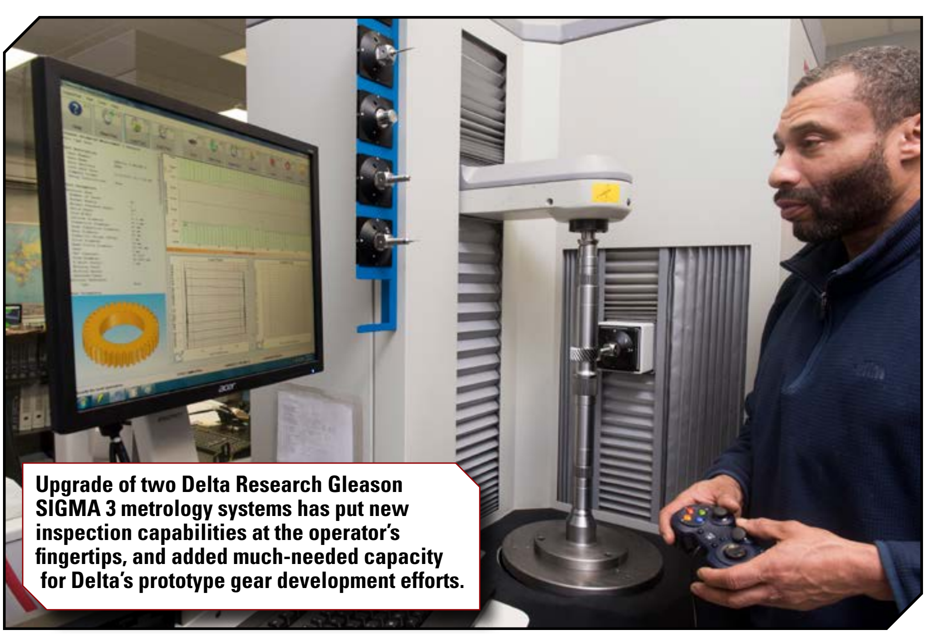
GAMA simplifies the creation of new part programs, and aids the operator with dynamic charts that depict index, lead, and involute tests as they progress.

"It's like having a new machine — we now can do things with the SIGMA machines that would have been impossible before," says Werschky. "The new probe system, along with the added *GAMA* software, makes it easy to change over and apply a broad range of styli to do everything from root scans to tooth contact analysis to unknown gear checks to inspection of hobs, shaper cutters — even straight bevel gears. We even have the capability now to do surface finish inspection. But it's the *GAMA* software package that really makes the difference. Our operators have found it to be very easy to use, and we now have the capability to quickly and easily output data to conform to all the international industrial standards (AGMA, DIN, ISO, JIS, GOST) as well as utilize the many custom analysis packages developed by Gleason for leading gear OEMs."

Note that, with the addition of *GAMA*'s GearNet feature, both machines now can share a common database of part programs and inspection history, eliminating the time-consuming duplication of programming on two machines.

Werschky says that a day or two of training was all it took for his operators to begin using *GAMA* and performing gear inspections. The point-and-click graphical user interface makes it much easier to create new programs, and the operator is aided throughout the gear inspection with an information panel that displays all pertinent information on the workpiece and type of inspections being performed as well as dynamic, real-time charts that depict index, lead and involute tests as they progress.

"Not every OEM is around to adequately service their older machines, let alone offering such an effective way to extend their useful life," concludes Werschky. "The Gleason upgrade solution nicely fills the gap between the limitations of older machines, and the significantly higher cost of brand-new machines."



Upgrade of two Delta Research Gleason SIGMA 3 metrology systems has put new inspection capabilities at the operator's fingertips, and added much-needed capacity for Delta's prototype gear development efforts.

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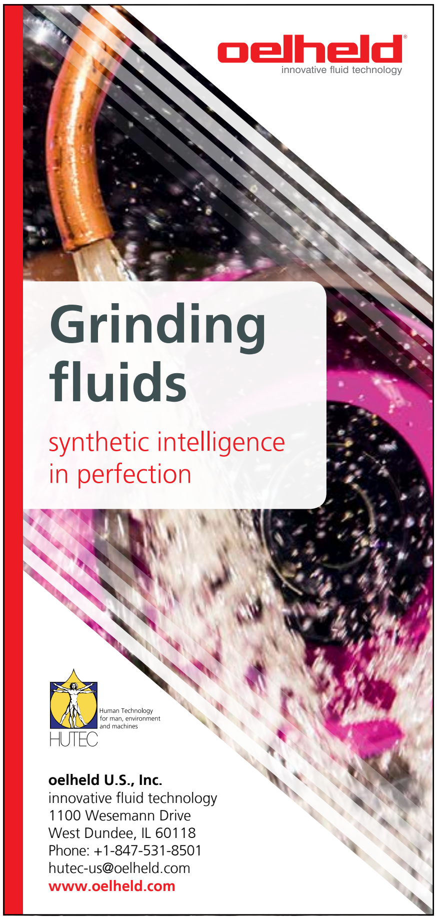
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A Comparison of Current AGMA, ISO and API Gear Rating Methods

John M. Rinaldo

Introduction

There are many different gear rating methods in use today, and they can give substantially different results for any given gearset. This paper will make it easy to understand the choices and the impact the choices have on gearbox design. Eight standards are included — AGMA 2001; AGMA 6011; AGMA 6013; ISO 6336; API 613; API 617; API 672; and API 677. A brief introduction and history of each standard is presented, and the basic differences between them are highlighted. Two sets of examples are used to illustrate the differences. These examples are presented in both tabular and graphical format, and are fully discussed. The first set contains a wide range of gears, and each gearset is rated by each standard. The second set compares gears designed for a specific set of requirements according to each of these standards. The perils of increasing service factor are mentioned, particularly in regard to high pitch line velocity gears. Finally, there is a discussion of how to make a gearbox more reliable without changing the rating method or service factor. The choice of rating method can have a huge impact on the size of the gearbox, and this paper should help avoid specifying the wrong standard and having an oversized gearbox. It should also be useful as an aid to customers who are unsure of the differences between the standards.

Description of the Standards

API 613 — 5th edition (2003): ***Special Purpose Gear Units for Petroleum, Chemical and Gas Industry Services.*** Most of the main gearboxes in refineries must conform to this specification. This is the most conservative standard, and if you specify this, you will probably pay substantially more for the gearbox than if another standard was specified. This standard is for parallel shaft helical gear units that are in continuous service without installed spare equipment. The gears may be single or double helical, one or two stage, and may be designed as reducers or speed increasers, but it does not apply to integrally geared units such as integrally geared compressors (which are covered by API 617 and 672). Most of its requirements do not apply to general purpose gears since they fall under API 677; however, gear ratings calculated according to API 613 and API 677 are the same. API 613 covers not only gear rating, but also the related lubricating systems, controls, and instrumentation. It was first published in 1968 based on AGMA formulas, but in 1977, the second edition was published with a very simplified approach. It was designed so preliminary sizing of gearing could easily be done with just a slide rule. It does require the Geometry Factor "J" from AGMA 908, but before the age of computers, this was often estimated from graphs. This simple method is still the one used in API 613, even though slide rules are hard to find and engineers who know how to use them are becoming quite rare. The very conservative ratings stem mainly from basing the material allowable stresses on the lowest grade materials (grade 1) from the AGMA standard in effect in 1977, even though use of the better "grade 2" materials is required. Although AGMA allowable stresses have increased over the years to reflect increasingly stricter metallurgical requirements, improved metallurgy, and extensive field experience, the API ratings have remained unchanged. The sixth edition is currently in development and may be published this year (2018). It appears that the rating equations will change to mirror those in AGMA 2001, but there will be a derating factor introduced so the resulting ratings may be similar to those of the prior editions. However, it does incorporate language to allow the use of alternate rating methods if the API method would result in excessive pitch line velocity or excessive face width.

API 617 — 8th *Edition* (2014): ***Axial and Centrifugal Compressors and Expander-Compressors; Part 3 — Integrally Geared Centrifugal Compressors***. This was first published in 1958 and covered only barrel-type centrifugal compressors, since integrally geared centrifugal compressors did not exist at that time. The 2002 seventh edition expanded the scope to cover Integrally Geared Centrifugal Compressors and Expander-compressors. It is now essentially three standards packaged as one. Each section has its own set of annexes, and for integrally geared centrifugal compressors, an annex in part 3 specifies a rating method based directly on ANSI/AGMA 2001. This method specifies how each factor is to be calculated, and then imposes an additional 20% derating factor. So, it is quite conservative, but not nearly as conservative as API 613. The eighth edition of API 617 was published in 2014 and did not change this rating method.

ANSI/AGMA 2001-D04 (2004): ***Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth***. AGMA 2001 and 2101 (the metric version) are the basic AGMA gear rating standards that most other AGMA rating standards are based on, and they have evolved from standards originally published in 1946. The ratings calculated by these standards have slowly risen over the years as a result of higher allowable stress numbers that have been introduced along with stricter metallurgical requirements. The user is given some flexibility in selecting the values of the factors to be used in the rating, so even given complete information on a gearset, two engineers may use different values for some factors and come up with different ratings using this standard. Therefore, specific application standards such as API 617 part 3, AGMA 6011, or AGMA 6013, provide guidance on selecting the factors to be used in the rating. The AGMA Helical Gear Rating Committee has been working for many years to revise this standard, but it may be a while before a new revision is released.

ANSI/AGMA 6013-B16 (2016): ***Standard for Industrial Enclosed Gear Drives.*** This standard is for low- to moderate-speed gears. This, and its metric version AGMA 6113-B16, is a combination of prior standards ANSI/AGMA 6009-A00 and ANSI/AGMA 6010-F97 — which in turn were based on AGMA 480, AGMA 460, and AGMA 420. It presents general guidelines for design, rating, and lubrication of parallel, concentric, and right-angle shaft drives. However, this paper will only consider the rating of parallel shaft gearboxes. For these gearboxes, this standard only applies when the pitch line velocity does not exceed 7,000 ft/min (35.56 m/s). It specifies that ANSI/AGMA 2001-D04 is to be used for the rating, and provides the specific factors to be used. The rating is for 10,000 operating hours, using the least conservative life factors.

ANSI/AGMA 6011-J14 (2014): ***Specification for High-Speed Helical Gear Units.*** The first high-speed gear unit standard was adopted in 1943 and has evolved over time. It is now based on ANSI/AGMA 2001-D04 and applies when the pitch line velocity exceeds 6,890 ft/min (35 m/s). The factors to be used for rating are either specified or a specific calculation procedure is given. The rating is for a minimum of 40,000 operating hours, using the most conservative stress cycle (life) factor. However, if the number of stress cycles exceeds the stress cycle factor graph endpoint, then the designer has the option of using the graph endpoint or extrapolating the curve to lower values.

ISO 6336-2006 (with the exception of part 5, released in 2003): ***Calculation of Load Capacity of Spur and Helical Gears.*** This standard, which is composed of five separate parts, is largely based on prior DIN standards and is generally accepted everywhere outside of the United States. It contains multiple methods to establish ratings, including method "A" (testing the gears under simulated or actual operating conditions) and various calculation methods. In general, method "B" should be used. There are a number of fundamental differences between the AGMA and ISO rating methods. The ISO standard finds the calculation points for bending strength by fitting an equilateral triangle into the base of the tooth, whereas the AGMA method is to use the Lewis parabola. The ISO dynamic factor is based on shaft vibration and proximity to a critical speed based on a very simplistic model of the shaft, while the AGMA dynamic factor is based mainly on allowable single tooth pitch variation. Yet despite these and other differences, the gear ratings are often fairly similar. The working group ISO/TC60/SC2/WG6 is currently revising Parts 1–3, and a new edition might be published in 2018 or 2019.

API 672 — 4th edition (2004): ***Packaged, Integrally Geared Centrifugal Air Compressors for Petroleum, Chemical, and Gas Industry Services.*** This was originally published in 1979, with the fourth edition published in 2004. This standard directs the user to rate the gears according to ANSI/AGMA 6011.

API 677 — 3rd edition (2006): ***General-Purpose Gear Units for Petroleum, Chemical and Gas Industry Services.*** This was first published in 1989 and used a modified K factor rating method. The 1997 second edition changed the rating method to that given in API 613. The current third edition was published in 2006.

Some Standards Use Service Factors, Others Use Safety Factors

Service factors have long been used as a simple method to provide an appropriate margin when designing gears. API 617, API 672, AGMA 6011, and AGMA 6013 use a service factor that includes the combined effects of safety factor, overload, and reliability (for pitting, these factors are *SH*, K_O , Y_z, and for bending SF, K_O , Y_z). API 613 and API 677 use the service factor as the sole factor, so their service factors also include the dynamic, size, load distribution, stress cycle (life), and temperature factors — plus either surface condition factor (for pitting) or rim thickness factor (for bending strength).

AGMA 2001 allows the use of either service factor or safety factor — but they are NOT interchangeable. ISO 6336 uses safety factors, and in addition to a lot of other factors also uses an application factor. It should be noted that, with the exception of the load distribution factor, the factors used in ISO are calculated quite differently from those used in AGMA.

Differences between Ratings Standards for Specific Gearsets

In this section the maximum power ratings according to six different gear rating methods will be compared for fourteen sets of gears covering a range of sizes and speeds. There are only six unique methods in the eight gear rating standards mentioned here. API 672 states that the gears shall be rated to ANSI/AGMA 6011. Similarly, the section on gear rating in API 677 has the same equations, factors, and limits as API 613, except for a minor difference in allowable L/d ratio (pinion face width to reference diameter) for nitrided gears.

The gearsets used in this comparison are presented in Table 1. All are grade 2 (MQ for ISO) alloy steel, and carburized (58 Rc), nitrided (R 15N 90), or through hardened (321 BN) as noted. No profile shift was used and all sets were run on standard center distance. Speeds range from 700 to 45,000 RPM. The resulting ratings range from 200 to over 20,000 HP. An even wider range of gears could have been analyzed, and additional examples could show more variability, but that probably would not change the general conclusions of this study. The values and factors chosen are sufficient for the purposes of this study, but they were selected for simplicity; they do not represent actual gears in production and should not be used as a recommendation or guide for gear design.

Ratings are for 20 years of continuous operation, except ANSI/AGMA 6011-J14, which specifies that ratings are for a minimum of 40,000 hours. Therefore, for comparison, ANSI/AGMA 6011 ratings are presented both for 40,000 hours and 175,200 hours (20 years). The ANSI/AGMA 6013 ratings are for 10,000 hours, as stipulated. The rating results are presented even if the pinion speed or the pitch line velocity was too high or low for the standard to apply.

Table 1 Geometry and speeds of example gear sets

Set Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Type	increase	increase	increase	increase	increase	increase	reduce	increase	reduce	increase	increase	reduce	reduce	reduce
Bull gear teeth	151	167	151	151	167	167	167	97	173	367	151	173	59	97
Pinion teeth	29	35	29	29	35	35	35	29	35	30	29	35	35	29
Module, mm	5	3	5	5	3	3	3	6	2	2	5	2	3	6
Pressure Angle	20°	25°	20°	20°	25°	20°	25°	25°	25°	25°	20°	25°	25°	25°
Helix Angle	18°	16°	18°	18° Double	16°	16°	16°	25° Double	16°	20°	18°	16°	15°	25° Double
Center distance	18.63	12.41	18.63	18.63	12.41	12.41	12.41	16.42	8.52	16.63	18.63	8.52	5.75	16.42
Face width, inch	6.25	5.50	6.25	8.25	5.50	5.50	5.50	8.00	3.00	2.75	6.25	3.00	4.50	8.00
Reference diameter, inch	6.00	4.30	6.00	6.00	4.30	4.30	4.30	7.56	2.87	2.51	6.00	2.87	4.28	7.56
Input Speed, RPM	3600	3600	3600	3600	3600	3600	3600	4500	3600	3600	3600	3600	3600	4500
Output Speed, RPM	18,745	17,177	18,745	18,745	17,177	17,177	754	1,345	728	44,040	18,745	728	2,136	1,345
Pitch line velocity, ft/min	28,796	19,339	29,456	29,456	19,339	19,339	4,053	8,905	2,702	28,983	28,796	2,702	4,034	8,905
Heat Treatment	Nitrided	Nitrided	Carb.	Carb.	Carb.	Carb.	Carb.	Carb.	Carb.	Carb.	Thru Hard	Thru Hard	Thru Hard	Thru Hard
Notes	RPM above 6013 limit	RPM above 6013 limit	RPM above 6013 limit	RPM above 6013 limit	RPM above 6013 limit	RPM above 6013 limit	RPM below 613, 677, 672, 6011 limits	RPM above 6013 limit	RPM below 613, 677, 672, 6011 limits	RPM above 6013 limit	RPM above 6013 limit	RPM below 613, 677, 672, 6011 limits	RPM below 613, 677, 672, 6011 limits	RPM above 6013 limit

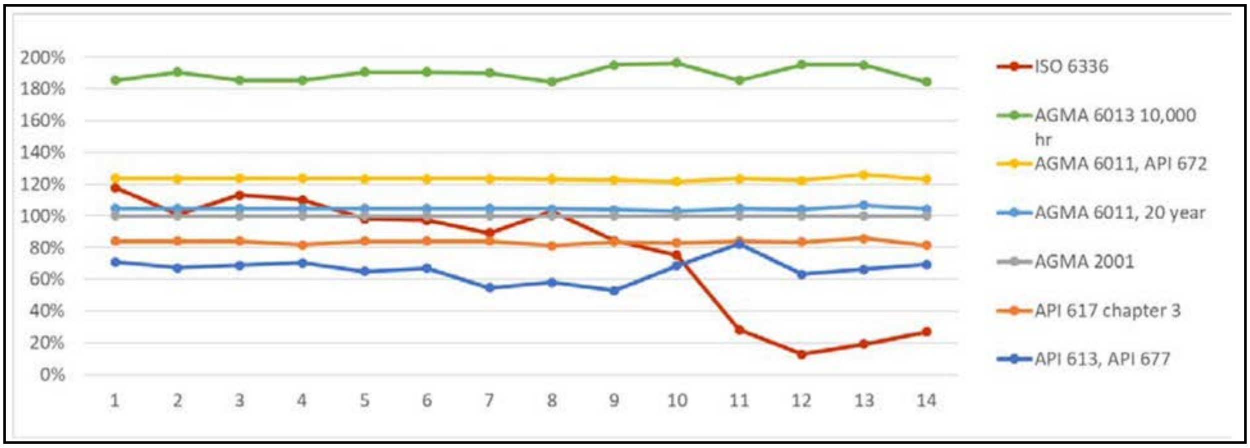

Figure 1 Pitting ratings as a ratio to AGMA 2001 pitting rating.

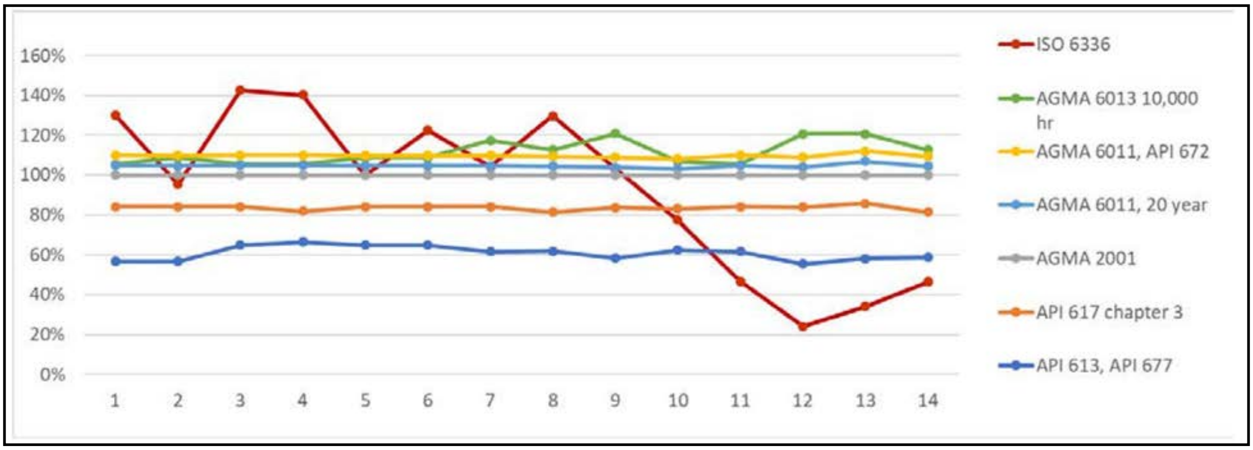

Figure 2 Bending ratings as a ratio to AGMA 2001 bending rating.

