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THE JOURNAL OF GEAR MANUFACTURING

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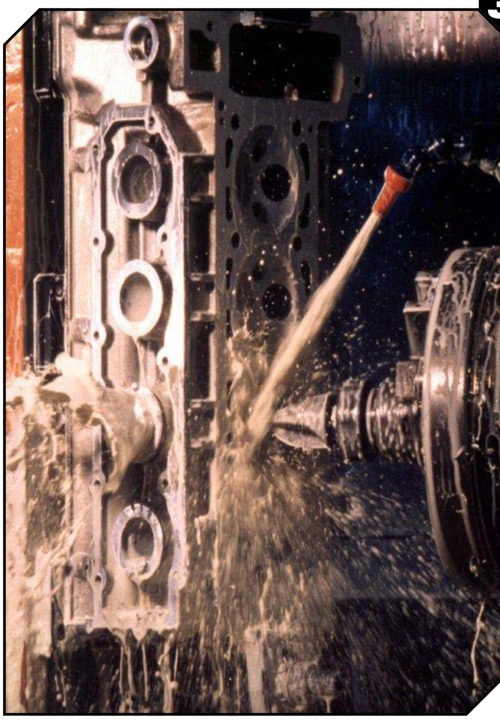

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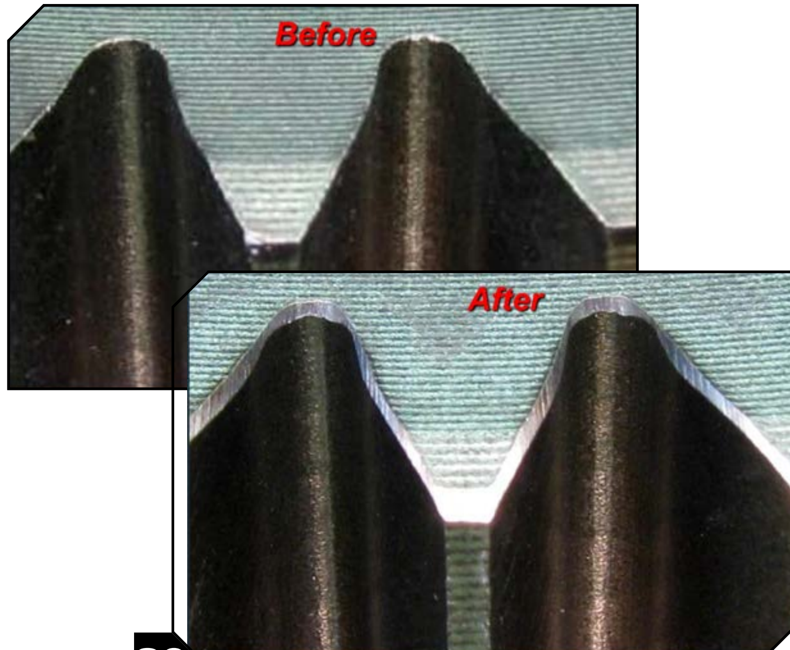

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Photo courtesy of James Engineering Corp.

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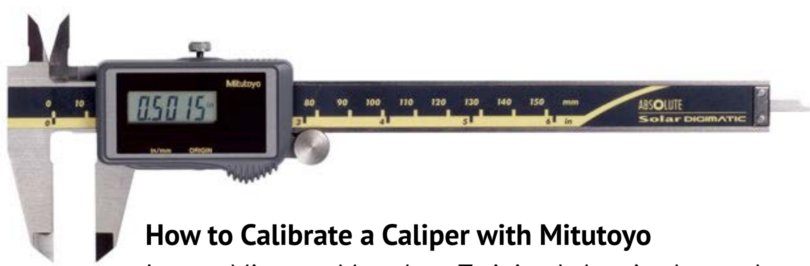
THE GEAR INDUSTRY'S INFORMATION SOURCE

www.geartechnology.com

NXT Tool Grinder

Star's latest CNC 5-axis tool grinder provides a versatile tool grinder with less moving parts and a small footprint, a large grind zone, the ability to run small and large diameter wheels, with easily configurable options, a modular design, and a competitive price point. Learn more here:

www.geartechnology.com/videos/Star-NXT-Tool-Grinder-/



How to Calibrate a Caliper with Mitutoyo

In past Mitutoyo Metrology Training Lab episodes, we have defined the concept of calibration, discussed the purpose of calibration, and introduced important aspects of what makes a good calibration method. In this episode, we will apply all those ideas to the calibration method for a caliper. Learn more here:

www.geartechnology.com/videos/Mitutoyo-Metrology-Training-Lab:-How-to-Calibrate-a-Caliper-/