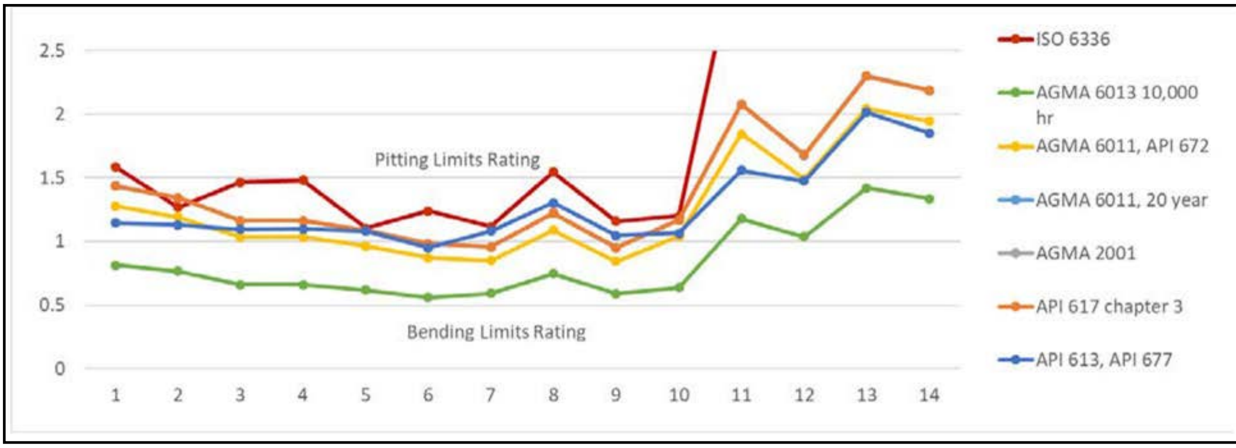

Figure 3 Ratio of bending rating to pitting rating.

Because of the wide range of power these sets are capable of transmitting, the results in Figures 1 and 2 are presented as the ratio of the rating to the ANSI/AGMA 2001-D04 rating. Each line represents one rating standard. A line chart is used for clarity; it is not meant to imply any relationship between different gearsets other than they are being rated with the same method. The order of the sets is arbitrary, except that the nitrided sets are presented first, followed by the carburized sets, and then the through hardened ones. For the pitting ratings shown (Fig. 1), all the ratings that use AGMA methods as their basis are quite consistent for the cases studied. API 613 ratios show a lot more variability, due to factors in the AGMA standards that API 613 does not use. The major change comes with a change to through hardened material (sets 11–14), and ISO rates through hardened steels far lower than AGMA does. This may be due to historical differences — particularly cleanliness — between the through hardening steels used in Europe and those used in the United States.

For most of the example gearsets, the AGMA 6011 ratings are about double the API 613 ratings. This is a staggering difference! The API 613 ratings for case and surface hardened gears are consistently the lowest, both for bending and pitting. The highest ratings come from ISO 6336 and ANSI/AGMA 6013, though the inclusion of 6013 may be a bit unfair since it uses stress cycle factors for only 10,000 hours of operation. All the other AGMA ratings are fairly consistent.

Figure 2 compares the bending ratings to ANSI/AGMA 2001-D04. Again, all the ratings that use AGMA methods as their basis are quite consistent for the cases studied. It is not surprising that the ISO 6336 methods do not track the AGMA method very well at all, since the rating methods are quite different. Also, the low ISO ratings for sets 11–14 correspond to the through hardened gearsets.

The ratio of bending rating to pitting rating is shown for each example and each rating method in Figure 3. When the ratio is above 1.0, i.e. — when the bending rating is above the pitting rating — bending ratings are ignored and the surface durability ratings determine the gearset ratings. It can be seen that whether it is pitting or bending that determines the overall rating, both depend on the gearset in question and the rating standard used. For any standard, examples can always be found where pitting limits the set rating, and other examples will show that bending limits the rating.

Many designers strive for gearsets that have close to "balanced" ratings, but often with the pitting rating slightly lower than the bending rating. This means that the gears are more likely to pit than break. It is far better for the gears to become noisy due to pitting and therefore get inspected and repaired or replaced, rather than breaking and potentially ruining the whole gearbox. But a balanced gearset according to one method may not be balanced according to another method.

It should be noted that when using AGMA or API standards, usually the same service factor is used for both the pitting rating and bending rating. However, when using ISO 6336, often a much higher safety factor is used for bending than is used for pitting.

It is interesting to note that the graphs show that the ratings remain consistent even outside the scope specified in the standards. However, a standard should not be specified if the application is not within the scope.

Most gear experts recognize that the ratings from the standards are just a rough approximation of the power that can be safely transmitted through the gears. The truth of this becomes obvious as the results of this study are examined. There is only one power level that will cause failure after a specific number of hours of operation, yet different standards give vastly different approximations of what that load is. Since gear failures are not common, clearly even the least conservative standards are sufficient for most applications. Yet when a standard has been specified, the gear vendor must ensure that the gear rating according to the specified standard meets the specified power.

The Positive and Negative Consequences of Imposing a More "Conservative" Design

Purchasers sometimes try to assure themselves that gears will be very reliable by the selection of a "conservative" rating standard or by increasing the required safety or service factors. The advantage of doing this is the supposedly lower chance of failure. However, if an adequately sized gearset will not fail, it is already sufficiently reliable. A larger gearset will not be more reliable. For low-speed sets, the only negative consequences of being "conservative" may be size, price, and slightly higher operating costs due to higher losses. For high-speed sets, being "conservative" can lead to high face widths or high pitch line velocities that can have significant negative consequences. Increased face width not only makes the gearset more sensitive to alignment, it is detrimental due to the heating of the oil, which is transported across the face width as the contact line sweeps across. The further the oil travels across the face, the higher its temperature gets. Increased pitch line velocity leads to increased sliding velocities, which also lead to a higher temperature in the contact zone and higher risk of varnishing or scuffing. In some cases, high tooth temperatures have resulted in a metallurgical transformation that distorted the helix, thereby adversely affecting the load distribution across the tooth flanks. As John Amendola (CEO, Artec Machine Systems; AGMA standards committees) has said: "So bigger is not necessarily more conservative. In reality, the most important factors are good load distribution, low sliding velocities, and proper lubrication."

How to Reduce the Risk of Failure

The load that will cause failure depends on many things, so an accurate rating can only be determined by testing. However, in many cases, testing to determine a safe load over the full life of a gearbox is not practical — *which is why rating standards exist*. The rating standards provide minimum requirements that must be met for the rating to be valid. The gear cost can be minimized by just meeting these minimum requirements, but by going beyond them, an extra margin of safety can be achieved. Rather than simply increasing the required service or safety factors or specifying the use of a very conservative rating standard, every aspect of the gearbox should be carefully examined. The first step is to determine the maximum load and the load spectrum based on a full analysis of the application. Additionally, there are many things that should always be considered —especially for critical applications. There are many standards — such as those from AGMA and ISO, as well as many books — that provide a great deal more information on these topics. The following very brief list just touches on some of the things that should be considered to reduce the risk of a failure:

- ***Lubricant used.*** The viscosity, the FZG load stage, the base stock, and the additives used all have a significant role in the life of a gearset. The lubricant can make the difference between successful operation and failure not only for pitting, but also for scuffing and micropitting. It is essential to keep the oil free of water and to change it at appropriate intervals. Proper filtration of the lubricant is critical, since entrained particles can result in wear. In some cases, use of an electrostatic filter to remove submicron particles may even be justified. See ANSI/AGMA 9005-F16 for more information on lubricants.
- ***Application of lubricant to the gear teeth.*** While in some cases, occasionally painting tar on the teeth of very large and slow-moving gears may be sufficient, and dip or splash lubrication is adequate for moderate speed gearing (up to about 15 m/s or 3000 ft/min pitch line velocity), high speed gears require spray lubrication. This spray may be directed into the in-mesh of the gears, or on higher speed gears into the out-mesh where the partial vacuum created by the separating teeth helps suck the oil mist onto the tooth flanks, or the system may use multiple nozzles on both the in-mesh and out-mesh to provide optimal lubrication and cooling. When spraying both the in-mesh and out-mesh, usually about one third of the flow goes to the incoming side for lubrication and the rest goes to the outgoing side for cooling.
- ***Temperature of the gear teeth.*** The gear teeth normally are cooled by the flow of lubricant, both on the teeth themselves and on their sides. While sufficient lubrication is essential, with high speed gears, excessive lubricant flow can be detrimental and lead to excessive heat generation and power losses. In high speed gears, oil that gets between the teeth is often ejected axially, sometimes at supersonic speeds when the gears have high pitch line velocity and low helix angles. Excessive oil mist surrounding the gears can lead to high windage losses, raising the bulk temperature of the gears. Excessive temperatures in the contact zone can lead to varnishing, scuffing, or other problems. With pressure-fed systems, the oil temperature is typically controlled with oil coolers. When the gearbox is in a cold environment, it is good practice to preheat and circulate the oil prior to startup so it has an acceptable viscosity during startup.
- ***Micro-geometry of the gear teeth.*** Proper profile modifications will decrease the chance of problems. Highly loaded gears often require tip relief to avoid the tip of the driven gear from gouging into the flank of the driving gear. Helix (lead) modification can, and in many cases should, be used to compensate for tooth deformations that will occur during operation, both from the load and the temperature profile of the tooth flanks. The use of ISO1328-1 class 4 or better tolerances for the tooth flanks may be appropriate for some gears to assure that the specified modifications are achieved, although the use of such tight tolerances may not be appropriate for general purpose or low speed gears where class 6 or 7 is considered good.
- ***Alignment.*** The best gears in the world can fail if not properly aligned. In addition to the parallelism of the bores machined into the gearbox, bearing play, differential thermal growth, and internal or external load-induced distortions of either the gearbox or gears themselves should be accounted for.
- ***Material used.*** The gear material is obviously critical to the life of the gears. It is important to consider the specific material chemistry, the material cleanliness, its processing (hot or cold worked, total reduction ratio, forged or rolled), and heat treatment. The following brief comments barely scratch the surface of gear metallurgy. For more information, see AGMA 923-B05 or consult with a gear metallurgist.
  - The appropriate alloy should be selected for the application. Some steels are easier to harden than others, but note that there can be significant differences between different batches of the same alloy. The material chemistry of the specific batch can affect the hardenability. Jominy end-quench tests can be used to assess hardenability, and published ranges can be used to aid in the selection of which alloy to use. They may also be incorporated into the specification of the properties the alloy must have.
  - Material cleanliness is critical, since inclusions can be stress risers and be the initiation points for failures. Cleaner steels can safely carry higher loads.
  - The processing of steel from billet to final part can have an effect on the

life of the part. Sufficient reduction ratios are beneficial, and appropriate forging, such as pancake forging for bull gear disks, can result in favorable grain size and structure.

¤ Heat treatment is used to obtain the proper hardness distribution in the gear. Specification of a better hardenability material can be negated by improper heat treatment. The spacing of the gears in the furnace and during quenching, the quenchant used, and the flow rate and amount of agitation of the quenchant will all affect the heat treatment results. Larger sections are more difficult to properly heat treat than small ones, and so may require materials with better hardenability.

◊ Hardness and strength are generally proportional, so the harder the gear, the higher the rating will be. For a given required power, it is not unusual for a higher hardness specification to result in a less expensive gear since the harder gear can be smaller. For case or surface hardened gears, just as critical as the hardness is the hardness profile. If the hardness falls too rapidly with depth, then at some depth from the surface, the sub-surface stress can exceed the strength, leading to a subsurface failure that can grow to the surface. Jominy data along with knowledge of the part size, heat treatment, and quench severity is useful to predict the hardness profile.

◊ Use of through hardened gears is common, even though their hardness is considerably lower than that of surface or case hardened gears. Since they are heat treated before machining, they can be machined to final size without worrying about the changes that can occur during heat treatment. Machining becomes more difficult or impossible as hardness increases, but the hardness cutoff point for through hardened gears varies by manufacturer, and it has increased over the years due to advances in manufacturing technology.

◊ Flame or induction hardening can produce a hardened surface layer, and dual frequency induction hardening can produce a particularly good surface layer. However, API 613 and 677 do not recognize flame or induction hardening. Also, these hardening processes require numerous test pieces to certify the process, so they may not be suitable for very low volume or one-off production.

◊ Nitriding produces a very thin but very hard surface layer, so it is very good at reducing the chance of pitting.

◊ Some people consider case carburized gears to be the best, and in some cases, they may also be the least expensive since they can be smaller than other gears rated for the same power. Case depth needs to be controlled to be sure that it is sufficient to avoid a subsurface failure, but not excessive since gear tooth tips may become brittle and break.

◊ It is not unusual to use different hardness for the pinion and bull gear specifications. When there is a difference, the pinions are usually harder due to higher stress in the pinions, resulting from their tooth shape and their having more stress cycles.

- ***Surface finish***: Improved surface finish generally leads to improved gear performance. In addition to minimizing surface roughness, the lay of any machining or grinding marks can be important. There used to be a theory that some roughness was required to hold an oil film, but testing on isotropic superfinished surfaces has disproved that. Careful grinding can produce a $16r_a$ (micro-inch) finish, while isotropic superfinishing can bring it down to $2r_a$. Claimed benefits include reduced noise, reduced gear wear, increased power output, increased part life, and lower operating costs. Of course, as with all manufacturing processes, a cost benefit analysis should be performed to determine the optimal level of surface finish for the application.
- ***Dynamic loads including vibration***: It is critical to know the maximum load that the gearset will ever see, and preferably the lifetime load spectrum will be known. The entire wind energy business was almost brought to a complete halt due to miscommunication of maximum loads. Vibration, either lateral or torsional (which may be difficult to detect), can ruin gears. Proper analysis during the design stage can generally be used to guide any necessary changes so damaging vibrations will not occur during operation.

A good gearbox designer or vendor will look at all of these, and thus be able provide a very reliable design no matter which standard is specified. However, the size and therefore the price of the gearbox will be affected by the rating standard chosen.

Effect of Rating Standards on the Size of a Gearset Designed for a Specific Application

As an example of the effect the rating standard can have on the size of a gearbox, Table 2 presents designs of gearsets that are rated at 4,800 HP for 20-year life, according to five standards. In all cases, the rating is pitting limited. The only changes made to meet the rating were to adjust the module and face width, keeping the L/D ratio for the pinion at approximately 1.0. While it would be very unusual to actually make gears with such odd modules, this example serves to illustrate the average effect rating standards have on one particular set of design conditions. Actual designs would use standard modules, so changes in numbers of teeth would be made to get close to the rating. If only number of teeth were changed, then for designs such as this, which are close to being balanced between pitting and bending, increasing the number of teeth could cause the set to become bending limited.

Since the cost of a gearbox is roughly proportional to the volume of the gears, the API 613 gearbox will cost about 60% more, even if all other design criteria are kept the same. But even if the extra cost of the gearbox is not a concern, the increased pitch line velocity and increased face width should be. It can be seen that for this case, use of API 613 results in almost 20% higher face width and pitch line velocity than that which would result from designing to AGMA 6011. While this may not be a serious issue when the pitch line velocity is not very high, it can become a major problem when the power and speed requirements require a pitch line velocity approaching or exceeding 30,000 ft/min (150 m/s). So being "conservative" in the specifications can sometimes result in a compromised design.

Conclusions

When a gearbox is properly specified and built so it will not fail, then there is no way to make it more reliable. There is an old engineering saying: good enough is best. Specifying a different standard or increasing service or safety factors can make the gear box more expensive, but if the gearbox would be adequate without the additional expense, then nothing is gained by adding requirements. In fact, being too conservative in the specification of a gearbox may have negative consequences.

It is important to fully understand all the loads and environmental conditions the gearbox will be subjected to so that the gearbox requirements can be properly specified. It is very important to properly specify all loads, the expected operating life, and any special circumstances so the proper factors can be specified for the rating. The standard specified for gearbox rating and the service or safety factors should be appropriate for the application and should not be excessively conservative.

Table 2 Gearbox size as a function of rating standard

	units	ISO 6336	ANSI/AGMA 6011 20 year	ANSI/AGMA 2001	API 617 chapter 3	API 613, API 677
Number of teeth, bull gear		173	173	173	173	173
Number of teeth, pinion		35	35	35	35	35
Module	mm	2.84	2.97	3	3.18	3.54
Pressure Angle	deg	25	25	25	25	25
Helix Angle	deg	16	16	16	16	16
Material		carburized	carburized	carburized	carburized	carburized
Face Width	inch	4.03	4.2	4.3	4.65	5.06
Pinion Pitch Diameter	inch	4.071	4.257	4.300	4.558	5.075
L/D		0.990	0.987	1.000	1.020	0.997
Gear Pitch Diameter	inch	20.123	21.044	21.257	22.532	25.083
Pinion volume	inch^3	52.5	59.8	62.5	75.9	102.3
Gear volume	inch^3	1281.7	1460.8	1526.0	1854.1	2500.3
Total volume	inch^3	1334.1	1520.6	1588.4	1930.0	2602.6
Input Speed	rpm	3600	3600	3600	3600	3600
Output Speed	rpm	17794	17794	17794	17794	17794
Pitch line velocity	ft/min	18965	19833	20034	21236	23640
Pitch line velocity as % of ANSI/AGMA		94.7%	2001 99.0%	100.0%	106.0%	118.0%
Volume ratio to 2001		84.0%	95.7%	100.0%	121.5%	163.8%

Note: The ANSI/AGMA 6013 standard was not included in this comparison since it specifies 10,000-hour life, as opposed to the 175,200-hour (20-year) life used in these examples.

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3. API 672 Fourth Edition: Packaged, Integrally Geared Centrifugal Air Compressors for Petroleum, Chemical, and Gas Industry Services.
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John Rinaldo is retired from Atlas Copco Comptec LLC where for 25 years he designed gears for high-speed, integrally geared centrifugal compressors. He is currently a member of the API 613 taskforce, and serves as the vice chair of the AGMA Gear Accuracy committee and the Nomenclature committee. He is the convener of ISO TC60/SC1/WG4 "Terminology and notation of gears" and is the U.S. delegate to ISO TC60/WG2 "Accuracy of gears" working group. His varied career started with the aerodynamic design of compressor impellers, shifted to the design of compressor control systems and then moved to general research and development of centrifugal compressors. He has been licensed as a Professional Engineer in both Wisconsin and New York, has been granted 4 patents, and is a recipient of the AGMA Distinguished Service award.

For more information, see the Appendix for this paper in its digital version at *www.geartechnology.com/issues/0718/*.

Complete Measurement of Gearbox Components

Christof Gorgels

Introduction

In today's production environment, a variety of different measurement devices is used to assess the quality and accuracy of workpieces. These devices include CMMs, gear checkers, form testers, roughness testers, and more. It requires a high machine investment and a high handling effort—especially if a full end-of-line measurement is needed.

One approach to reduce quality costs is to include all measurements in one single machine that is suitable and robust enough for use in production. This reduces machine investment, handling efforts, and set-up time. Being able to measure in production also helps to reduce idle times by reducing transport ways to climate-controlled measuring facilities. Klingelnberg combines the experience from machine tool development and high-precision measurement.

This report describes how a CCMM (circular CMM) can be integrated into a production environment. The main challenges are dust and oil fog contamination, temperature changes throughout the day, and vibrations from production machines. Operator qualification is also an issue, since the measuring machine is handled by production machine operators.

The result is a measuring machine showing the capability and necessary accuracy in measuring gear components. This accuracy applies to all features of rotational, symmetric parts within a gear box. Finally, it will be shown how capital-intensive gauges can be substituted using the full flexibility of a modern CNC- controlled measuring machine. Compared to gauges, much more useful information can be gathered and statistically evaluated to support production control. Furthermore, component design changes only require slight software modification—at no cost. Using gauges, expensive parts need to be reworked or reinvested, including their high costs and lead times.

Productivity Improvement in Measurement Technology

In manufacturing gearbox components, such as gears and shafts, a multitude of measurement tasks occur at different points in the process chain. The results of all these measurements are either used for process monitoring or documentation of the final state of a component. Various measuring instruments are used for the various measuring tasks. These range from gauges for a simple test of component features to complex measuring machines. Which measuring or checking instrument is used depends on many factors; the environmental conditions, measurement time, qualification of the operator and, of course, investment and operating costs, play a decisive role.

In the area of pure production monitoring, simple and also more complex gauges are often used, which are easy to handle and very robust against the environmental influences of a typical shop floor environment.

However, the low flexibility of gauges is a big disadvantage.

Gauges are often exactly designed for one characteristic only. Design changes to this feature require a new gauge, resulting in high costs and lead times. On the other side, high-precision measuring machines are used. CMMs typically require the clean and air-conditioned environment of a measuring room. Measuring machines are characterized by a higher degree of flexibility—compared to gauges—while being operated by trained staff.

Increasingly, system manufacturers and OEMs are shifting their quality control to suppliers. The component suppliers are required to measure and document all relevant features classified by their customer as part of a final inspection. For this purpose, an overall measurement of all relevant features at the end of the production chain is necessary; but this requires the use of different measuring devices present in the measuring room. This inevitably requires time- and personnel-intensive set-up and clamping processes.

One approach to increasing the efficiency in quality control and documentation is to integrate different measurement tasks on one single measuring machine in an automated process in order to reduce the number of setups and clamping processes to a minimum. For this purpose a measuring device is required in which all measurement tasks of the coordinate, form and surface inspection are integrated as much as possible. However, no compromises can be made with regard to the accuracy of the measuring medium. Ultimately, the measuring equipment's capability for the required accuracy must be given for each individual characteristic.

A further step towards improving productivity is the integration of a measuring machine directly into production. As a result, in the first step—the transport distance to the measuring room—and often also the costly measuring room itself—can be omitted. For this purpose a measuring machine must be consistently designed to the requirements of the shop floor environment. The essential components are the compensation of temperature fluctuations, environmental influences caused by dust and oil mist, as well as floor vibrations at the installation site. This allows shifting shop floor checks from gauges towards a high-accuracy coordinate measuring machine. This enables us to use all advantages of a CMM, including accuracy, documentation, and statistics.

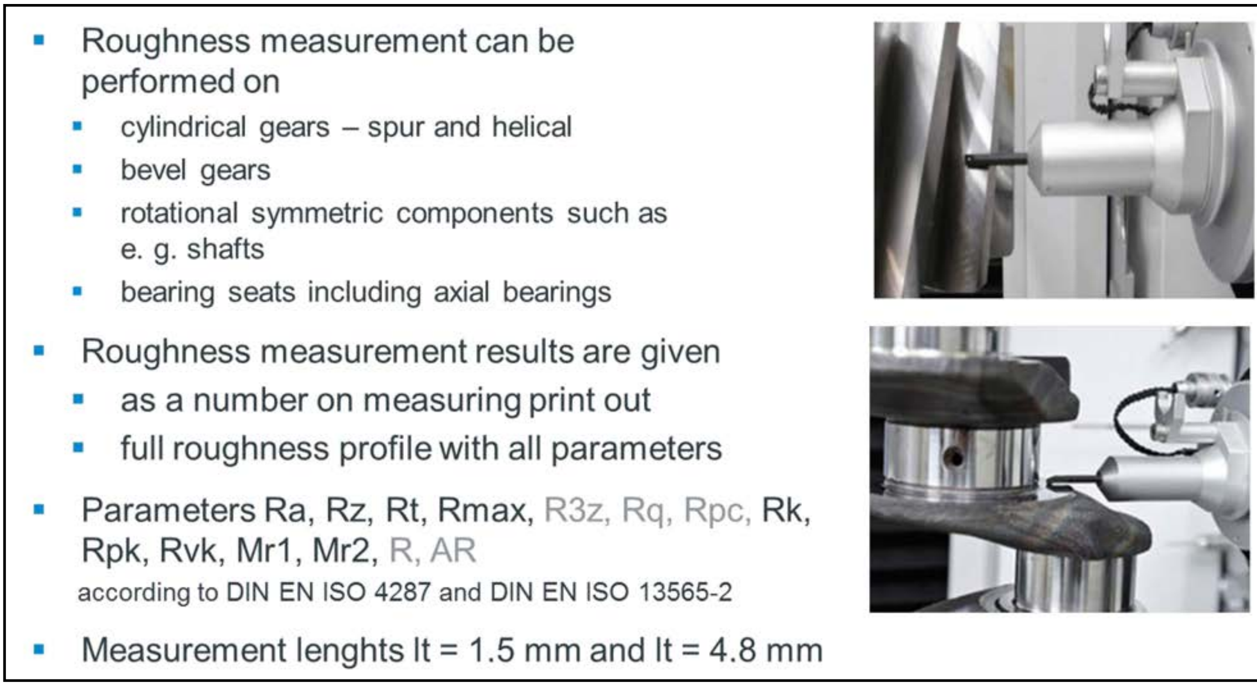

Figure 1 Surface roughness measurement on precision measuring center.

Integrating Surface Roughness Measurement into the CMM

The roughness measurement is typically carried out on special measuring devices with linear feed. In this case the component and the roughness sensor are manually positioned relative to one another for every measurement. So, a lot of manual adjustment and set-up process for each component is required. Since the positioning is done manually, the position at which the roughness measurement is performed cannot be absolutely identical, and thus the reproducibility of the measurement result is impaired.

Integrating the roughness measurement on a coordinate measuring machine offers several advantages. The highly accurate axes of the coordinate measuring machine are available for positioning the probe. The measurement can therefore always be carried out at exactly the same position. In addition, the roughness measurement can be integrated into the measuring sequence. In conjunction with an automatic probe changer, set-up and set-up times are completely eliminated. Figure 1 shows the roughness measurement on the tooth flank of a cylindrical gear (upper photo) and on the axial bearing seat of a crankshaft (lower photo).

A skidded system for roughness measurement is used. Thus, the reference plane for the measurement result is the surface of the component and not the feed axis of the machine. This is an important difference from standard surface roughness measurement systems using a straight axis as the reference plane. With a straight reference, the involute curve of a gear flank is part of the measurement. This has two main disadvantages; one is that the involute is part of the measurement and has to be filtered, including the risk of also filtering information about the surface. The second disadvantage is that the probe cannot be kept perpendicular to the surface as the standards call for, which can, depending on the curvature, also influence the measurement result. Using the four axes of the measuring machine, a generating movement can be realized by always keeping the probe perpendicular to the surface. The downside of a multi-axes movement is that the control quality of the axes can influence the measurement result. This can be avoided by using a skidded system where the skid forms the reference.

The skid itself has a large radius so that the measuring results cannot be falsified by the reference plane. The blade with the probe tip is rotatable-mounted. The rotation to the measuring position is automatically controlled by the measuring software. As a result, the left and right tooth flanks of a gear can be measured without a manual set-up effort with only one probe. In addition, it is also possible to directly measure other different geometry elements on the clamped part. By means of this design, different gears and bearing seats can be measured on a component in one clamping. The usual characteristic values of the roughness measurement are calculated (Fig. 1).

Especially for the measurement of small contours with small measuring lengths, it is important that as little measuring distance as possible is lost by the skid as a reference system. Therefore the skids and stylus can be integrated in such a way that the full available measuring range can be utilized as far as possible. An example of this integrated solution is shown in Figure 2. With this very small-sized roughness probe, the roughness measurement on tooth flanks of cylindrical gears is possible, starting from a module of $m_n = 0.9$ mm (DP 28). The skid is positioned to the side of the roughness probe itself in order to be able to measure such small gear flanks. The photo on the lower right shows the automatic exchange of the roughness probe system. In this case there are two positions in the probe changer magazine in order to measure surface roughness on a bevel gear, and a bearing seat in one clamping and in an automated measuring sequence.

A major advantage of the skidded system on a coordinate measuring machine is shown in Figure 2. To avoid falsifying the measuring results, the probe tip must

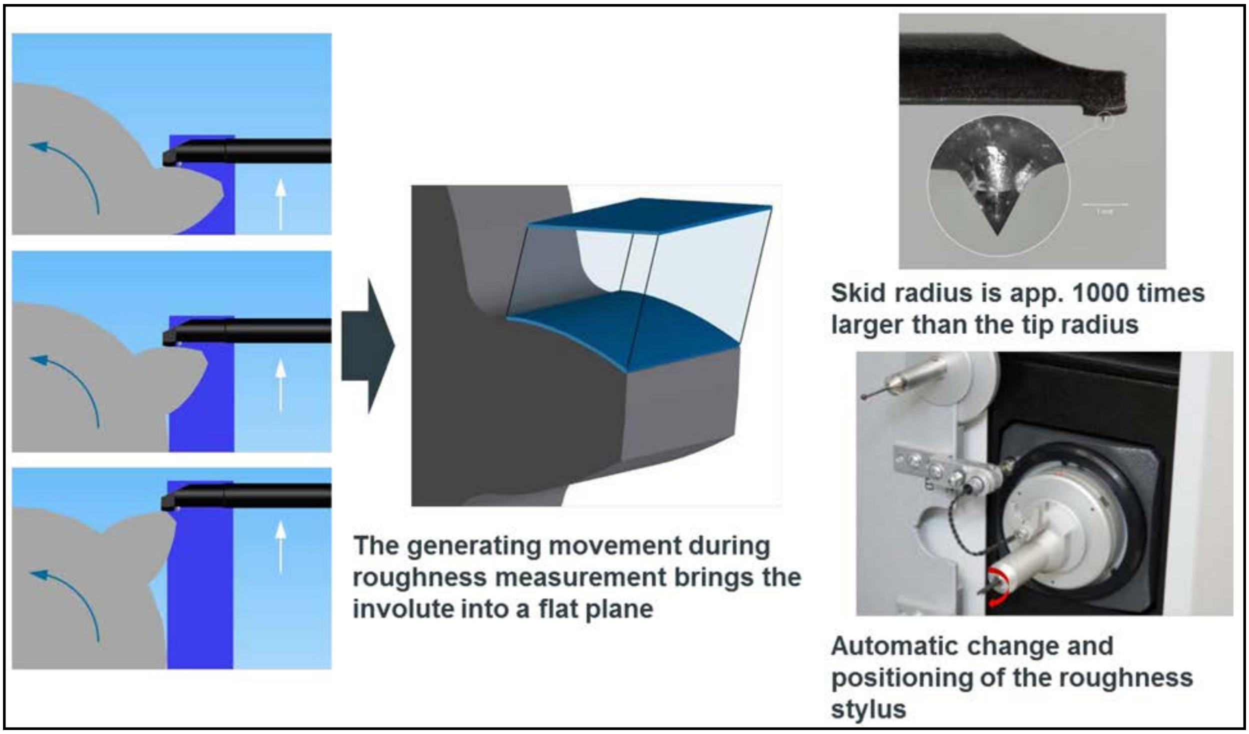

Figure 2 **Design of surface roughness probe.**

always be positioned perpendicular to the surface during the roughness measurement. Traditional roughness measurement systems with a straight reference plane cannot achieve this on curved surfaces, such as an involute gear tooth flank. In addition, in the case of involute gear flanks, the tooth curvature is in the measurement results and has to be filtered. This represents a significant disadvantage of these systems, since this makes it impossible to achieve a standard measurement perpendicular to the surface.

Measurements of involute gear flanks are carried out on four-axes, precision measuring centers. In this case, as in a standard gear measurement, the C-axis and the X-axis perform a coupled movement. This is the typical generating movement following the involute flank, i.e. — keeping the position between flank and measuring stylus constant. In this way the involute tooth flank is transferred into a flat plane relative to the touch probe. The sketches in Figure 2 show that the probe tip is always perpendicular to the measured surface. This ensures that the roughness measurement is carried out according to the relevant standards.

The possibility of automatically rotating the surface roughness probe presents the possibility of reaching many different positions and geometries on the parts to be measured. Still, the flanks of internal gears cannot be reached this way. Therefore a further extension of the surface roughness measurement is shown (Fig. 3). The surface probe is mounted to a special construction and turned by 180°. This now makes it possible to measure internal gears using the same probing system described and shown before. It can also be handled by the automatic probe changer, and gears can be measured starting with module $m_n = 0.9$ mm (DP 28).

Figure 4 represents an example of a roughness measurement. In this case,

Figure 3 **Roughness measurement — internal gears.**

three different teeth of a gear have been checked in profile direction on the left and right flank. The results are shown on a printout very similar to the printout for a standard involute check. On the right flank, it is clearly visible that the characteristic profile features can be found at identical positions of the profile. One such example is marked in the printout. In conjunction with the very reproducible machining result from a generating grinding process, it is also clearly visible that the measurement and the measuring position are very reproducible.

Finally, it can be stated that a roughness measurement on a coordinate measuring machine offers many advantages. The first is the fully automated integration into the measurement cycle. This eliminates the need for setting up the measurement each time a new part needs measuring. Another important advantage is the reproducibility — not only of the measuring result — but also of the measuring position. The user influence on the measuring result is completely eliminated. Finally, however, the possibility also exists of placing curved surfaces, such as a tooth flank, in a measuring plane and thus testing it in a standardized manner. Still, it is important to note that the reference is always a straight plane. So there is a clear separation between the roughness measurement only reflecting the surface, but not the involute or lead with corrections. Involute and lead are still represented by the standard gear measurements; surface roughness is always additional information.

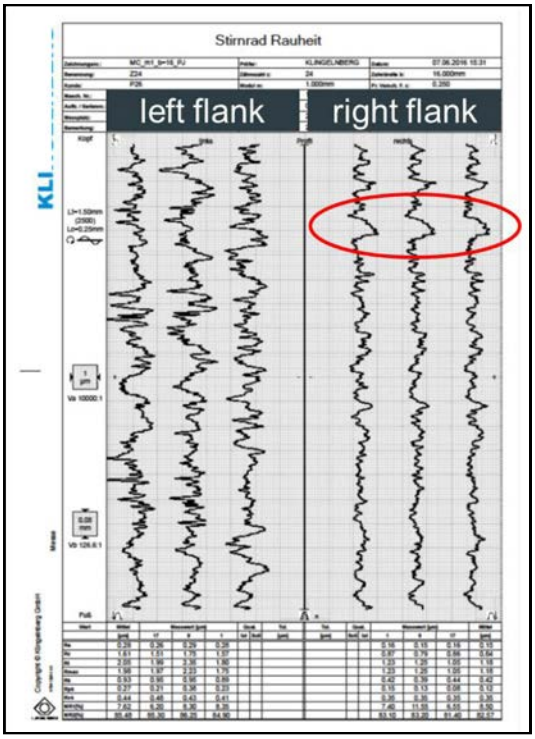

Figure 4 Example measuring sheet for surface roughness measurement.

Precision Measurement on the Shop Floor

The precision measuring centers are uncompromisingly developed for use in production. Here the experience gained in machine tool development is combined with the expertise in precision measurement technology. The main success factors are the robustness of the machine in conjunction with a temperature model in order to compensate for the influence of temperature gradients on the shop floor (Fig. 5). In combination with vibration isolation, this is the basis for Klingelnberg ambience neutral technology.

The production environment is characterized by contamination of the air with oil and dust. A measuring machine used on the shop floor has to be designed to operate in this environment. The main components in need of special attention are the guides, bearings, and scales. Though robustness is the key factor, accuracy cannot be compromised. In the production environment, the only option is to use roller bearings instead of air bearings, and also roller guides instead of air guides. For a machine with form

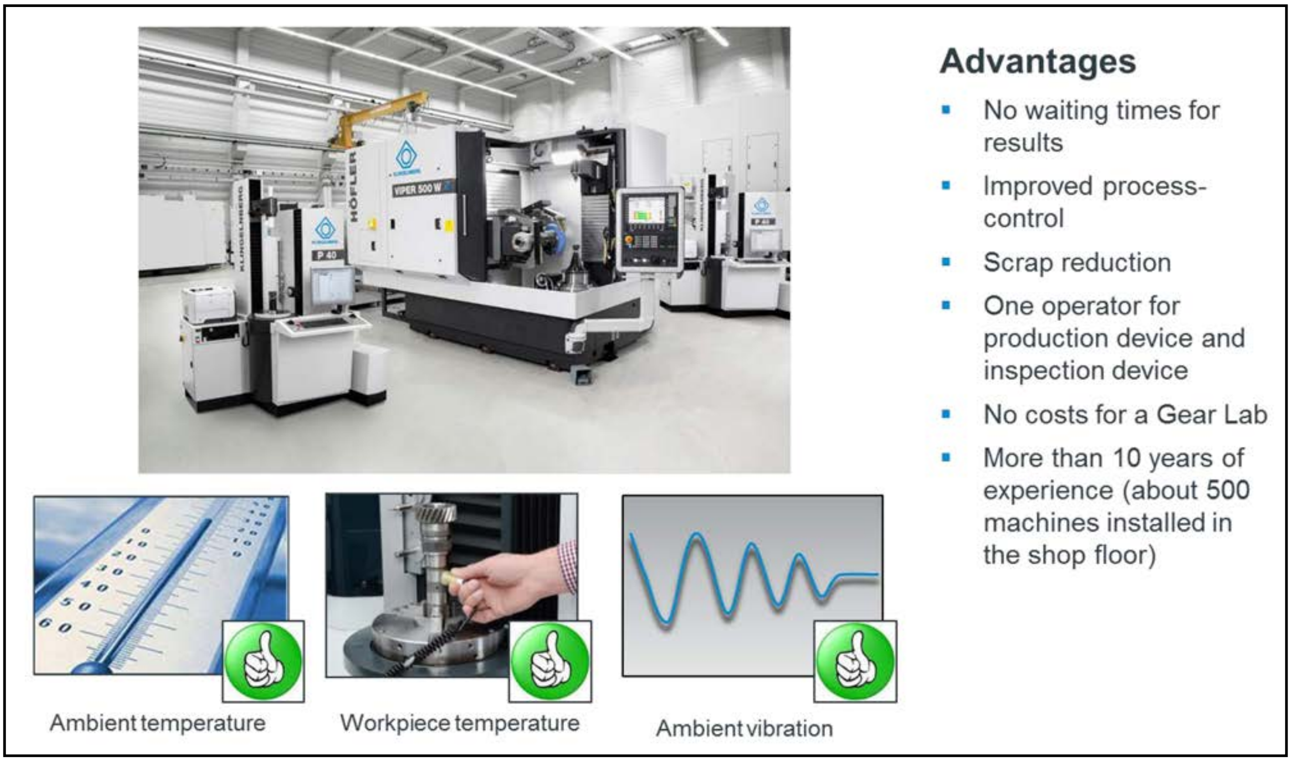

Figure 5 Precision measurement on the shop floor.

testing capability, the design and also precision manufacturing of a precision roller bearing is a challenge. Basically, for a good gear measuring machine being capable of form testing on shafts, a radial runout of the rotating axis of less than 0.5 mm is necessary. Also, it is rather difficult to keep the glass scales absolutely safe from any dust. Therefore the best solution is to strike a compromise between isolation and accessibility — thus enabling the user to include the glass scale cleaning into the yearly maintenance. Experience shows that a yearly cleaning is sufficient in approximately 90% of the cases, and increasing the frequency to twice a year has proven to be sufficient in all cases.

On the shop floor, vibrations induced into the floor by different sources, such as manufacturing machines or fork lifts, are another challenge; those floor vibrations are often below 15 Hz. In order to isolate a machine against such low frequencies, very soft damping isolation material is required. Since this would result in a "shaking" machine when axes or masses are moved, an active controlled system with pneumatic springs is absolutely necessary. In this way it is possible to achieve the necessary isolation against low-frequency vibrations below 15 Hz from the shop floor, while keeping the machine stable and avoiding all influences on the measurement results.

Another aspect of the production environment is temperature fluctuation. The main challenges are the compensation of the machine changes due to temperature change, and ensuring that different materials used in the machine with different temperature growth do not cause inner tension, and so influencing machine performance. In order to keep the system simple, one good way is to ensure that all components of the measuring machine have the same temperature growth. This can be achieved by limiting the material choice to steel and cast iron. Therefore, the machine bed is made from cast iron instead of granite. By measuring the temperature of the machine, the environment, and the workpiece, all necessary information is there in order to use an analytical temperature model for the compensation. This model has been proven in a temperature range from 15° C up to 35° C. Still, the temperature gradient throughout the machine is another important factor. Therefore, the maximum temperature change per hour to make the system work has been set and proven to $\Delta T = 2°$ C/h.

Complete Measurement of All Features

In addition to roughness and gear measurement, numerous other measuring tasks can be carried out on a precision measuring center. Basically, it is a coordinate measuring machine with a rotary table for rotational symmetric components — which we like to call a circular coordinate measuring machine (CCMM). In addition, important features are required to significantly increase the accuracy. The rotary table bearing has a radial runout deviation of significantly less than 0.5 µm, and thus has a sufficient accuracy for form measurement. This is achieved by a highly accurate probing system with low masses, which is well suited for both form testing and rapid coordinate measurement. This means that all requirements are fulfilled in order to carry out nearly all measurement tasks on shafts, in addition to the roughness and gear measurement.