Check out the latest reports from IMTS 2018 with our GT-TV Revolutions video series here:

www.geartechnology.com/tv/

Event Spotlight: JIMTOF 2018

JIMTOF 2018 in Japan includes a keynote lecture by Hideyuki Sakamoto, director, executive vice president, Nissan Motor Co., Ltd., and a wide range of lectures, seminars and talk sessions to introduce and discuss the prospects of machine tools in various sectors. Learn more here:

www.geartechnology.com/news/9116/JIMTOF_2018/

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ZE24B
Maximize Production and Profits With Mitsubishi's Fast and Accurate ZE Series Generative Grinding Machines.
When you improve productivity you reduce costs. With that in mind Mitsubishi developed its ZE Series of generative gear grinders. It's simply more efficient with automatic part loading and grinding and polishing with one setup. To learn how you can leverage all the possibilities of Mass Production, visit www.mitsubishigearcenter.com or contact sales at 248-669-6136.
ZE24B
LEGENDARY RELIABILITY
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We Hope You Enjoy(ed) the Show

Publisher & Editor-in-Chief
Michael Goldstein

IMTS 2018 was the biggest ever, no matter how you want to measure it. With 129,415 registrations, the show far surpassed the previous record of 121,764 set twenty years ago, in 1998. There were also more exhibiting companies (2,563) taking up more floor space (1,424,232 sq. ft.) than ever before.

More importantly, most of the exhibitors we talked to were extremely busy—and I don't just mean at the show, either. Sure, the level of foot traffic was good. But most of the exhibitors also told us they're extremely busy back home. They report increasing backlogs and strong demand. Manufacturers are buying manufacturing equipment, including machine tools, cutting tools, inspection equipment, and everything else.

Backing up our own anecdotal evidence, the most recent Purchasing Managers Index (PMI) also indicates continued expansion. The PMI registered 61.3% in August and 59.8% in September (any reading above 50 is considered expansionary).

There's no doubt that manufacturing is still going strong in America.

We saw a lot of innovation at the show, too. Aside from the focus on Industry 4.0, which we saw in nearly every booth, most of the suppliers serving our industry were showing new gear manufacturing technology, with quite a few new machines making their worldwide debuts at IMTS.

Don't worry if you didn't make it to the show, though. Our editors spent the whole week learning as much as we could, and we're going to be bringing that information to you over the next several months. For example, you can read about some of the new technologies in our Product News section, beginning on page 10, as well as online at *www.geartechnology.com*.

But we're also working hard to bring that information to you in as many ways as possible. That's why we're pleased to announce the launch of *Revolutions*, the new video series that focuses on the technology of the gear industry, as well as relevant and interesting topics related to the day-to-day activities of the gear industry. *Revolutions* represents both the cutting edge changes in technology that can help you increase productivity and improve quality, as well as other information that will help you stay competitive in the gear industry.

We recorded 20 segments of *Revolutions* while we were at IMTS, and each segment features a one-on-one interview conducted by one of our editors with a leading expert from the gear industry. Each episode lasts about 5–10 minutes, and it includes insights you can't get anywhere else on topics like gear skiving, inspection, grinding, automation, chamfering, honing and much more. We even sat down with the leaders of the AGMA to find out about some of the new and exciting things going on with the association.

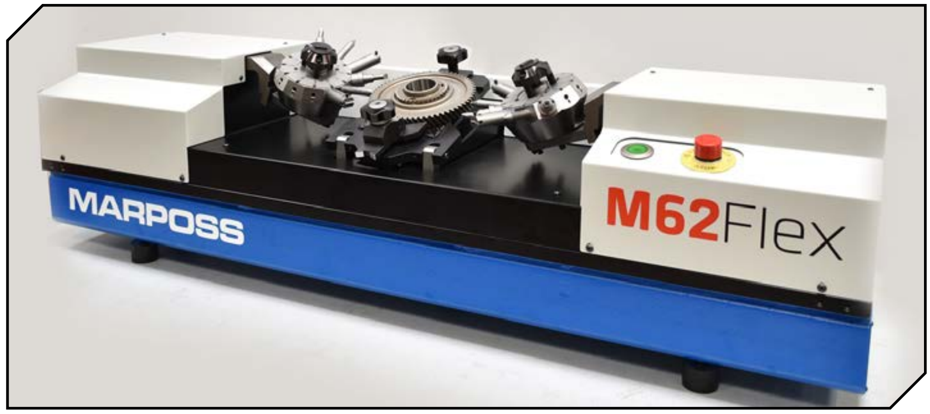
Over the next several months, we'll be highlighting various episodes of *Revolutions* as they apply to the different subjects we cover. We'll try to let you know if there's a video related to whatever we're talking about. We'll also be featuring episodes in the *Gear Technology* newsletter over the coming months. By the way, if you're not currently receiving our bimonthly newsletter, you're definitely missing out, because we're continually putting new content online, and the newsletter is the best way to learn about it (subscribe at *www.geartechnology.com/subscribe.htm — it's FREE*).

Of course, you don't have to wait for us to trickle-feed you all the episodes of *Revolutions*. If you just want to binge-watch the whole series, you can head on over to *Gear Technology TV* (*www.geartechnology.com/tv/)* and see them all there. I encourage you to do so, because, in addition to *Revolutions*, you'll also find our previously recorded video interviews there, as well as two seasons of *Ask the Expert LIVE!* recorded at Gear Expo 2015 and Gear Expo 2017. Tune in for insight about what leading suppliers are working on now, and what you can expect in the near future.

If you were lucky enough to make it to IMTS 2018, we hope you enjoyed the show. But whether you did or not, we hope you'll tune in to *Revolutions*, and we hope you enjoy *our* show.

Marposs

M62 FLEX GAUGE INSPECTS WIDE RANGE OF GEARS



The Marposs M62 Flex manual bench gauge system was created for the production environment, this gauge provides the flexibility to measure gears with different diameters without mechanical retooling. Utilizing a universal reference "Vee" on a 30-degree angle eliminates the need of using an ID centering post (or nosepiece) to locate each part for measuring, and it reduces set-up time.

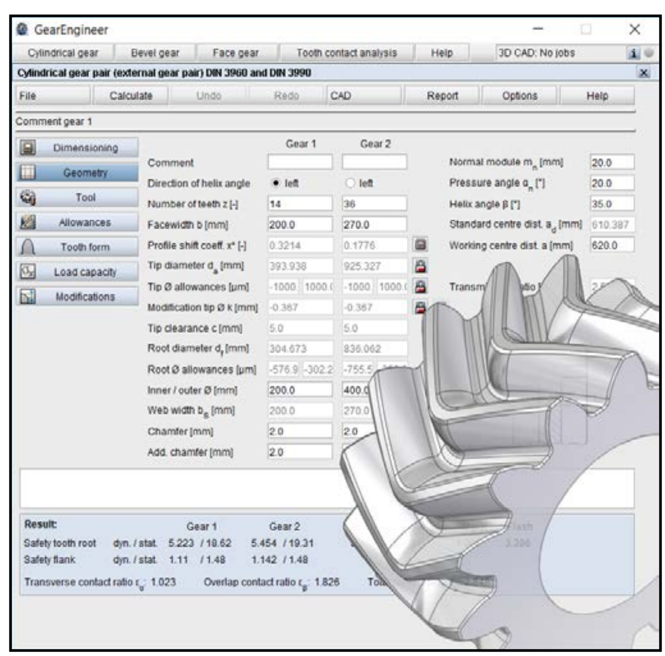
The gauge employs servo-driven actuators and is the first smart gauge that integrates "soft-touch" technology when engaging with the gear being measured. Soft-touch technology addresses the age-old issue where green parts and master parts could be damaged by the measuring contacts. The M62 soft-touch technology employs a software routine where the measuring group is able to approach a gear surface in velocity mode, with a controlled low force, while the position error is monitored, resulting in better control of the process and avoiding damage.

The M62 Flex can inspect odd or even toothed helical and spur gears with external diameters from 30 ÷ 180 mm, heights ranging from 15 ÷ 40 mm and modules from 1 to 4. It has mechanical turrets with capacity to locate up to 12 contacts each and is suited for inspecting DOB (MdK), major diameter and minor diameter.

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

GWJ Technology

RELEASES LATEST VERSION OF *GEARENGINEER* SOFTWARE



GearEngineer is a software program designed for calculating the real 3D tooth form in addition to the dimensioning and load capacity of cylindrical and bevel gears. *GearEngineer* calculates the gear tooth form based on a mathematical simulation of the manufacturing process analogous to traditional manufacturing on gear cutting machines. This geometry provides the basis to manufacture cylindrical and bevel gears in conjunction with multi-axis machining centers. The new version was introduced for the first time at AMB 2018 to a wide audience and comes with a number of new functions. All calculation modules now include two unit systems: the metric system and the U.S. customary unit system. The user can quickly switch between the units. Gear qualities according to ISO 1328 and ANSI/AGMA 2015 for cylindrical gears are now integrated. In addition to the load capacity calculation in

accordance with DIN 3990 and ISO 6336 Method B, the ANSI/AGMA 2101 standard was also added.