Figure 6 shows examples of measurement and evaluation options along the process chain in gear production. Before green machining of the gear teeth, the blank can already be measured completely with all relevant features. Both dimensional measurement tasks, as well as form measurement tasks, can be integrated. The same also applies, of course, to the measurement of all elements after heat treatment and before hard-machining of the gear teeth, such as gear grinding.

In addition to classical gear

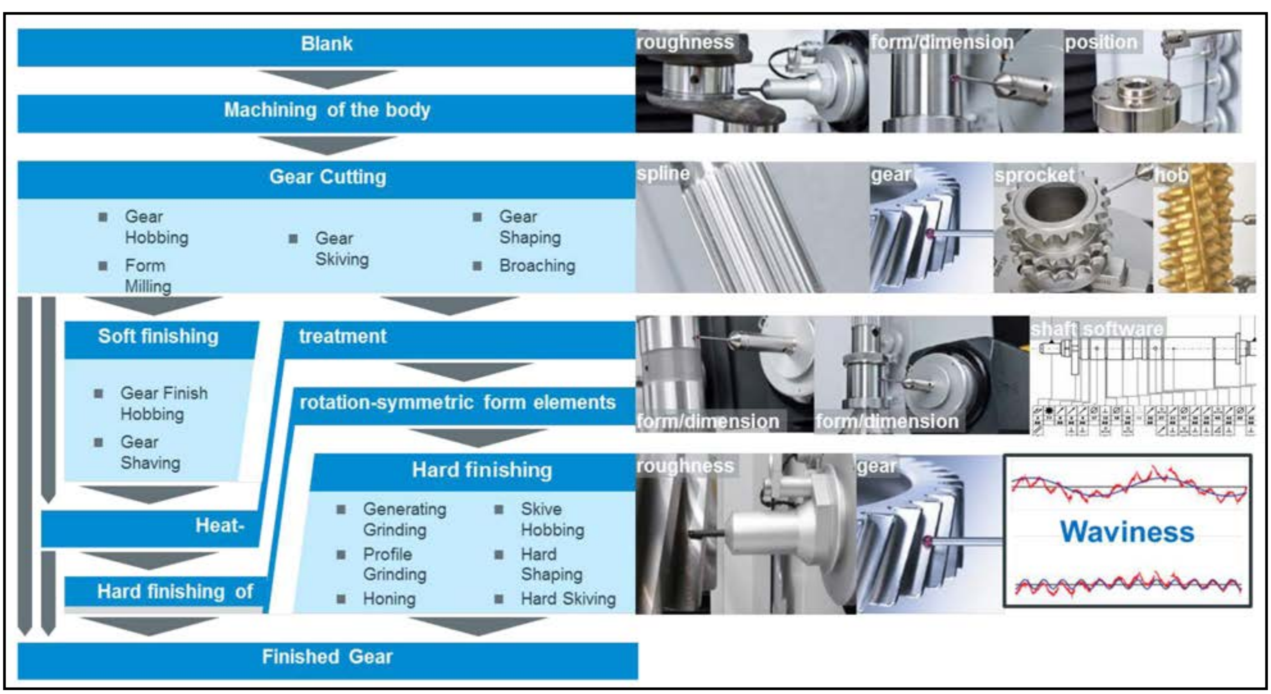

Figure 6 **Measuring possibilities along the process chain of gear manufacturing.**

measurement, tools used can also be measured; shown here (Fig. 6), for example, on a hob. The advantages of roughness measurement on a coordinate measuring machine were described in the previous section. What's more, the evaluation of ripple on the tooth flanks after the gear grinding process is possible in order to assess gear noise issues. The capabilities of the precision measuring centers for form measurement make a highly precise measurement of the ripples possible. With the corresponding evaluation software "deviation analysis," sound phenomena, such as so-called ghost frequencies, can be analyzed and important information for their avoidance in production can be gathered.

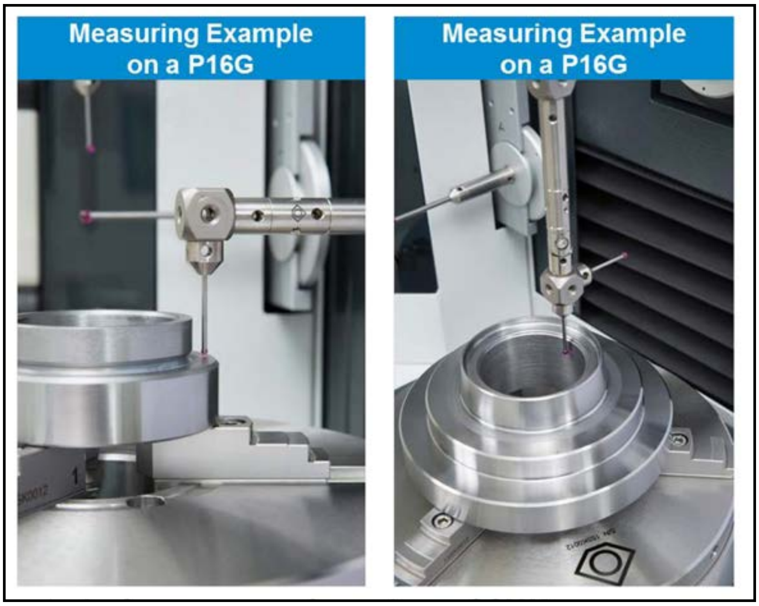

Figure 7 Typical measuring tasks for gauges performed on a CCMM.

P 16 G: Replacing Gauges in Production

On today's shop floor, gauges are used for quality assurance of different process steps. Gauges can be used, without restrictions, directly on the shop floor and close to the machine tools. They are characterized by a high robustness against the shop floor environment and "built-in temperature compensation." If the gauge consists of a material with the same coefficient of thermal expansion as the workpiece, and has the same temperature, the thermal influence on the test result is thereby excluded or compensated. The test is also very simple and can be performed directly by the operator of the machine tool itself.

The main drawbacks of gauges are the individual adaption to the component and the test task combined with a high investment and long delivery times. Basically, this makes gauges very inflexible. Design changes are especially critical since they require a new gauge, resulting in another high investment combined with the long lead time. In addition, documentation of the test result is only qualitative and cannot be used for process control. It is therefore desirable to have a measuring machine that has the advantages of gauges and is suitable for use in production, showing a much higher flexibility.

In the previous sections it is shown that nearly all measurement tasks on rotational-symmetrical components can be carried out on a Klingelnberg precision measuring center. There also exists the possibility of using the measuring machine directly on the shop floor. The necessary robustness, in combination with temperature compensation and vibration isolation, makes this possible. So with these preconditions, it is possible to replace gauges as described before by a measuring machine.

Figure 7 shows typical measuring tasks for gauges carried out on a P 16 G. In this case, for example, diameters, distances and lengths, positions to a reference, and many other different parameters are measured. These can be realized as measurement tasks on a coordinate measuring device. The flexibility of the measuring device is much higher compared to a gauge. Any number of different components can be checked; only the appropriate measuring program has to be created. The adaptation to geometrical changes of existing components can be realized by only small changes of the measurement program.

Figure 8 shows the P 16 G — a measuring machine for disc-shaped components and short shafts. This represents a high number of typical parts in the automotive industry. Measuring on the shop floor allows improvements for process control. By means of the statistical evaluation of measured values, for example, trends can be detected at an early stage, thus an intervention can take place before the first component is out of tolerance and needs to be scrapped.

Another important factor for moving a measuring machine on the shop floor is the qualification of the operators. In the measuring room, experienced measuring machine operators are typically available. A CMM on the shop floor used for replacement of a gauge is normally used by the machine operators; they have a lot less experience in measuring technology. Still, the quality and reliability of the measurement results must be ensured. For this purpose a system called *EasyStart* has been developed. This is software that consequently separates the setup of the measuring program and the measurement itself. In order to start an already-programmed measuring cycle, very little knowledge is required; this helps to reduce training efforts. The operator finds the necessary measurement program for his specific part directly on the start screen. In order to start the cycle, only one click on the button is necessary. This procedure can be further simplified by using a scanner in conjunction with an identifier on the component. This identification can be handled in multiple ways; the most common today is a QR-code on the surface of the part.

Conclusion

The measurement technology is an integral part of the production of transmission components. Quality control is an important part of the process chain and, like the manufacturing process itself, should be part of continuous efforts to

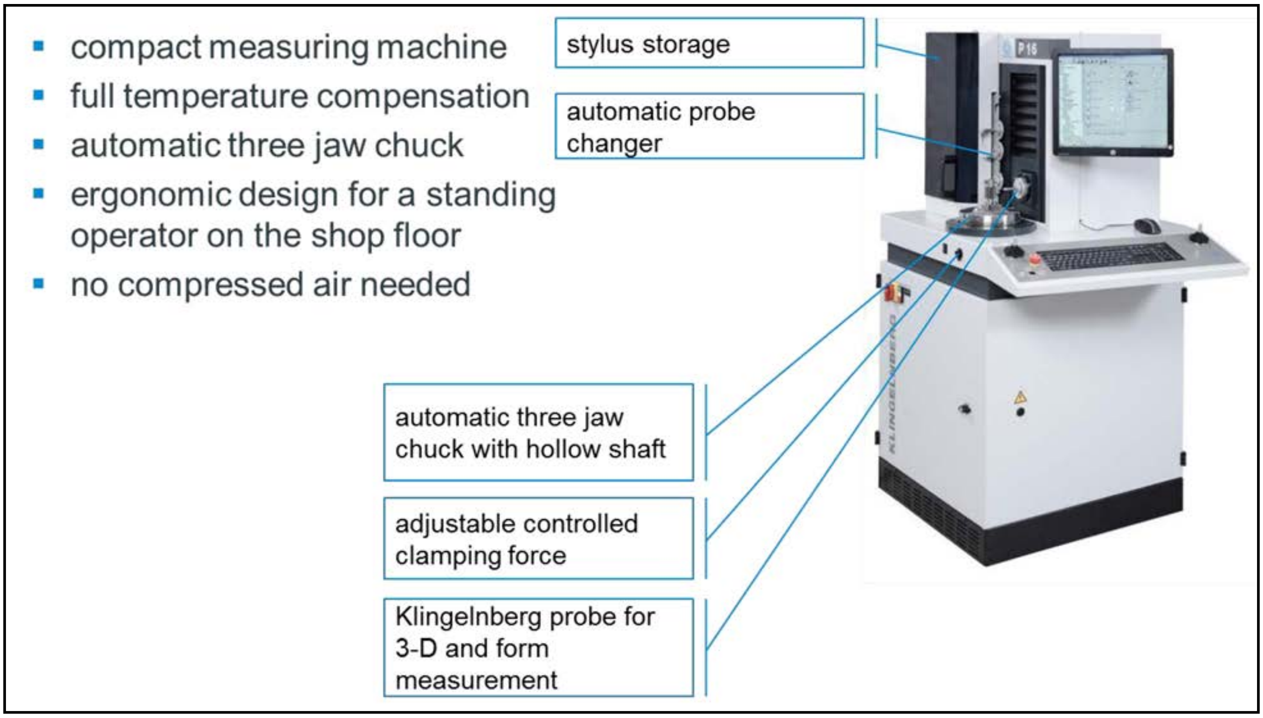

Figure 8 **P 16 G as a replacement for gauges on the shop floor.**

improve productivity. On the one hand, costs for the measurement processes can be saved. On the other hand, important information for an optimization of production processes can be collected by utilizing measurement capabilities.

It is shown in this paper that the process integration of different measurement tasks—which typically take place on multiple machines—is possible on one machine. On a precision measuring center, all coordinate measuring tasks, as well as form testing, can be carried out in addition to the classical gear measurement. This is supplemented by the roughness measurement, which results in both efficiency advantages and starting points for improving the reproducibility of the measurement result.

If the measuring machine is moved out of the measuring room and placed on the shop floor, further productivity increases can be achieved. In addition, cost savings are possible if the number of measuring rooms can be reduced. With a measuring machine on the shop floor, gauge checks, and thus the investment into gauges, can be replaced by CMM measurements. In this way the possibilities of statistical process monitoring can be used more intensively. Qualitative measurements have to be carried out within the scope of quality documentation, so that a gauging test is often an additional process step anyway. Ultimately, measurement in production, coupled with statistical process control, also enables the acquisition of trends, for example, so that intervention can take place in the process before the first part is out of quality and needs to be scrapped.

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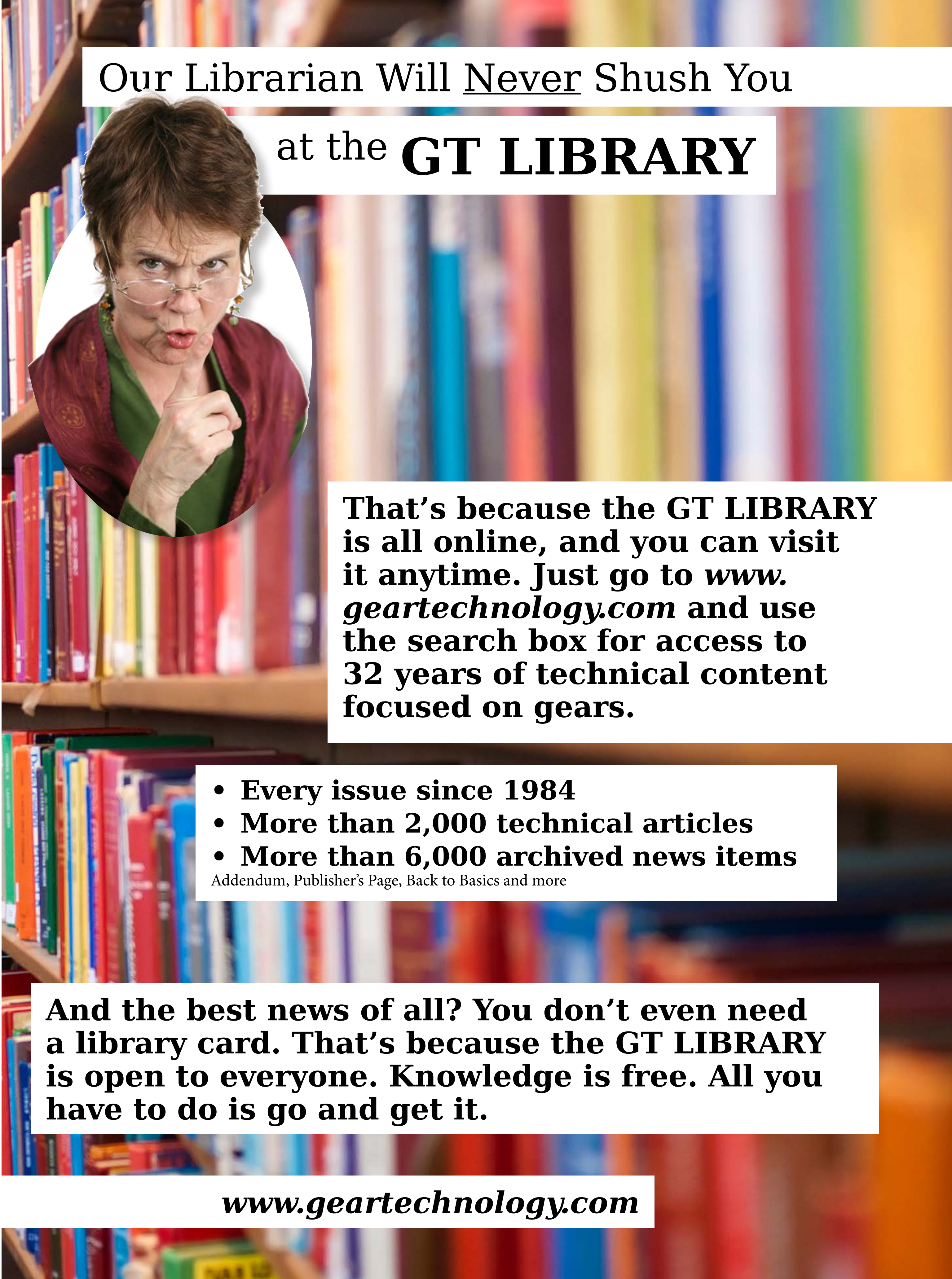
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Sensitivity Study of Press Quench Process and Concept of Tooling Design for Reduced Distortion by Modeling

Zhichao (Charlie) Li and B. Lynn Ferguson

Press quenching is designed to harden steel gears while minimizing distortion, and the process is especially applied for hardening large diameter thin-wall gears, face gears and bevel gears. The dimensional control aims at maintaining flatness, out-of-round, straightness and consistency of radial size. The press quench tooling and the process design have been mainly experience-based, using a trial and error approach for implementation of new processes, new gear materials and gear configurations. Both the out-of-round distortion and the radial distortion, including straightness and size change of thin-wall gears, are critical due to the maximum allowed grinding amount of the carburized case. Factors affecting the dimensional consistency of a press quench process can be classified as originating from gear/material conditions or the process parameters. The gear/material conditions include the variations of the initial gear dimensions, carbon distribution, residual stresses and material microstructures prior to hardening. The press quench process parameters include the heating rate, austenitizing temperature, applied load type, load amount, load location on the part from the tooling, friction between the tooling and the gear, and the quench rate, etc. All these factors may lead to inconsistent distortion, including the size and shape in quench-hardened parts. In this paper, the effects of several critical factors on dimensional inconsistency are analyzed using the heat treatment modeling software *DANTE*. The analysis results indicate that the current press quench with expander design does not effectively maintain a consistent radial size for thin-wall gears after hardening. By replacing the expander with an oversized plug, the effects of austenitizing temperature, cooling rate and initial gear size on the distortion are analyzed, and the press quench with plug design leads to consistent radial size. This concept of tooling design is demonstrated by modeling a hardening process for a simplified thin-wall spiral bevel gear made of carburized AISI 9310 steel.

Introduction

Quench hardening is used to increase the hardness, strength, and fatigue performance of steel gears. A combination of carburizing and quenching can generate beneficial surface compressive residual stresses due to its delayed martensitic transformation in the case. The compressive residual stresses in the surface benefit the high cycle fatigue performance.

During quenching, stresses caused by the thermal gradient and phase transformations generate plastic deformation and distortion in hardened parts. Gear components with large distortion will increase gear noise and reduce the fatigue life in service. Final machining of case hardened gears often leads to nonuniform case depth distribution, so a maximum amount of distortion allowed by hardening is often specified for quality control, and parts with distortion exceeding the specification will be scrapped. Press quenching is one effective process to reduce distortion during hardening. Quench hardening is a transient thermal stress process; the main sources of distortion include the thermal stress and phase transformation stress during both heating and cooling processes. The phase transformations make the quench hardening process highly nonlinear due to the changes of the thermal properties, mechanical properties and density of the material, and it is difficult to investigate the sources of distortion through experiments. Heat treatment results that are of common interest include the volume fractions of phases, hardness, residual stresses and part dimensional change. The development of heat treatment simulation software makes it possible to understand the material response during the heat treatment process, including the evolution of internal stresses and deformation, the phase transformation sequences and the probability of cracking. Computer simulation has increased the level of understanding of heat treatment processes because the events that occur during heating and cooling can be accurately modeled. In turn, advances in computer hardware, in combination with accurate simulation, have made the design and optimization of heat treatment processes more cost effective than traditional experimental trial-and-error methods. *DANTE* is a coupled thermal, carbon diffusion, phase transformation and solid mechanics finite element based program for simulating the heat treatment of steel parts (Refs. 1, 2). *DANTE* material models link with either *ABAQUS Standard* or *ANSYS Mechanical* solvers. The modeling results include residual stress state after hardening, the evolution and final volume fractions of metallurgical phases, hardness, and part distortion. *DANTE* can be used to model austenitizing, gas carburizing, low pressure carburizing, immersion quench, high pressure gas quench, spray quench, induction hardening, press/plug quench, and tempering processes. In this paper, *DANTE* is used to investigate the sensitivities of several critical process parameters on distortion for a press quenching process of a simplified thin-wall bevel gear.