The user can work with a tip radius instead of the addendum chamfer for cylindrical gears. The definition of basic rack profiles for external cylindrical gear pairs was supplemented by the semi topping flank and topping. Using the definition of the semi topping flank, the corresponding hobs can then be specified, and they generate an addendum chamfer or tip relief during the gear hobbing process.

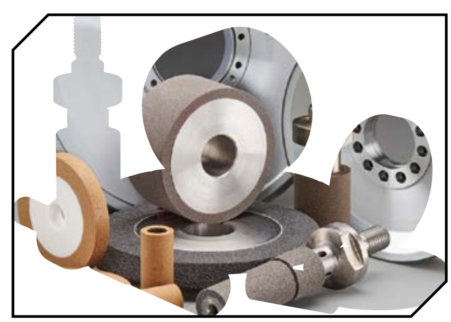
The calculation of the 3D gear tooth form of true herringbone gears is the highlight of the new *GearEngineer* version. True herringbone gears are two connected helical gears but they do not have a gap separating the two helical faces. There is a rounded connection between the two halves. The tooth geometry including the rounding process of herringbone gears is very complex but can be calculated and generated by using *GearEngineer*. The complete flank and root geometry can now be created automatically for the manufacturing of herringbone gears and used for further CAM programming. This opens completely new perspectives for the manufacturing of herringbone gears on multi-axis machine centers instead of using obsolete Sykes machines. Whereas, previously soft machining was usual, today it is possible to use the hard machining process for manufacturing herringbone gears.

For more information:
GWJ Technology
Phone: +49 (0) 531 1293990
www.gwj.de

Norton|Saint-Gobain

INCREASES GRINDING PRODUCTIVITY WITH CBN WHEELS

Saint-Gobain Abrasives has announced the introduction of its new Norton Winter Vitron7 cBN Grinding Wheels. The wheels feature a high-precision vitrified bond specifically designed for the high performance external grinding of cam and crankshafts and internal grinding applications in automotive and bearing industries.



"Our Vitron7 wheels provide an ideal solution for the increasing demands of grinding in these applications where high surface quality, reduced cycle times and manufacturing costs are critical," said Bill Lane, senior product manager, Norton|Saint-Gobain.

Norton Winter Vitron7 wheels feature premium cBN grain particles uniformly dispersed throughout the bond matrix for maximum grinding efficiency. This enables manufacturers to achieve substantial increases in the number of finished parts between dress cycles,

significantly reducing cycle times and extending wheel life up to 40 percent over existing products. Vitron7 wheels also grind cooler due to a lower specific grinding energy (SGE) that ensures minimal residual stress, for superior part quality with surface roughness degradation reductions of up to 30 percent. When ID grinding, lower power results in less defection and minimizes taper while maximizing part straightness.

For more information:
Norton | Saint-Gobain
Phone: (508) 795-5921
www.nortonabrasives.com

Mitutoyo America

INTRODUCES U-WAVE FIT TO DATA MANAGEMENT SYSTEMS PRODUCT LINE

Mitutoyo America Corporation is pleased to announce the release of U-Wave fit to its data management systems product line.

The U-Wave fit is a new, compact attachment for Mitutoyo calipers and micrometers that transmits measurements wirelessly to a PC using the digimatic protocol. The elimination of long, cumbersome data cables help improve measurement efficiency and speed while maintaining precise accuracy. The unit's user-friendly interface allows data to be loaded into any software product that accepts keyboard input.

Named for its comfortable, ergonomic design, the U-Wave fit quickly and easily installs for over 1,600 different Mitutoyo calipers and micrometers. The unit's design allows the operator to handle and use the tool with comfort and confidence without sacrificing accuracy.

The U-Wave fit is available in models including IP67 and buzzer types for 4", 6", 8" and 12" IP67 calipers, standard calipers and coolant-proof (IP65) micrometers. During standard operation, the U-Wave fit has a wireless range of 20 m (60 ft.) and its 220 mAH battery lasts for over 400,000 transmissions. The Digimatic2 communication format is high resolution and sends polarity and the unit of measure.