Phase Transformation Models

Quench hardening is a highly nonlinear process due to the phase transformations, and the accuracy of the phase

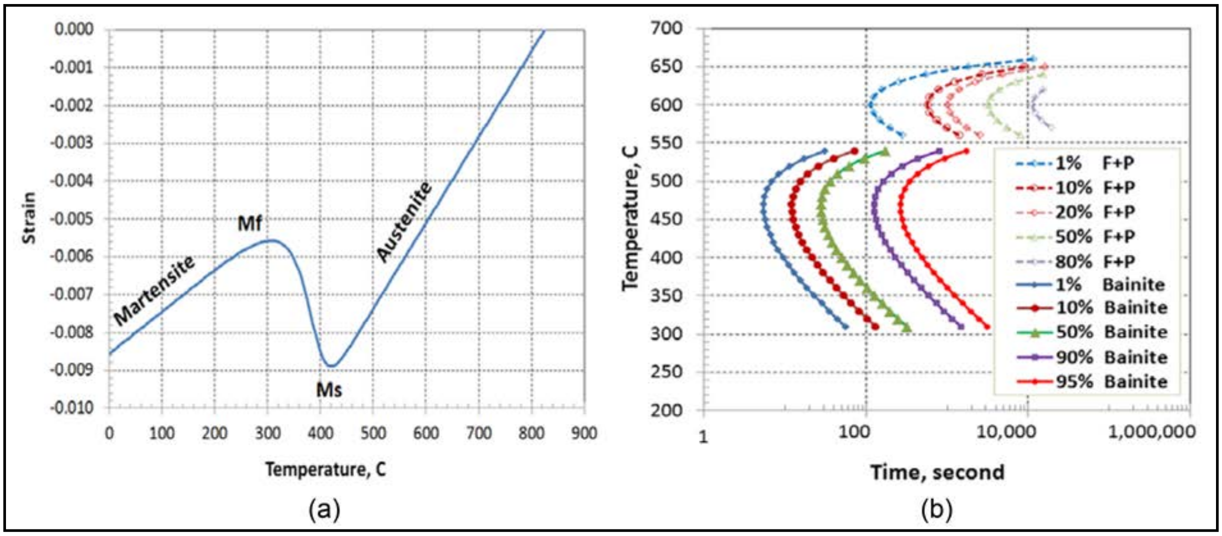

Figure 1 **a) Dilatometry strain curve with martensitic transformation. b) TTT diagram of diffusive transformation for AISI 9310 steel.**

transformation models is critical to the modeling results. The diffusive and martensitic transformation models in *DANTE* are described in Equations (1) and (2) below.

$$\frac{d\Phi_d}{dt} = v_d(T)\Phi_d^{\alpha 1}(1-\Phi_d)^{\beta 1}\Phi_a \quad (1)$$

$$\frac{d\Phi_m}{dT} = v_m(1-\Phi_m)^{\alpha 2}(\Phi_m + \varphi\Phi_d)^{\beta 2}\Phi_a \quad (2)$$

Where Φ_d and Φ_m are the volume fractions of individual diffusive phase and martensite transformed from austenite; Φ_a is the volume fraction of austenite; v_d and vm are the mobilities of tranformation products, α1 and β1 are material related constants of diffusive transformation; α2, β2, and ϕ are constants of martensitic transformation. For each individual phase formation, one set of transformation kinetics parameters is required.

Dilatometry data are often used to characterize the martensitic phase transformation behavior of steels. Figure 1(a) is a continuous cooling dilatometry strain curve generated from the *DANTE* database, representing the martensitic formation of AISI 9310. The horizontal axis in Figure 1(a) is temperature, and the vertical axis is the strain caused by temperature change and phase transformation. The strain change due to martensitic transformation is clearly quantified by the dilatometry experiments.

When the dilatometry test sample cools below the martensitic transformation start (Ms) temperature, its volume expands with the crystal structure change from austenite's face centered cubic (FCC) lattice to martensite's body centered tetragonal (BCT) lattice. Martensite's BCT structure has a lower density than austenite's FCC structure. The strain change during transformation is a combination of thermal shrinkage and phase transformation expansion. The data obtained from this specific type of dilatometry test include coefficient of thermal expansion (CTE) for austenite and martensite, martensitic transformation starting (Ms) and martensitic transformation finishing (Mf) temperatures, transformation strain, and phase transformation kinetics (transformation rate) from austenite to martensite. These data are critical to the accuracy of modeling the internal stress and deformation caused by quenching.

Diffusive phase transformations are also characterized by dilatometry tests. A series of dilatometry tests with different cooling rates can be used to fit a full set of diffusive and martensitic phase transformation kinetics parameters. Once the full set of phase transformation model parameters are fit from dilatometry tests, isothermal transformation (TTT) and continuous cooling transformation (CCT) diagrams can be generated for users to review. TTT/CCT diagrams are not directly used by *DANTE* phase transformation kinetics models, but they are useful because users can see the hardenability of the material graphically. Figure 1(b) is an isothermal transformation diagram (TTT) for AISI 9310 steel created from the *DANTE* material database.

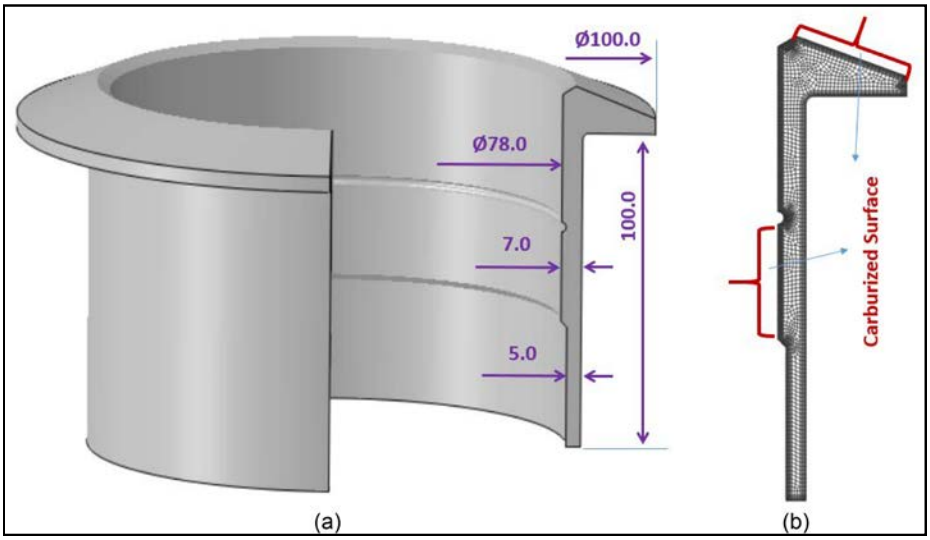

Figure 2 **Simplified thin-wall bevel gear. a) CAD model and dimensions. b) Finite element mesh.**

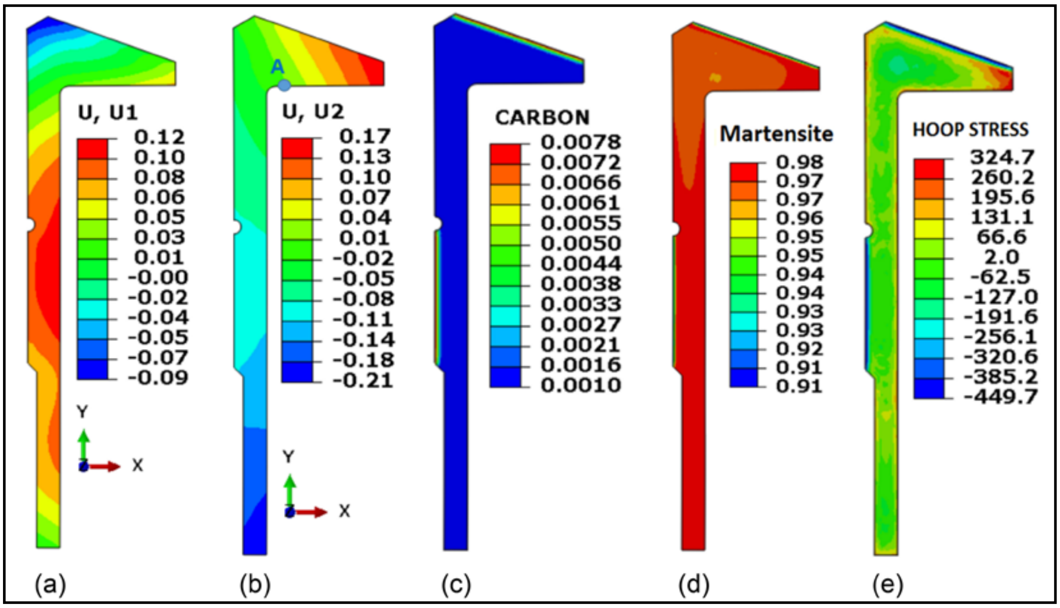

Figure 3 Modeling results of immersion oil quench process. a) Radial displacement. b) Axial displacement. c) Carbon fraction. d) Martensite fraction. e) Circumferential residual stress.

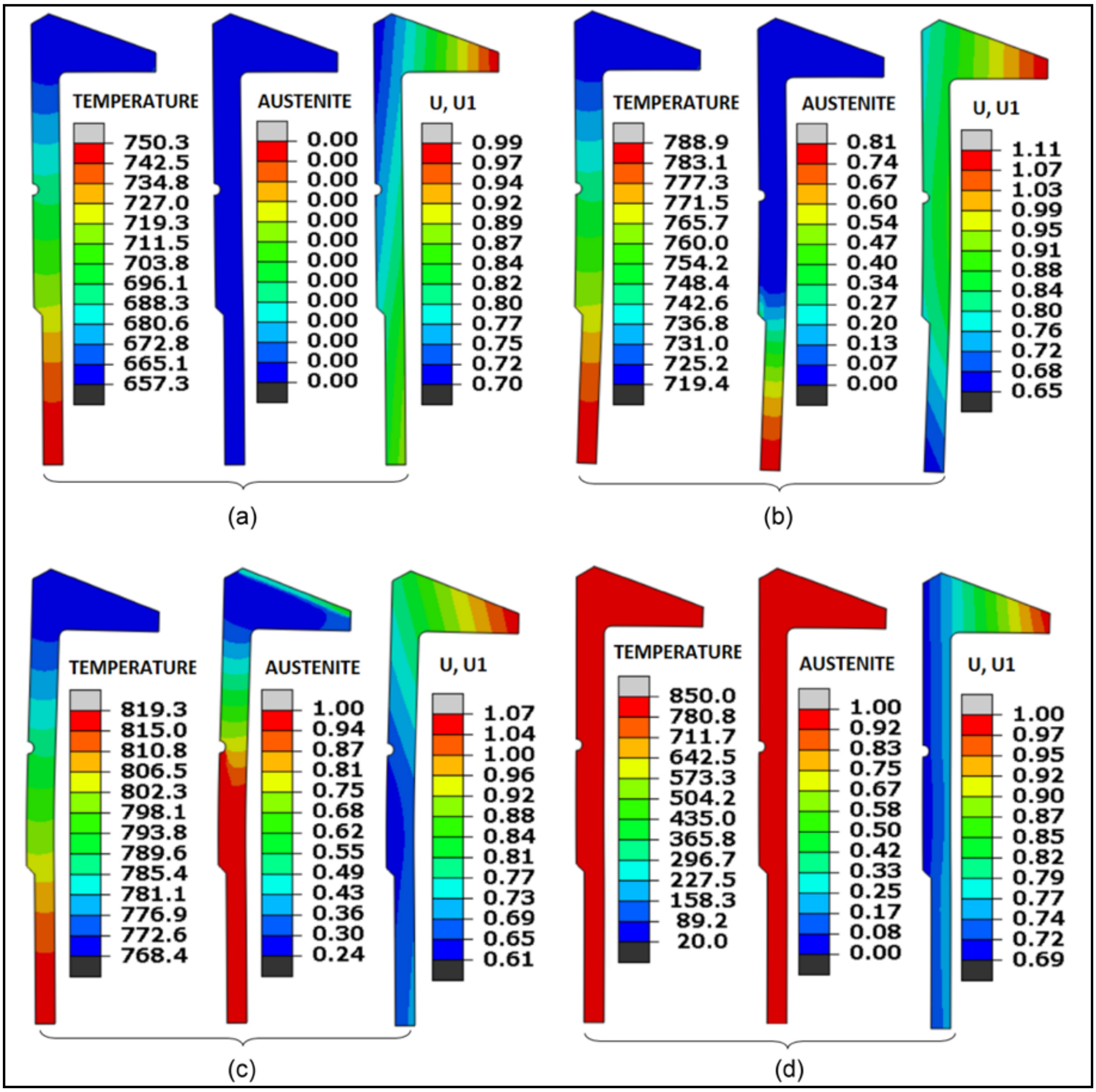

Figure 4 Temperature, austenite and radial displacement distribution contours during heating process. a) At 422.6 s. b) At 515.5 s. c) At 627.0 s. d) At the end of heating.

Description of Gear Geometry, Finite Element Model and Heat Treatment Processes

A simplified thin-wall bevel gear is used in this study. The CAD model of the gear is shown in Figure 2(a). The inner diameter of the gear is 78.0 mm, the height is 100.0 mm, and the outer diameter of the tapered bevel tooth section is 100.0 mm. The thickness of the upper wall is 7.0 mm, and the thickness of the lower wall is 5.0 mm. This gear geometry is selected because of its tendency for large distortion during quench hardening, mainly due to its stepped thin-wall and conical bevel tooth section geometric features. The gear material is AISI 9310, and a portion of the inner wall surface is selectively carburized, as shown in Figure 2(b). The out-of-round, straightness and size of the gear wall are the main distortion modes. It is expected that the bevel tooth section will affect the straightness and radial size distortion. The bevel teeth are not modeled to simplify the model geometry, but the conical angle of the tooth tip surface is kept to more accurately catch the top die load effect during press quench. After removing the bevel teeth, the volume of the simplified model is kept the same as that of the original model by adjusting the conical surface position. For press quench using either expander or plug tooling design, the out-of-round distortion can be controlled effectively, but the radial distortion is difficult to control in general. The two-dimensional axisymmetric model can be used to predict the radial distortion, including the straightness and the radial size effectively. In this study, one cross-section of the gear is used to model the gear response during quench hardening, and the finite element mesh is shown in Figure 2(b). The FEA model contains 3,659 nodes and 3,468 4-node linear elements. Fine elements are used in the part surface to catch the steep gradients of carbon, temperature, phase transformation and stress evolutions during the entire hardening process.

Heat Treatment Process Problem Statement

The gear is gas carburized, followed by reheating and quench hardening. The bevel tooth surface and the middle section of the bore surface are carburized selectively, as shown in Figure 2(b). Other surfaces are copper plated during carburization to block the carbon flux into the surface. A two-step carburization process is used. The first step is a boost step: with the temperature being 925° C, the carbon potential being 0.9%, and the time duration being 14400 seconds. The second step is the diffuse step: with the temperature dropping down to 875° C, the carbon potential being 0.8%, and the time duration being 7200 seconds. The predicted effective case depth (ECD) is 0.75 mm, and the predicted carbon distribution contour is shown in Figure 3(c).

After carburization, the gear is slowly cooled to room temperature, followed by reheating for hardening. In this study, the residual stresses and distortion from the carburization process are ignored. The reheating temperature is 850° C, and the total heating time is 1800 seconds, including soaking, with the assumption that all the carbides are dissolved into the iron matrix. After heating, the gear is transferred from the furnace to the quenching equipment in 10 seconds. The quench oil temperature is 65° C, and the total quenching time is 300 seconds, which is long enough for the gear to cool to the oil's temperature. After quenching, the gear is taken out and cooled to room temperature. To better understand the press quench tooling effect using expander or plug tooling design, an immersion oil quench without any mechanical tooling constraint is modeled first. With the assumption of a uniform thermal boundary condition applied on the entire surface of the part, the modeling results are shown in Figure 3 for the immersion quench process, including the axial and radial displacements, carbon distribution, volume fraction of martensite, and the circumferential stress distributions. Again, the distortion is due to the austenitizing and quench hardening without including the distortion from the carburizing process. Figure 3(a) shows a barrel shape The bore of the bevel tooth section shrinks after hardening about -0.09 mm radially. The bevel tooth section also has an axial warpage upward of about +0.17 mm, as shown in Figure 3(b). The reference point "A" for the axial displacement, being 0.0 mm ($U2 = 0.0$), is located at the inner bottom surface of the bevel tooth section as shown in Figure 3(b). After quenching, the thin-wall section is through hardened with close to 100% martensite, and the carburized surface has about 10% retained austenite because of its lower martensitic transformation starting and finishing temperatures, due to higher carbon content. Compressive circumferential residual stresses are predicted in the carburized case due to the delayed martensitic phase transformation and corresponding volume expansion, as shown in Figure 3(e).

During heating, the initial phases of the gear transform to austenite when the material is above the austenitizing temperature. The temperature distribution in the part varies during heating due to its nonuniform wall thickness and the thicker bevel tooth section. Figure 4(a) shows the temperature, austenite and radial displacement distributions at 422.6 seconds during heating. The temperature is just below the austenitizing temperature, so the internal stresses are caused purely by the temperature gradient. The predicted radial displacement is from the thermal expansion. At 515.5 seconds during heating, the temperature at the lower portion of the wall reaches 788° C, and the transformation to austenite occurs. With the transformation to austenite, the material volume shrinks, and the radial displacement of the lower portion of the wall is reduced from 0.7 mm before the austenitic transformation starts to 0.65 mm when transformation occurs, even though the temperature increased from 750° C to 788° C. With further heating, the temperature distribution of the middle axial section of the gear wall exceeds the austenitic transformation temperature, and radial shrinkage occurs along with the transformation, as shown in Figure 4(c). After the gear reaches 850° C, transformation to austenite has been completed, and the radial displacement of the wall is relatively uniform, as shown in Figure 4(d). The main interest of this study is to investigate the distortion during quench hardening, so the heating rate is carefully controlled, and the stresses caused by the thermal gradient and phase transformation during heating are low enough to avoid excessive distortion. However, excessive distortion may occur in heat treatment practice with a high heating or austenitizing rate, especially for parts with large section

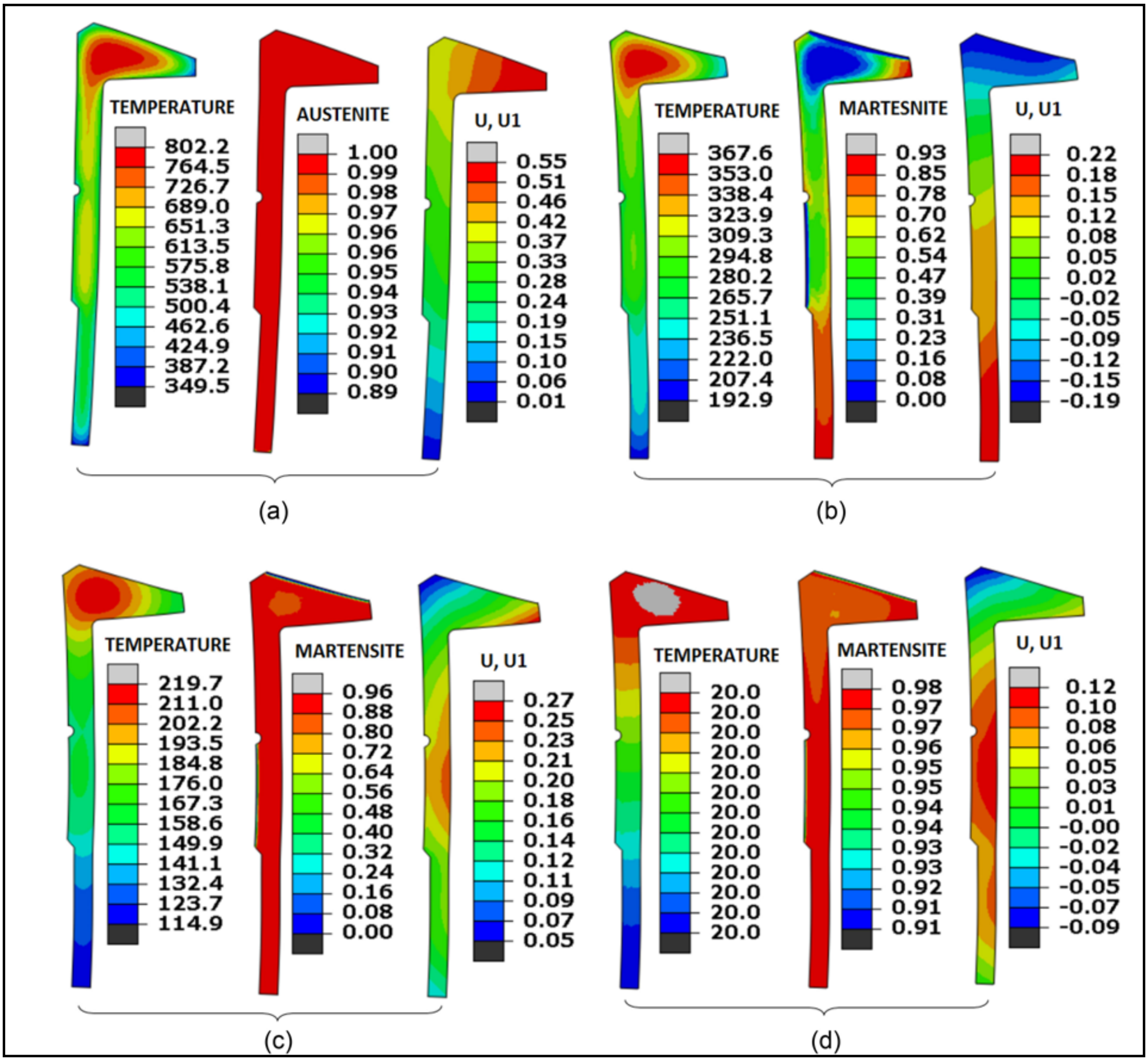

Figure 5 **Temperature, austenite/martensite and radial displacement distribution contours during quenching. a) At 2.0 s. b) At 12.1 s. c) At 32.4 s. d) At the end of quenching.**

thickness variations (Ref. 3). Stepped heating can be used to obtain more uniform temperature in the part when phase transformation to austenite occurs, which is an effective method to control the distortion caused by heating process.