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

C & B Machinery

EXPANDS CBV SERIES CLAMP BORE GRINDERS

C & B Machinery's lineup of vertical clamp bore microfinishing grinders has been expanded yet again. The company continues to strive to meet customers' ever-growing needs for flexibility, throughput volumes, integration with plant automation and maximizing perishable tooling life.

The single spindle models can be an economical choice for lower volumes and lower tooling cost. The double spindle models work well for applications where different work holding at each station has advantages and volumes are a bit higher. To the other extreme, C & B's rotary index models can offer the tooling flexibility and the very highest level of throughput.

C & B now offer a higher speed grinding spindle option to maximize efficiency for customers using CBN grinding wheels vs. conventional free cutting, self-dressing vitrified wheels.

The CBV Series offers multiple part handling options including operator hand load/unload, robotics integration (Fanuc Authorized Integrator), gantry load/unload with part flipping capabilities, and in-process gauging with load pre-check for stock and runout. The gauge fixture is designed for quick adjustments with no tools required. Software is designed for control of stock removal on each side and part orientation entering or exiting the cell. Error proofing for part load and part type can also be designed into this system.

For more information:
C & B Machinery
Phone: (248) 264-9800
www.cbmachinery.com

DMG MORI

INTRODUCES NEW HORIZONTAL MACHINING CENTERS TO NORTH AMERICAN MARKET

With a production capacity of up to 1,200 machines per year, the DMG MORI Davis, California location manufactures and assembles vertical machining centers such as the CMX 1100 V and horizontal machining centers such as the NHX 4000 3rd Generation and NHX 6300 2nd generation.

At IMTS this year, DMG MORI presented the NHX 4000 3rd Generation machining center with a 21 RPP rotary pallet pool feature. It includes a spindle speed of 20,000 rpm, a power rating of 50 hp and a maximum torque of 163 ft. lbs. Added to this is a 36-month warranty that DMG MORI provides for all its own MASTER spindles – with no runtime limitation. Standard auto coupler hydraulic fixture interface enables the NHX 4000 3rd Generation to automate in a more efficient manner. This horizontal machining center handles workpieces up to 882 lbs. and is ideally equipped for ensuring flexible and economic production thanks to its extensive range of machine and automation options.

The NHX 6300 2nd Generation is equipped with a standard 12,000 rpm, 75 hp powerMASTER spindle with maximum torque of 595 ft lbs. An optional high-speed version from the powerMASTER spindle range has a maximum speed of 16,000 rpm and up to 1,042 ft lbs of torque for demanding heavy-duty machining. The NHX 6300 2nd Generation offers space for pallets up to 25 × 25 inches, a workpiece height of 51 inches, and maximum loading capacity of 3307 lbs. By using a FANUC control, DMG MORI has managed to considerably reduce the throughput times of this horizontal milling machine.

For more information:
DMG MORI USA
Phone: (847) 593-5400
www.dmgmori.com

Nixon Gear

ADDS GRINDING MACHINES TO INCREASE QUALITY AND PRODUCTIVITY

Two new grinding machines were recently added to production at Gear Motions' Nixon Gear Division in Syracuse, NY.

The Studer S121 is a 2-spindle universal cylindrical grinder capable of grinding IDs and faces. It was purchased to accommodate a program for a new customer with Nixon Gear. The machine adds new capabilities to grind small diameters with its 60,000 rpm spindle, while still being able to handle larger gears with its 10" chuck and 36,000 rpm spindle. It also vastly improves productivity by offloading work from older, mechanical Heald bore grinders. The S121 is also capable of grinding bores and faces in one setup, saving even more valuable production time.

LK Metrology

DISPLAYS CMM TECHNOLOGIES AT IMTS 2018

LK Metrology, Inc. featured their Altera "S" multi-purpose compact CMM, their Altera "M" high-speed production-type CMM with probe and laser scanning, including applications of Renishaw PH20 and REVO2 probes during IMTS 2018. All the LK Metrology CMMs will be fitted with CAMIO8 multi-sensor CMM software and Renishaw Modus Software. In addition, a CMM robotic cell with an Altera "S" equipped with a Nikon L100 laser scanner.

The Altera "S" is LK's multi-purpose CMM with the most advanced capabilities in the compact CMM class. The machine is multi-sensor ready, allowing the user to expand the capability of the CMM as requirements change without the need for expensive controller upgrades.

The Altera "M" range of performance CMMs delivers exceptional throughput and enhanced precision for production applications. Exclusively designed for high-speed tactile probe scanning and laser scanner applications, the Altera 'M" is the preferred choice for automotive

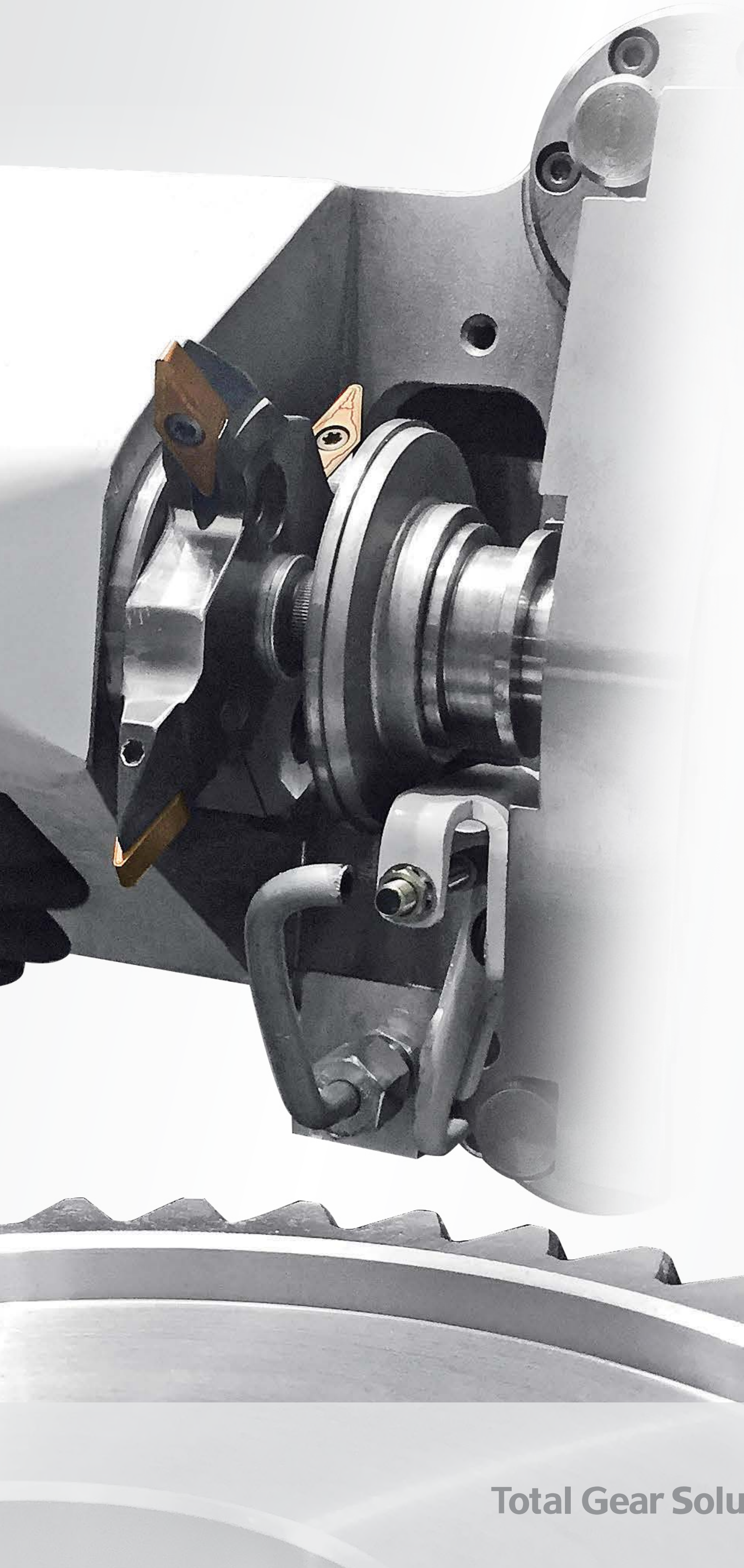
The Toyoda GL4Ai-50 OD Grinder is another new addition to Nixon's fleet of gear manufacturing equipment. It has a Ø12.6" swing and 19.6" distance between centers. Nixon already uses a model GL4A in production, and the purchase of this newer model adds even more shaft grinding capacity. The GL4Ai-50 includes two part auto-sizer gauges, which is an increase over the older GL4A's single gauge. The 2nd auto-sizer gauge saves time and increases productivity as two different tight tolerance diameters can now be ground in the same setup.

For more information:
Gear Motions
Phone: (315) 488-0100
gearmotions.com

and aerospace and other manufacturers of performance critical components.