After heating, the gear is taken out from the heating furnace to quench using oil, and the transfer time is 10 seconds. Figure 5 shows the temperature, austenite/martensite phase, and radial displacement of the gear at different times during quenching. The martensitic transformation starting temperature is about 400°C for AISI 9310 base carbon steel, as shown in Figure 1(a). The internal stresses caused by the temperature gradient and phase transformations during quenching are much higher than those of the heating process, which is why the distortion caused by quenching is higher than that of heating. At 2.0 seconds of quenching, the bottom of the gear wall has cooled to about 400°C (Ms), and the martensitic transformation is about to start. At this point, the internal stresses in the part are caused purely by the temperature gradient. With lower temperature at the bottom of the wall, its radial displacement decreases to +0.01 mm from the +0.70 mm at the end of the heating process, as shown in Figure 5(a). The radial displacement at the top of the wall is about +0.40 mm. With further cooling, the bottom of the wall drops to about 200°C, and the top is still above 350°C, as shown in Figure 5(b), at 121.1 seconds during the quench. The martensitic transformation in the lower portion of the wall is almost finished, while the upper portion has about 50% martensite formed. With martensitic transformation, the material expands, and the radial displacement is a combination of thermal shrinkage and volume expansion caused by the martensitic phase transformation. The radial displacement difference between the lower and upper portion of the gear wall is reduced at this moment due to a combination of temperature and phase transformation effects on dimensional change.

After 32.4 seconds of quenching, the martensitic transformation in the core of the thick bevel tooth section is completed, while the carburized case is still austenite due to its lower Ms temperature. The predicted radial displacement shows that the gear has a barrel shape at this moment, as shown in Figure 5(c), and the positive values of the radial displacement mean the gear size is large than the original size. Between 32.4 seconds and the end of quenching, the carburized case has further phase transformation to martensite. The volume expansion caused by the martensitic phase transformation leads to compressive stresses in the case, which are balanced by tensile stresses in the core of the gear. Because the carburized case has a relatively small region, its delayed martensitic transformation has an insignificant effect on further deformation of the part. The main contribution of deformation is from the thermal shrinkage of the part. At the end of quench, the middle section of the wall has a radial displacement of about +0.12 mm, the bottom is about 0.0 mm, and the top (bevel tooth section) is -0.09 mm. These results will be compared with press quench modeling results in later sections of this paper.

Press Quench using Expander/Plug Tooling Design

The immersion oil quench modeling analysis shows that the sources of distortion can be summarized as the plastic deformation caused by the thermal stress and phase transformation stress. A 2D axisymmetric model is used to investigate the press quench process by assuming the gear behaves uniformly in the circumferential direction, so the out-of-round distortion is not modeled. In heat treatment practices, the oil flow around in the circumferential direction of the gear may not be uniform, which will cause out-of-round distortion. For gears with thin-wall feature, press quench is often used to reduce the distortion. For the simplified thin-wall bevel gear used in this study, an expander/plug is required to control the out-of-round distortion, straightness, and the radial size of the thin-wall section. Bottom and top dies are required to control the warpage of the bevel tooth section. Iterations of tooling designs are modeled using *DANTE*, with variations of tooling load applied. Four schematic tooling designs are shown in Figure 6. In each of the tooling designs, the expander/plug is modeled as two pieces, so the radial positions of the lower and upper portion of the expander/plug can be more flexibly adjusted to control the straightness of the gear. The expander/plug is short axially in the tooling-1, tooling-2 and tooling-3 designs, as shown in Figures 6(a), 6(b) and 6(c). In the tooling-1 design, both the bottom and the top dies have small contact areas with the bevel tooth section. In the tooling-2 design, the size of the lower die is increased. In the tooling-3 design, both the bottom and top dies have increased contact area. In the tooling-4 design, the expander/plug size is increased to cover the entire bore of the gear wall. To model the press quench processes using either expander or plug, all the tool members are modeled as rigid surfaces. The bottom die is constrained, and the top die moves freely in the axial direction. A concentrated force is applied on the top die to control the axial warpage of the bevel tooth section. In a press quench model using the expander, a concentrated force is applied on the expander to control the radial distortion of the gear wall, and the expander can move in the radial direction. If the plug is used instead of the expander, the radial degree of freedom of the plug is constrained in the model. The radial position of the plug can be adjusted to represent different plug sizes. In later sections of this paper, a plug size of +0.0 mm means that the plug has a perfect contact with the gear wall at room temperature, while a plug size of +0.1 mm means the plug has a +0.1 mm overclosure radially with the bore of the gear at room temperature.

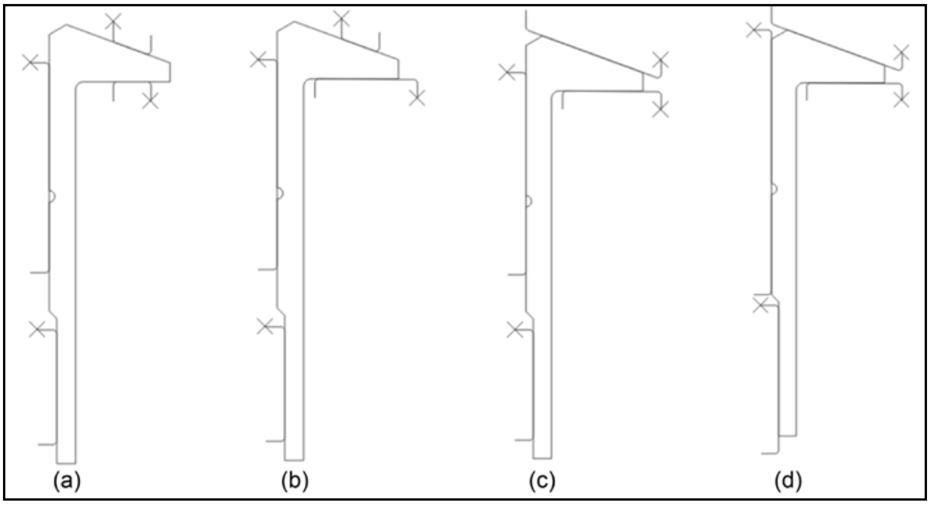

Figure 6 **Press/Plug quenching tooling design. a) Tooling-1. b) Tooling-2. c) Tooling-3. d) Tooling-4.**

Using the press quench with the plug design, the effect of the four tooling designs shown in Figure 6 on the radial distortion of the gear wall and the warpage of bevel tooth section is compared in Figure 7. A concentrated force of 10 KN is applied on the top die for all the four models. The plug size is +0.0 mm, which means the plug size is the same as the bore size of the gear at the room temperature. The predicted radial displacements (U1) of the four models have no significant difference. However, the predicted axial displacements (U2) of the bevel tooth section have noticible differences, indicating warping of the bevel tooth section. In tooling-1, tooling-2 and tooling-3 designs, the expander/plug doesn't cover the entire bore surface of the gear, which makes both the radial and axial distortion of the bevel tooth section sensitive to the load applied on the top die. From modeling results with various plug size and die load combinations, it is found that the tooling-4 design produces the most consistent results in the four expander/plug tooling designs. In later sections of this paper, all the sensitivity studies of different process parameters are based on the tooling-4 design.

It is expected that the load applied on the top die doesn't have significant effect on the radial distortion of the gear wall. Using the plug size +0.0 mm and the tooling-4 design, the effect of the top die load on the axial warpage of the bevel tooth section is investigated. Figure 8 shows the predicted axial displacements with 2.5 KN, 5.0 KN, 7.5 KN, 10.0 KN, and 12.5 KN loads on the top die. Without applying die load (immersion quench), the warpage of the bevel tooth is about +0.17 mm upward, as shown in Figure 3. By comparing the magnitude of axial

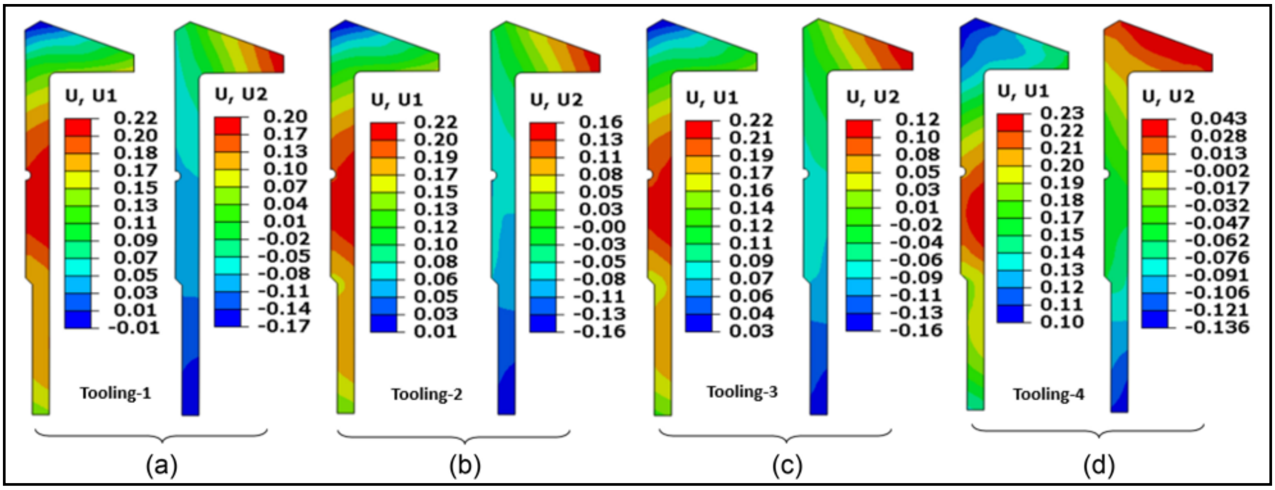

Figure 7 Predicted radial and axial displacements from press quench model using the plug design with +0.0 mm plug size and 10 KN load applied on the top die. a) Tooling-1. b) Tooling-2. c) Tooling-3. d) Tooling-4.

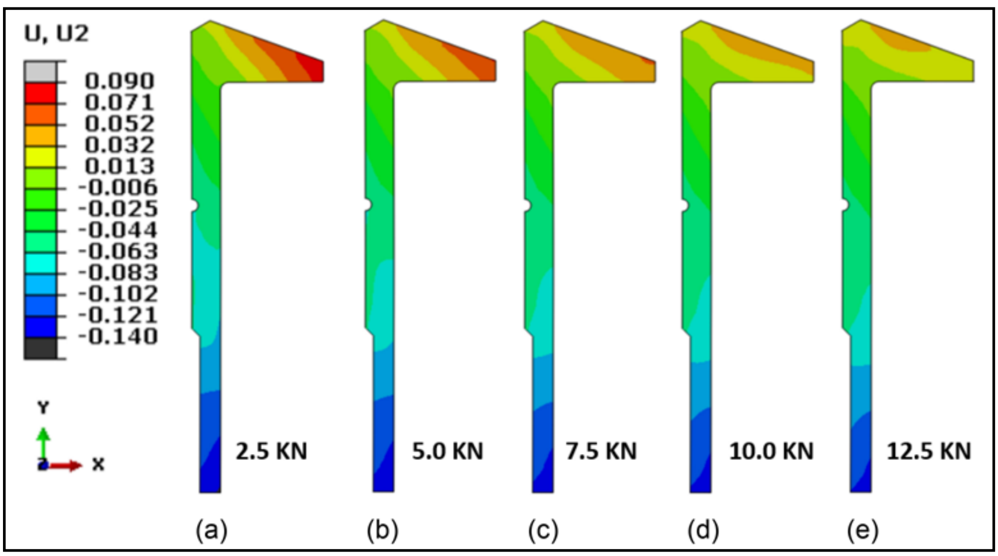

Figure 8 Effect of top die load on predicted axial displacement using plug +0.0 mm and the tooling-4 design. a) 2.5 KN. b) 5.0 KN. c) 7.5 KN. d) 10.0 KN. e) 12.5 KN.

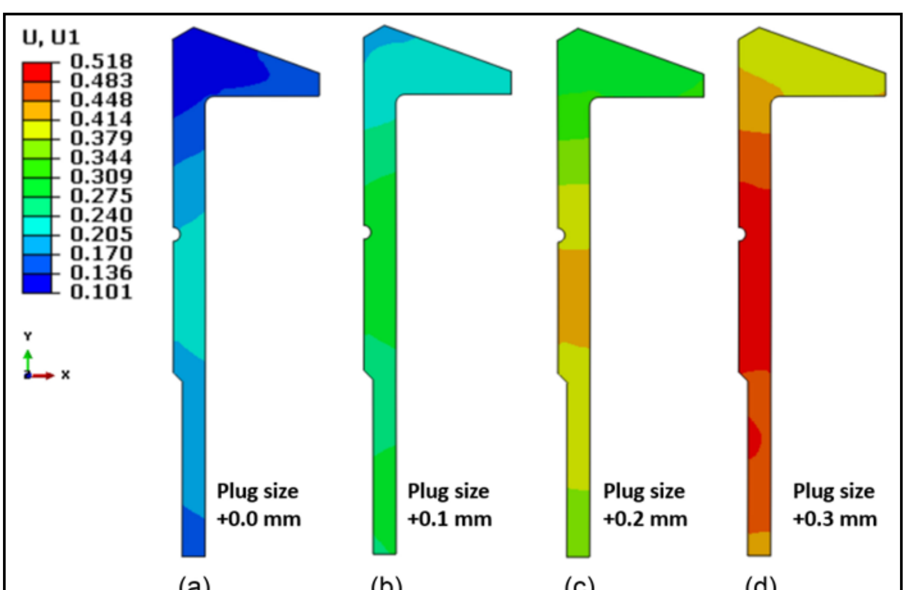

Figure 9 Effect of plug size on predicted radial displacements with the tooling-4 design and 10 KN applied on the top die. a) Plug size +0.0 mm. b) Plug size +0.1 mm. c) Plug size +0.2 mm. d) Plug size +0.3 mm.

displacement predicted in Figure 8, a 10 KN die load is necessary to control the warpage of the bevel tooth section. The axial displacement predicted at the end of quenching includes the effects from both warpage and size change. A top die load that is too high will lead to low straightness of the gear wall because the top die pushes the bevel tooth section inward from the conical surface of the bevel tooth surface. After comparing the predicted axial distortion, the 10 KN die load is selected for further process variable sensitivity investigation in later sections of this paper.

In a press quench hardening process, either expander or plug designs can be used to control the radial displacement of thin-wall gear components. The radial displacements include the out-of-round distortion, straightness and the radial size of the hardened parts. In this study, the effect of plug size on the radial displacement is investigated, and the modeled plug sizes are +0.0 mm, +0.1 mm, +0.2 mm and +0.3 mm. Higher expander load or larger plug size will reduce the out-of-round distortion in general. However, if the plug size is too large, it will be difficult to insert the plug into the part due to possible out-of-round shape change and thermal shrinkage from the air transfer step. In this study, the largest plug size modeled is +0.3 mm. The predicted radial displacements are shown in Figure 9 for the several plug sizes. The load applied on the top die is 10 KN for all the models. With the plug size being +0.0 mm, the predicted minimum radial displacement is +0.101 mm at the bore of the bevel tooth section, and the maximum radial displacement is +0.23 mm at the middle height of the gear wall section. Compared to the radial displacements of -0.09 mm and +0.12 mm predicted for the immersion quench process as shown in Figure 3(a), the plug is effective in controlling the radial size of the gear. However, the straightness of the gear wall is not improved using this plug. By increasing the plug size, the predicted radial displacement of the gear wall is getting more consistent, as shown in Figures 9(b), (c) and (d). Figure 4(d) shows that the radial displacement of the gear after heating is +0.69 mm, which will allow a maximum plug size of +0.69 mm. However, considering a possible out-of-round shape change and thermal shrinkage during air transfer, a plug size of +0.3 mm is selected for further sensitivity analysis of other process parameters. The process consistency can be defined as the variation of process parameters that are found to be less sensitive to the obtained distortion in the hardened part. If the process is consistent, the initial gear configuration can be adjusted to compensate for distortion and size change. The goal of this study is to investigate the sensitivity of critical process parameters and how to improve the process consistency.

Sensitivity Analysis of Press Quench Hardening Process with Expander or Plug Design

The critical process parameters in a press quench process include the austenitizing temperature, the quenching rate and the applied loads, etc. In this modeling study, the effect of several critical process parameters on distortion is investigated. The difference between the press quench with expander and plug tooling designs is also analyzed. If the expander is used, the load applied on the expander is expected to affect the out-of-round, straightness, and size of the gear after hardening. Figure 10 shows the predicted radial displacement distribution contours from press quench with 2.5 KN, 5.0 KN, 7.5 KN, 10.0 KN, and 15.0 KN loads applied on the expander, respectively. The load doesn't have a significant effect on the maximum radial displacement of the gear wall. However, its effect on the radial displacement of the bevel tooth section is significant. Higher expander load increases the radial displacement of the bevel tooth section, so the straightness of the gear wall is improved. The effect of the expander load on the radial displacement of the gear wall is highly nonlinear due to two main reasons: 1) different wall thickness leads to different thermal shrinkage between lower and upper portion of gear wall, and 2) martensitic transformation has a time difference between the lower and upper portion of the gear wall, which leads to material expansion at difference times. The two factors will cause different interactions between the expander and the lower/upper portion of the gear wall. The different interactions include contact time and reaction force, which makes the radial shape of the gear wall nonlinear in terms of the load applied. From the modeling results, 10.0 KN is required to make the expander effect more consistent. In this paper, the 10 KN expander load will be used for the sensitivity analysis of other process parameters, including the austenitizing temperature and quenching rate, as well as gear initial size effect.

During the quench hardening process, the gear is first heated to transform to the austenite phase prior to quenching. The effect of austenitizing temperature on the radial distortion is shown in Figure 11, with the austenitizing temperature being 810° C, 825° C, 850° C, 875° C, and 900° C, respectively.

Lower austenitizing temperature is preferred in press quench for more consistent results in general. However, the gear may not be fully austenitized if the austenitizing temperature is too low, plus the temperature variation in the furnace. An austenitizing temperature of 810° C is often used in the industry for gears made of AISI 9310. With 810° C austenitizing temperature, the model assumes a complete transformation to austenite.