Proven in the most challenging application environments, LK's new CAMIO 8.5 version software continues to be the CMM software choice for many of the world's largest manufacturers. By leveraging the productivity benefits of CAMIO 8.5, manufacturers can focus on accelerating lead times and improving product quality while reducing costs. CAMIO's interoperability across CMM platforms, sensor technology and manufacturing sites, is a unique advantage which guarantees the longevity of investment in software and inspection programs.

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



Get the Winning Edge

New 400HCD Hobbing Machine performs hobbing and chamfering/ deburring in parallel on workpieces as large as 400 mm in diameter. Gleason Contour Milling uses standard indexable carbide inserts to make chamfering highly flexible, economical and accurate – giving you the winning edge.

www.gleason.com/win

Total Gear Solutions Gleason

Chamfering/Deburring Still a Player — Now More than Ever

Jack McGuinn, Senior Editor

Chamfering and deburring have been described as "unloved," a "necessary evil" and, in fact — "dead." After all, *manual* deburring is still common in many shops. Meanwhile, this is one of *three* articles in this issue of *Gear Technology* dedicated to chamfering and deburring. Invoking Mark Twain, it is fair to say that any thought of its demise is not only premature, but misinformed. Indeed, chamfering and deburring are vital steps in making gears for aerospace, automotive, medical devices and robotics, to cite just a handful. And while smaller module gears are still a sweet spot, larger gears are now being improved by the chamfer-deburr process. Chamfering-deburring is indeed a "necessary evil" in that it can add additional cost and time to the final part. But it also adds something that in today's manufacturing trumps pricing — *quality*. That quality is why chamfered-and-deburred gears are typically required by many industries.

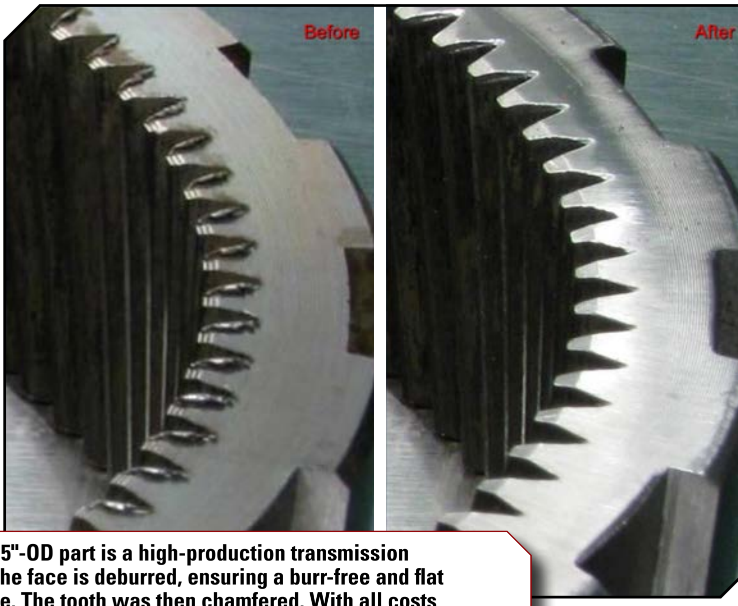
When speaking of technology, it is useful to understand just where chamfering-deburring has upgraded over recent years. What constitutes state-of-the-art chamfering-deburring? And what, for example, are the cutting-edge applications that require gear chamfering/deburring? Chamfering-deburring is not cookie-cutter; it depends on the manufacturer. Some do both, some do one.

"Since 1980, Abtex has focused on one business, brush deburring," says Jason Saner, Abtex Corp. president. "For Abtex customers in three major industries — automotive, aerospace, and medical-device — "state-of-the-art" has become the new normal. Technology is advancing so rapidly that our customers are under continual demands from *their* customers to use technology to improve quality and reduce cost. Our primary mission is to support them by designing deburring systems and brushes specifically for their ("exacting") needs. Recently, a manufacturer wanted a machine that could deburr three gear forms that were roughly similar in geometry. Today's customer doesn't want any specific machine that isn't flexible to the changing demands and uncertain horizon of customer demand."