Using the same process setting with the plug +0.3 mm tooling design, the austenitizing temperature effect on the radial displacement is shown in Figure 12. With the same legend range magnitude

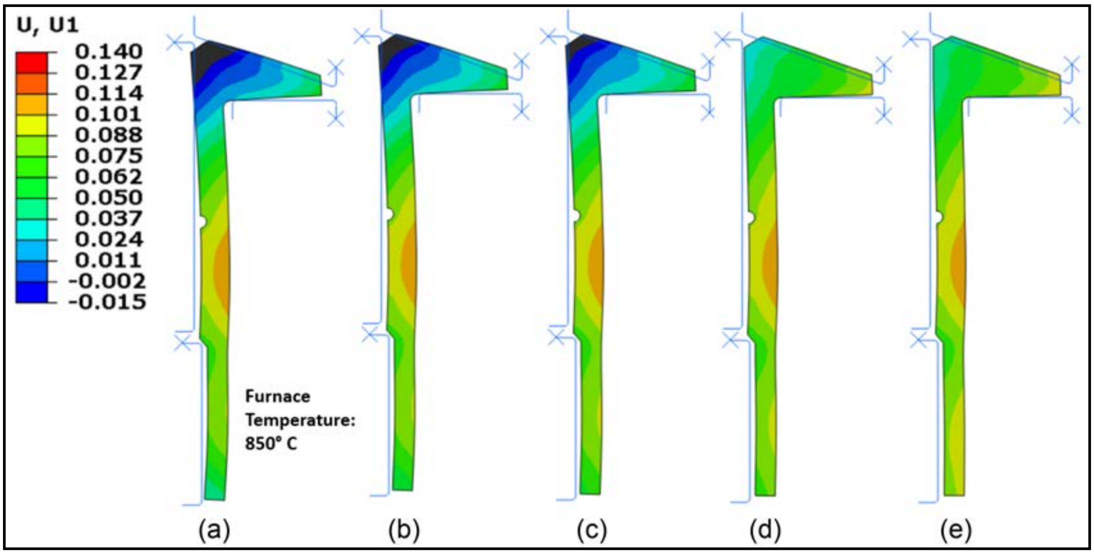

Figure 10 Effect of expander load on predicted radial displacement using press quench with 850° C austenitizing temperature. a) 2.5 KN. b) 5.0 KN. c) 7.5 KN. d) 10.0 KN. e) 15.0 KN.

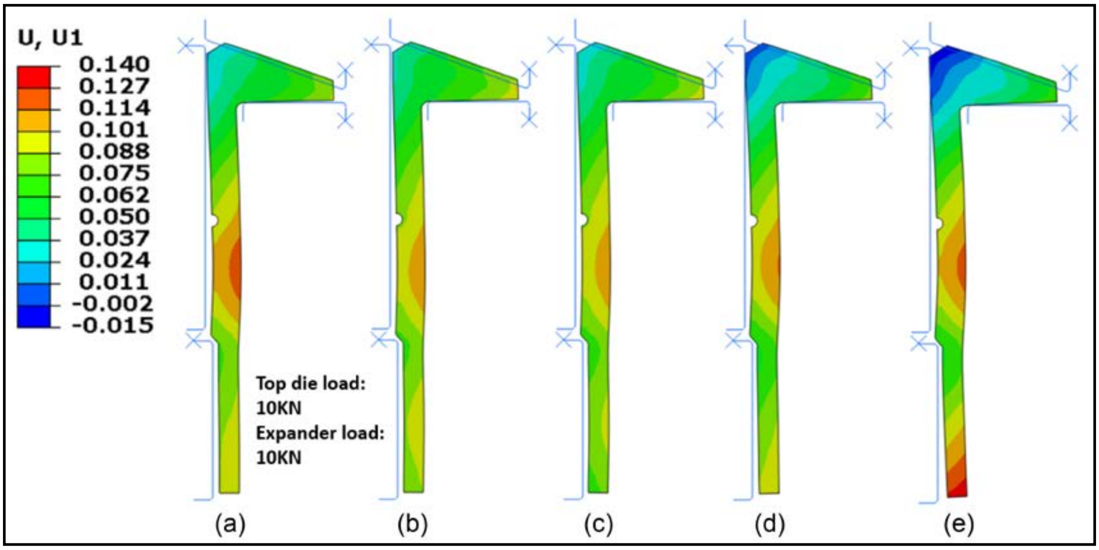

Figure 11 Effect of austenitizing temperature on predicted radial displacement using press quench with a 10 KN load on top die and a 10 KN load on the expander. a) 810° C. b) 825° C. c) 850° C. d) 875° C. e) 900° C.

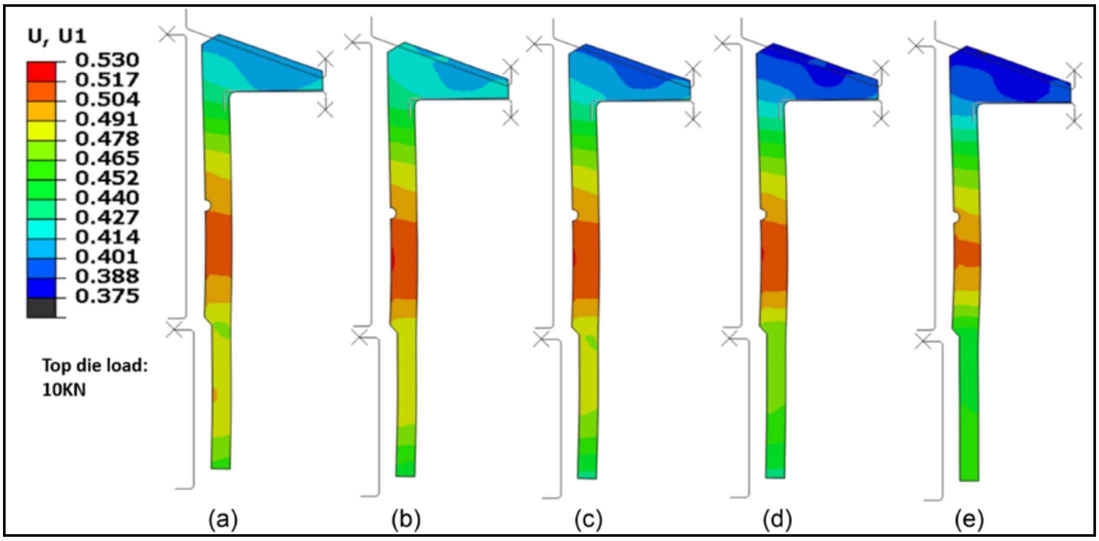

Figure 12 Effect of austenitizing temperature on predicted radial displacement using press quench with 10 KN load on top die and plug +0.3 mm design. a) 810° C. b) 825° C. c) 850° C. d) 875° C. e) 900° C.

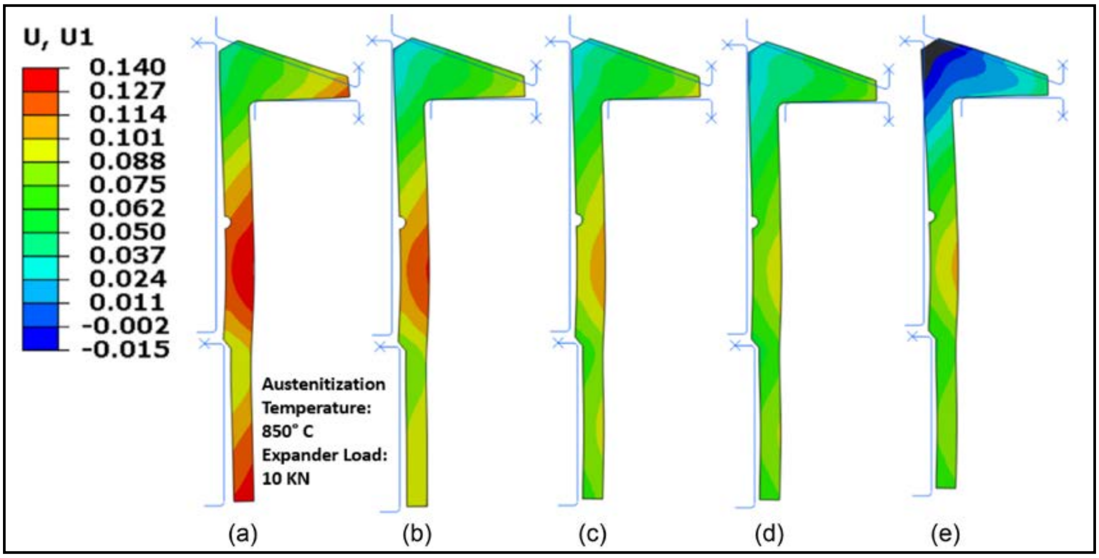

Figure 13 Effect of quenching rate on predicted radial displacement using press quench with 850° C austenitizing temperature and 10 KN expander load. a) 50% HTC. b) 75% HTC. c) 100% HTC. d) 125% HTC. e) 150% HTC.

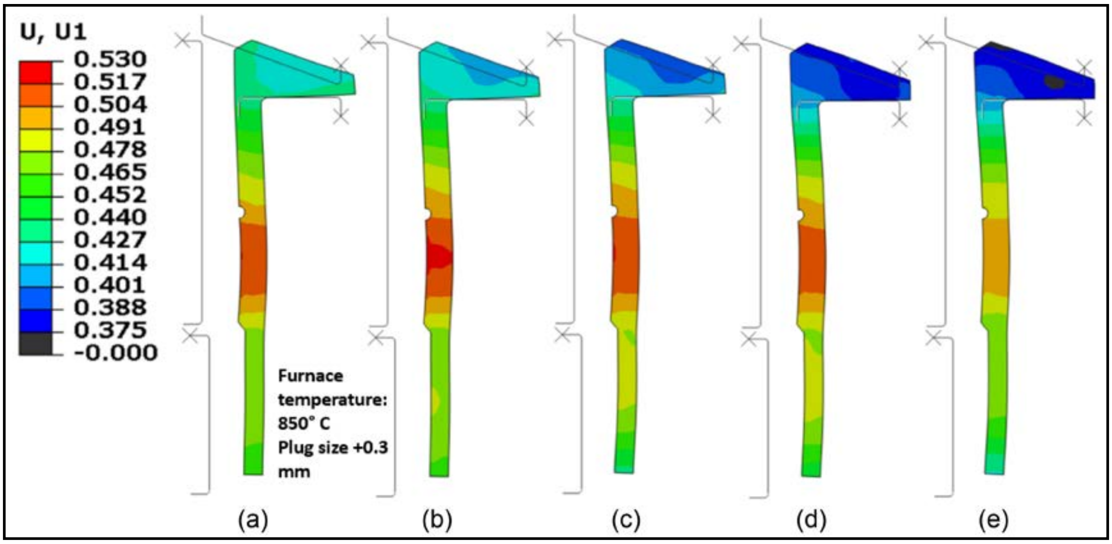

Figure 14 Effect of quenching rate on predicted radial displacement using the plug quench with 850° C austenitizing temperature and plug +0.3 mm tooling design. a) 50% HTC. b) 75% HTC. c) 100% HTC. d) 125% HTC. e) 150% HTC.

(0.155 mm) used in Figures 11 and 12, the contour plot color can be used to compare the predicted radial displacements directly. With higher austenitizing temperature, the predicted radial size of the bevel tooth section decreases, which is true for press quench using either expander or plug design. The predicted straightness between the expander and the plug tool designs doesn't show any significant difference by comparing Figures 11 and 12.

The cooling rate of the gear during quenching is affected by the oil temperature, oil flow pattern, oil flow rate, etc. Oil pumps are used in press quench equipment to drive the oil flow around the part, and the pumping power can be adjusted as a process parameter to affect the quenching rate. To investigate the effect of the quenching rate on distortion, a series of heat transfer coefficients are applied on the gear surface. The heat transfer coefficient is defined as a function of the part surface temperature (Ref. 4), and it is assumed that the entire surface has a uniform heat transfer coefficient applied with a constant oil temperature of 65° C for all the models. To evaluate the quenching rate effect, the heat transfer coefficient curve versus part surface temperature is multiplied by a factor. For example, 50% HTC means the values of the HTC is half of the values of the standard HTC. Figure 13 shows the predicted radial displacements from 50% HTC, 75% HTC, 100% HTC, 125% HTC and 150% HTC using the press quench with the expander tooling design. With faster cooling rate, the radial displacements decrease. With 50% HTC, the maximum radial displacement of the gear wall is about +0.14 mm, versus about +0.10 mm with 150% HTC (Figs. 13[a] and 13[e]).

With the same thermal boundary conditions and the plug +0.3 mm tooling design, Figure 14 shows the predicted radial displacements. The predicted radial displacement of the gear wall is more consistent compared to the results using the expander design, shown in Figure 13. The radial displacements of the bevel tooth section have a similar sensitivity level to the cooling rate between the expander and the plug +0.3 mm tooling designs.

The gear dimensions prior to quenching may vary due to the following possible reasons: 1) dimensional difference due to previous machining processes, 2) residual stresses in the part prior to heating and shape change due to the stress relaxation during heating, 3) distortion caused by carburizing and sequential cooling processes, and 4) distortion due to reheating or austenitizing processes, etc. It is expected that the press quench process with either expander or plug design is effective for controlling the out-of-round distortion. However, controlling the radial size of the gear after hardening is critical if the part is carburized or selectively carburized, as only a small grinding amount after hardening should be permitted.

To make the post-processing of the final radial displacement contours more intuitive, the variation of the initial gear size is modeled by assigning the gear with specified initial temperatures, followed by ramping the gear to the room temperature of 20° C. The radial displacements, due to the thermal shrinkage or displacements of the bore to represent the gear sizes, the radial displacements are -0.10 mm, -0.05 mm, 0.0 mm, +0.05 mm, and +0.10 mm, as shown in the contour plots of Figure 15. Due to the thermal shrinkage or expansion, there are also initial radial displacements in the bevel tooth section, which will be carried over to the final predicted distortion after hardening. The internal stresses in the gear are zero prior to heating because the temperature in the gear is uniform during the temperature ramping process.

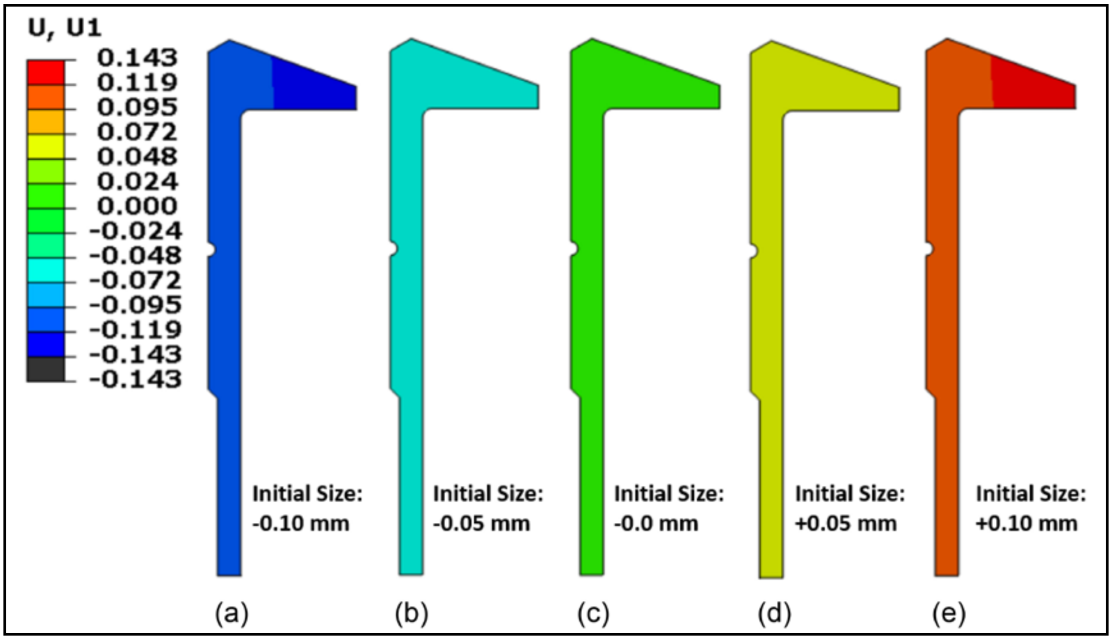

Figure 15 Radial displacement contours (initial gear sizes) of the gear at room temperature prior to heating. a) –0.1 mm. b) –0.05 mm. c) 0.0 mm. d) +0.05 mm. e) +0.1 mm.

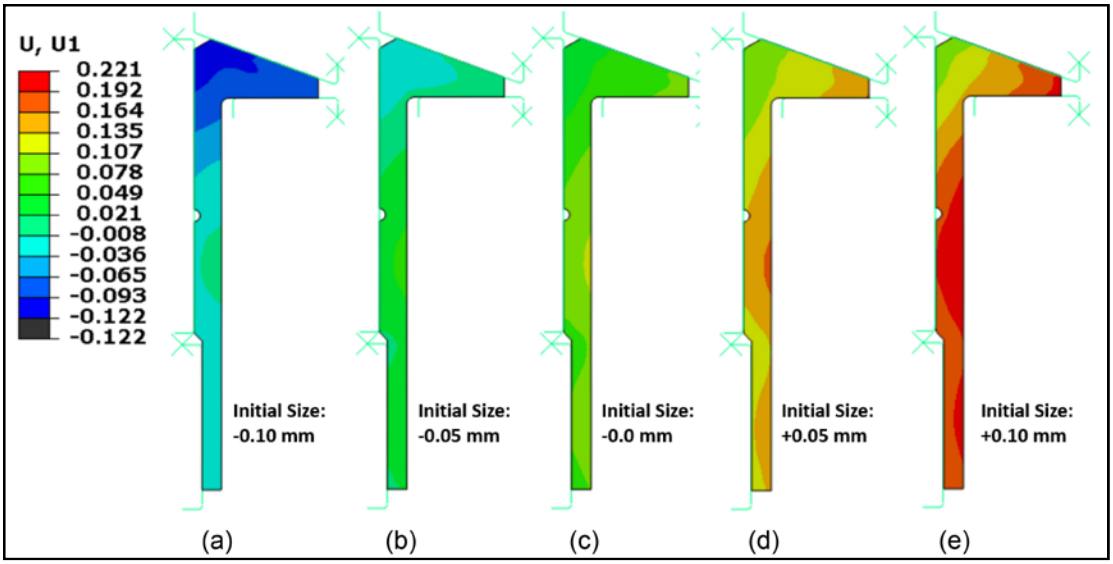

Figure 16 Effect of initial gear size on predicted radial displacements using the press quench with 10 KN expander load and 850° C austenitizing temperature. a) –0.10 mm. b) –0.05 mm. c) 0.0 mm. d) +0.05 mm. e) +0.10 mm.

Using the displacements shown in Figure 15 as the starting point, the press quench processes with both the expander and the plug tooling designs are modeled. The uniform standard heat transfer boundary conditions described previously are applied for all the models, with the 10 KN load applied on the top die. Either the 10 KN will be applied on the expander, or the plug size +0.3 mm will be used for the two different tooling designs, respectively. The predicted radial displacements after hardening are shown in Figures 16 and 17 for various initial gear dimensions and the two tooling designs.

With a smaller gear dimension prior to heating, the final gear size is also smaller after hardening if the expander tooling design is used for the press quench process. As shown in Figure 16(a), the maximum radial displacement of the gear wall predicted is about 0.0 mm if the initial gear size is –0.10 mm. The predicted radial displacements are +0.057 mm, +0.112 mm, +0.170 mm, and +0.221 mm for the initial gear sizes of –0.05 mm, 0.0 mm, +0.05 mm, and +0.1 mm, respectively, as shown in Figures 16 (b) through (e). The predicted radial displacements after hardening in Figure 16 have significant difference. One conclusion is that the final gear size is approximately linear to the initial gear size prior to heating. For gears with a radial size variation before hardening, the final gear sizes after hardening will be scattered unless the press quench process can be adjusted accordingly, which may not be feasible in most cases.

Using the same process setting and replacing the expander by the plug +0.3 mm tooling design, the predicted radial displacements from various initial gear sizes are shown in Figure 17. The predicted radial displacements of the gear wall have a variation range of 0.03 mm (0.53 mm–0.50 mm). Compared to the

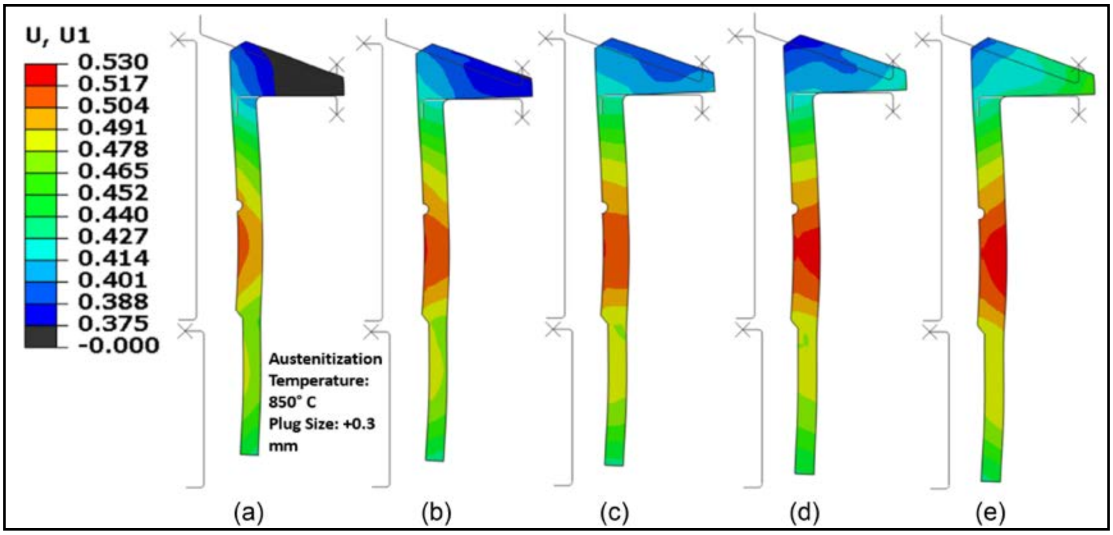

Figure 17 Effect of initial gear size on the predicted radial displacements using the press quench with plug size +0.3 mm and 850° C austenitizing temperature. a) –0.10 mm. b) –0.05 mm. c) 0.0 mm. d) +0.05 mm. e) +0.10 mm.

results of 0.22 mm (0.22 mm–0.00 mm) from using the expander tooling design, the press quench with the oversized plug is much more consistent. The predicted straightness of the gear wall doesn't have significant difference between the expander and the plug tooling designs. The straightness can be improved by using a profiled expander or plug configuration.

Summary

Using a simplified bevel tooth gear with stepped thin-wall geometric features, the concept of press quench using either expander or plug tooling design is analyzed by finite element models. The modeling results have clearly shown that the main sources of distortion are from the thermal stresses and phase transformation stresses. With phase transformations, the material will be in plastic deformation field due to the localized volume change of the material, which will make the gear shape change permanently even with low external load. Because of the phase transformations, the press quench can be effective with low load applied. During a press quench, the tooling interaction with the gear includes the contact region, contact timing, and contact force. The modeling results have shown that the press quench with an oversized plug is much more consistent in controlling the distortion of hardened gear, compared to using the expander design. With more consistent distortion from the quench hardening process, the initial gear configuration can be adjusted to compensate the distortion.

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Zhichao (Charlie) Li is the Vice President and one of the owners of DANTE Solutions, Inc., located in Cleveland, Ohio. Dr. Li's area of expertise is design, innovation and optimization for heat treatment processes, materials characterization, and finite element modeling. Dr. Li's responsibilities at DANTE are project management, heat treatment software development, new heat treatment process development, technical support, and new market development.

Dr. B. Lynn Ferguson, a graduate of Drexel University, is President of DANTE Solutions, Inc., formerly known as Deformation Control Technology, Inc., a company he founded in 1982. His career has focused on the broad field of mechanical metallurgy, with a concentration on thermal and mechanical processing of metals. Over the past twenty years, he has been primarily involved with analysis of the metallurgical events that take place during heat treatment of steel parts, including prediction of distortion, residual stress, and the evolution of microstructural phases. He has published more than 70 technical papers, authored many sections of various ASM handbooks, co-authored one book, and been an instructor in several sponsored short courses. He is a Fellow of ASMI, Alpha Sigma Mu and IFHTSE.

Zoller Inc.

INAUGURATES NEW NORTH AMERICAN HEADQUARTERS

Zoller Inc. inaugurated its new North American Headquarters on May 18th, 2018 in the presence of the Zoller family, esteemed architect David Gebhardt, and Paul Krutko, president and CEO of Ann Arbor SPARK. The entire North American employee base and their families and friends also attended the gala celebration event. The new facility encompasses more than 44,000 sq. ft. and houses the U.S. corporate offices including sales, service and administration. In addition the facility features an 8,800 sq. ft. Industry 4.0 Tech Center.

Zoller Inc. is a third generation family owned company that was founded in Germany in 1945 by Alfred Zoller. Alexander Zoller, president of ZOLLER Inc. was the visionary to execute the expansion plan for the new North American Headquarters.

"Our new Headquarters underscores our commitment to our customer base in North America and will ensure a superior customer service and aftersales experience for our existing and target customers"

Zoller is a market leader in presetting and measuring technology, and offers smart innovative solutions for manufacturing processes. These solutions range from design to machined part, and the entire Zoller product line, is available for training and demonstration at the new facility. Presetting and measuring machines and spare parts are stocked in the warehouse to ensure rapid delivery to customers across the U.S., Canada and Mexico once machine or service orders are placed. In addition to hardware such as presetting and measuring machines, universal measuring machines, robotic solutions, and tool cabinets, Zoller also offers relevant software solutions to prepare production companies for the smart manufacturing of the future and increase digitization with a consistent, clearly structured database.

Innovation is a part of everyday life at Zoller and the company has long recognized the opportunities computer technology afforded for the manufacturing sector. Therefore Zoller Inc. also has established an in-house software development team, whose expertise is constantly focused on the needs and requirements of their customers in North America.

(*www.zoller-usa.com*)

Siemens Award

GOES TO INDEX GROUP

With the delivery of an Index MS22-8 multi-spindle automatic lathe to Paul Bippus GmbH & Co KG in Oberndorf am Neckar, Germany, Index-Werke sold the 1000th license of its innovative "Virtual Machine" product. Siemens AG took this proud number as an opportunity to honor the Esslingen-based lathe manufacturer. On Thursday, April 26, 2018, Jürgen Köhler, division head of Digital Factory Germany, visited the Index Open House with a delegation to present the Siemens Award in the form of a glass cube with the hologram of a "Virtual Machine".

Dirk Prust, technical managing director, and Eberhard Beck, head of control technology, accepted the award on behalf of all employees involved in the Index Virtual Machine. Paul Bippus GmbH & Co KG, specializing in turned parts production and purchaser of the 1000th license, was also present at the award ceremony. Martin Melzer, head of production at Bippus, received a glass cube as well.

Index's Virtual Machine is a digital 1:1 copy of a real machine. Tried and tested for years, this proven Industry 4.0

(Left to right) Jürgen Albrecht, Dirk Prust, Eberhard Beck, Martin Melzer, and Jürgen Köhler.

product offers great potential for increasing productivity. With Virtual Machine, the user can virtually plan, test and even optimize in advance new startups and machining processes, away from production, in real time and with 100% transferability to the real machine. Possible problems can be detected at an early stage so that there is enough time to remedy them. As a result, setup times and downtime in ongoing production are reduced, while safety and cost-effectiveness increase. Index-Werke won only in December 2017 the "100 Places for Industry 4.0" award of the state of Baden-Württemberg for its "Virtual Machine" product. (*www.siemens.com*, *www.index-werke.de*)

JTEKT Toyoda Americas Corporation

ADDS PHILLIPS CORPORATION TO DISTRIBUTION NETWORK

JTEKT Toyoda Americas Corporation recently announced that Phillips Corporation was added to their distribution network. Phillips's full-service, 45-person sales force and 98-person service team will support Toyoda customers in Virginia, North Carolina, South Carolina, Georgia, Alabama, Tennessee, Arkansas, and the Florida Panhandle.

Having technical showrooms in 5 of the 8 southeastern states served, Phillips stands by their mission to be the best resource in manufacturing technology, for Toyoda CNC owners. For more than 50 years, the company has built a dedicated fleet of expert staff vested in continuous improvement of high performance results on a localized level.

In addition to carrying JTEKT Toyoda America's entire line of CNC machines (horizontal and vertical machining centers, bridge-type mills, turning centers, grinding machines and automation solutions), Phillips offers engineering and application support. JTEKT Toyoda Americas looks forward to working with the entire team at Phillips Corporation throughout their new endeavors carrying Toyoda and Takisawa Taiwan machining centers. (*www.toyoda.com*, *phillipscorp.com*)

Star SU

ANNOUNCES RICCARDO RUBINO AS OPERATIONS MANAGER

Star SU of Hoffman Estates, IL formally announces the appointment of **Riccardo Rubino** as its new operations manager for the Americas.

"Riccardo brings operations and supply chain leadership experience from positions held both in the U.S. and Italy. He will work closely with me overseeing operations starting with for the Star SU

Hoffman Estates and Star SU Federal de Mexico and taking over the quality control for those operations. I am confident in Riccardo's experience in his previous leadership role will help lead our team in continuous growth and enhance operational activities," says David Goodfellow, president of Star SU LLC.

Rubino has spent the last six years building a career surrounding operations, procurement, sales and product management with Somaschini North America (South Bend, IN) and Somaschini Automotive (Bergamo, Italy). He earned a BS and MS in Industrial and Management Engineering while studying in Italy. (*www.star-su.com*)

Kitagawa

ANNOUNCES REGIONAL SALES MANAGER

Kitagawa North-Tech, Inc., standard chucks, advanced chucks, custom engineered workholding and steady rests manufacturer, has announced **Mike Roberts** of ITEX Workholding, has joined the company as regional sales manager for the southwest region of the United States. His territory includes Arkansas, Louisiana, Oklahoma and Texas. Roberts, a seasoned veteran in oil and gas workholding chucks, will be selling and supporting Kitagawa's complete offering with a focus on oil and gas workholding.

Robert's has had a longstanding history and connection to Kitagawa Chucks starting with his first inside sales position in the machine tool and workholding industry. In 1990, Roberts started his career at Rex Supply, Machine Tool and Workholding Division as a master distributor representing Kitagawa NorthTech chucks. The Rex Workholding Division was later acquired by Regal Machine and Roberts continued in a sales capacity for the company. In 1997, he co-founded ITEX Workholding in Cypress Texas, specializing in serving the workholding needs and requirements of oil and gas tool manufacturers and services companies. ITEX was a master distributor of Kitagawa Chucks and the exclusive North American importer of Noble heavy duty brand manual chucks.

"It was an easy decision to merge ITEX Workholding operations with Kitagawa NorthTech, partially because of the long-lasting and successful relationship we've had for almost 30 years. Kitagawa also has an enduring heritage, great Chuck brand and reputation for manufacturing and engineering superior workholding for the metalworking industry and we believe they are a great fit for customers in oil and gas country," Roberts said.

Roberts resides in South Texas and will be report out of Kitagawa NorthTech's headquarters and full-service manufacturing facility for the Americas based in Schaumburg, IL. The Kitagawa NorthTech facility features in-house design, custom engineering, manufacturing and repair services for Kitagawa Workholding and other brands. (*www.kitagawa.us*)

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July 30–August 2—CAR Management Briefing Seminars Grand Traverse Resort, Traverse City, Michigan. Initiated by the University of Michigan in 1965, the first Center for Automotive Research Management Briefing Seminars (CAR MBS) hosted only 30 people. When the industry was at its highest number of employment, the event grew to attract more than 1,400 attendees annually from more than 35 states and 15 countries–representing industry, academia, media and the government. CAR MBS leads the industry in providing a context for auto industry stakeholders to discuss critical issues and emerging trends while fostering new industry relationships in daily networking sessions. Seminars include targeted sessions on manufacturing strategy, vehicle lightweighting, connected and automated vehicles, advanced powertrain, supply chain, sales forecasting, purchasing, talent and designing for technology. For more information, visit *www.cargroup.org*.

August 6–8—SAE Fundamentals of Modern Vehicle Transmissions Seminar Troy, Michigan. Starting with a look at the transmission's primary function—to couple the engine to the driveline and provide torque ratios between the two—this updated and expanded seminar covers the latest transmission systems designed to achieve the most efficient engine operation. Current designs, the components and subsystems used, their functional modes, how they operate, and the inter-relationships will be discussed. For more information, visit *www.sae.org/learn/content/99018*.

August 21–22—Fraunhofer CMI: Fundamentals of Gear and Transmission Technology Brookline, MA. In this course on gear and transmission technologies, basic properties of gears as machine elements, gear manufacturing technologies, methods for quality control, as well as testing and analysis of load carrying capacity and running behavior are presented. The course focuses on methods of interpretation, analysis and solving challenges in the design, manufacturing and application of gears. The course is meant for designers and manufacturing engineers working in gear and transmission technology, as well as for shop floor and department managers involved with the production and sale of gears and gearboxes. Fee is $1,495. For more information, visit *www.cmi.fraunhofer.org*.

September 10–15—IMTS 2018 Chicago, Illinois. More than 115,000 industrial decision-makers attend the International Manufacturing Technology Show to get ideas and find answers to their manufacturing problems. They will see new technology demonstrated in areas like aerospace, automotive, machine shop, medical and power generation. The IMTS Conference Program will focus on six topics in 2018 including Process Innovations, Alternative Manufacturing, Plant Operations, Automation, Quality and Industry 4.0/IIoT. Co-located shows include Hannover Messe USA: Integrated Automation, Motion & Drives, Surface Technology, ComVac and Industrial Supply. The Smartforce Student Summit will once again promote student and educator attendance and other familiar attractions such as AMT's Emerging Technology Center will highlight the latest manufacturing technologies. For more information, visit *www.imts.com*.

September 11–14—Basic Training for Gear Manufacturing (Fall) Hilton Oak Lawn, Chicago, Illinois. Learn the fundamentals of gear manufacturing in this hands-on course. Gain an understanding of gearing and nomenclature, principles of inspection, gear manufacturing methods, and hobbing and shaping. Utilizing manual machines, attendees will develop a deeper breadth of perspective and understanding of the process and physics of making a gear as well as the ability to apply this knowledge in working with CNC equipment commonly in use. 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, Peter Grossi and Allen Bird. For more information, visit *www.agma.org*.

September 17–20—Gear Dynamics and Gear Noise Short Course 2018 Columbus, Ohio. The Gear Dynamics and Gear Noise Short Course will be offered this year on the Ohio State campus from September 17 to 20, 2018. It has been offered for over 38 years and is considered extremely valuable for gear designers and noise specialists who encounter gear noise and transmission design problems. Attendees will learn how to design gears to minimize the major excitations of gear noise: transmission error, dynamic friction forces and shuttling forces. Fundamentals of gear noise generation and gear noise measurement will be covered along with topics on gear rattle, transmission dynamics and housing acoustics. This course includes extensive demonstrations of specialized gear analysis software in addition to the demonstrations of many Ohio State gear test rigs. A unique feature of the course is the interactive workshop session that invites attendees to discuss their specific gear and transmission noise concerns. For more information, visit *www.nvhgear.org*.

September 20–21—Fundamentals of Worm & Crossed Axis Helical Gearing Alexandria, Virginia. Provides an introduction and emphasize the differences between parallel (the experience base) axis and worm and crossed axis helical gears. Describe the basics of worm and crossed axis helical gears, their fundamental design principals, application guidelines and recommendations, lubrication requirement, a discussion of accuracy and quality and summarize with a brief review of common failure modes. The instructor is William "Mark" McVea. For more information, visit *www.agma.org*.

September 27–29—Epicyclic Gear Systems: Application, Design and Analysis Rosemont, Illinois. Learn and define the concept of epicyclic gearing including some basic history and the differences among simple planetary gear systems, compound planetary gear systems and star drive gear systems. Cover concepts on the arrangement of the individual components including the carrier, sun, planet, ring and star gears and the rigid requirements for the system to perform properly. This session provides an in-depth discussion of the methodology by which noise and vibration may be optimized for such systems and load sharing guidelines for planet load sharing. The instructor is Raymond Drago. For more information, visit *www.agma.org*.

Machine Tool Memories

Taking a Step Back Before Taking a Step Forward

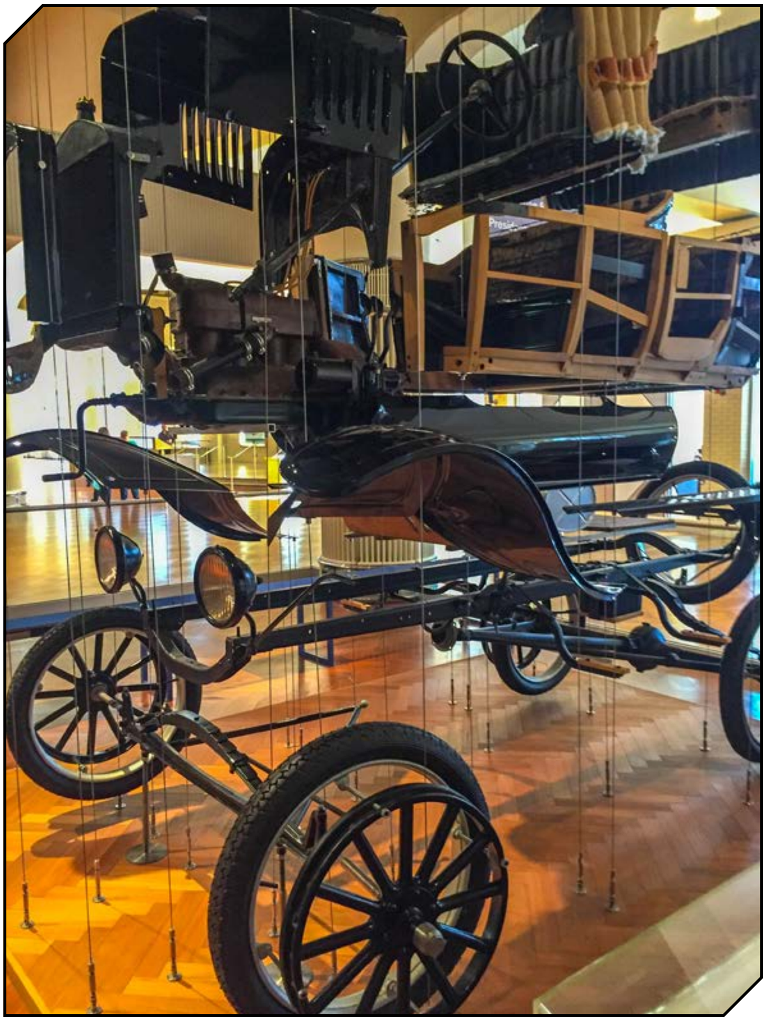
Matthew Jaster, Senior Editor

IMTS 2018 promises all the machine technology manufacturing has to offer. From 3D printing to digital manufacturing, Chicago will keep its biennial promise to wow the manufacturing industry with the latest innovations and machine developments. If your career has anything to do with manufacturing and engineering, it's essential to spend six days at McCormick Place to see these technologies up close and personal.

Before seeking out the new and the noteworthy, however, it's equally as important to jump in the time machine and see how far manufacturing has come. A recent visit to the Henry Ford Museum of American Innovation, located in Dearborn, Michigan, helped remind this editor how different the manufacturing floor looked when the Ford Model-T was first being produced in the early 1900s.

In fact, an exploded Model T in 3D on display at the museum hints at the innovation and technology that would be applied, redesigned, and reimagined in the automotive industry for years to come. Just beyond that fascinating 1922 Model T, visitors will find a room full of machine tools — everything from lathes to gear cutters to drills and planers. Here are a few highlights:

A precision gear cutter invented in the early 1890s by Duane H. Church, Waltham's superintendent of toolmakers was on display highlighting the company's tradition of automatic machinery. Church's inventions were so precise that gauges and templates were not needed to produce interchangeable parts.



An exploded Model T in 3D on display at the Henry Ford Museum of American Innovation.

The Waltham Watch Company began its operations in 1854 and, through innovation, introduced a system of interchangeable parts. The Company developed machinery that could make watch parts so precisely that they were interchangeable with one another. This innovation served to catapult productivity and place the Waltham Watch Company on the international forefront as the first company to mass produce a complete watch under one roof.

A Brown & Sharpe Co. gear cutter from around 1850 helped demonstrate just how difficult and delicate gear cutting was at the time. Getting just the right angle so the gears would mesh smoothly took both mathematical knowledge and practical experience. This machine made the work easier and the product more accurate and uniform, because of the rings of concentric holes used to "index" or measure the different angles. Brown and Sharpe — founded in 1833 — was one of the most influential machine tool builders and a leading manufacturer of micrometers and indicators.

If you're ever in Metro Detroit and have a day or two to spare, the museum and Greenfield Village are a great way to gather some historic context on engineering and manufacturing. In fact, the Armington & Sims Machine Shop in Greenfield Village is a building that essentially provides support for a system of shafts and pulleys that distribute mechanical energy to rows of metalworking machine tools arranged along the building's length. According to the website, the machinists who worked in shops like this could tackle a wide range of jobs. It was machine shops like this that were the training grounds for many technological innovators in the 19th century.

I asked my 8-year-old son what he thought of the old gear cutters, lathes and drills on display at the museum. I was given the all-too-familiar shoulder shrug from a kid that would rather be playing baseball or Nintendo than looking at machine tools. In his defense, it was lunchtime and when an 8-year-old has seen one gear cutter, he's seen them all.

"They look old and dusty," he finally shared his opinion. "I'm sure at the time they were good for something or they wouldn't be in here." (A fair and perfectly reasonable assessment)

Sources for this article include *www.walthamwatchfactory.com*, *www.thehenryford.org* and *brown-sharpe.com*.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