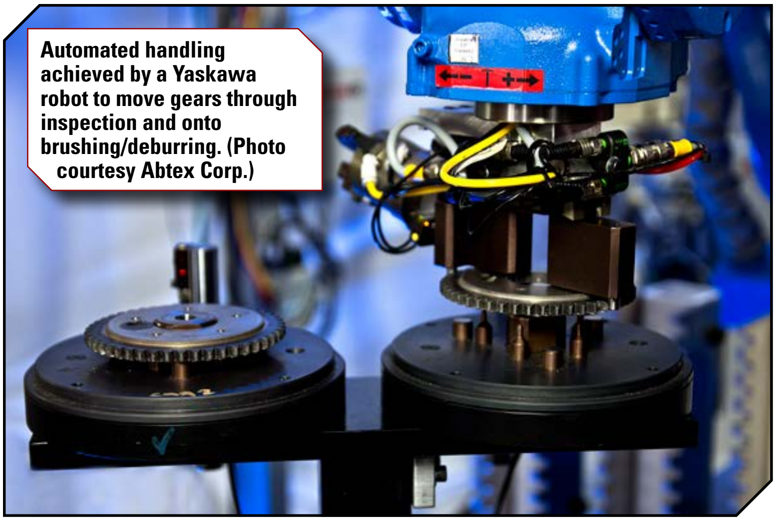
At James Engineering Corp. James Richards, president, enthuses over their "patented top-to-bottom MAX system. (This) is a real revolution in chamfering and deburring. The economic benefits, quality of work with zero recall for existing programs, offers customers real financial savings that show up in increased production numbers at reduced operating cost." He adds that, "Aerospace spells out the size and specific specifications of chamfer/deburring more than any other application."

And at Cleveland Deburring Machine Company (CDMC), co-owner Adam M. Mutschler says that "I would suspect that (state-of-the-art) is different for each manufacturer. For CDMC, we have been utilizing robot systems more and more frequently for a variety of reasons. The robot controls allow us to program 'recipes' for each different part type/size/style/etc. Since the biggest challenge with chamfering and deburring is often setup and consistency, this is a great solution for companies that have moderate-to-frequent part changeovers. Another new development is our single-flank chamfering feature. This combines a servo workpiece spindle and a tooth-detection sensor (that) allows us to chamfer only the areas of the teeth that are necessary. There are several benefits to this feature, and it's very straightforward to set up and to use."

Ken Bagdasarian, United Surface Solutions LLC president, points out that, "To date, most manufacturers deburr parts manually, which requires a skilled operator with years of experience. Unfortunately, even that is not enough to consistently produce parts that meet specifications. The problem with manual deburring is that the operator cannot control the amount of material removed and the angle of removal like machines can. These issues are eliminated when using a centrifugal barrel finishing (CBF) systems like ours. Once a process has been developed and part dimensions are set, the units will yield 99% consistency. The CBFs generate upwards of 30Gs, which reduces the deburring and chamfering process down to minutes. The edges are radiused to precise dimensions without inconsistencies. The other advantage to the CBF method is the surface finish; not only does it deburr and chamfer, it refines and polishes the surface as though the parts were plated. The biggest advantage to this method is that the cost of processing them is a



This 5.5"-OD part is a high-production transmission part. The face is deburred, ensuring a burr-free and flat surface. The tooth was then chamfered. With all costs considered, including the equipment cost, cost-per-part was approximately .02 cents. (Photo courtesy James Engineering.)



Automated handling achieved by a Yaskawa robot to move gears through inspection and onto brushing/deburring. (Photo courtesy Abtex Corp.)

fraction of the cost when manually deburring."

Revisiting where chamfering-deburring is most prevalent, at least for James Engineering it's aerospace." But at Abtex, says Saner, "The vast majority of brushes and systems that we have developed and built in the last five years are all for the automotive industry. We have experienced an increase in demand as a result of the more precise edge finish requirements being driven by the end customers." CDMC's Mutschler makes claim to "customers in a large variety of fields. Some of these include automotive, heavy equipment and fluid power, as well as several industrial manufacturing companies that produce things such as gear motors, sprockets, aerospace assemblies, etc.

Why, for example, is chamfering-deburring so important in the making of certain automotive-related gears?

"Transmissions in the automotive and off-road industries are becoming ever more efficient and smaller in size," Richards explains. "As that happens, they need to become more like their aerospace counterparts. This means that we have been seeing the automotive industries, generally speaking, adopt chamfer, deburring, and finish requirements that are much like (with aerospace). This is allowing the components to be stronger, quieter, faster, and more efficient, while reducing failures from things like hanging burrs that fall off (into a transmission, for example) through operation." Abtex's Saner says that "With rapidly changing competition, constant technological changes, increased safety considerations, and evolving regulatory requirements, it's become very clear that deburring plays a more important role than ever in helping manufacturers maintain rigorous quality and safety standards. Many of our customers' parts go into transmissions and steering and braking systems in cars and trucks as well as off-road equipment, so the need for precise deburring is pretty much universal."

At CDMC, Mutschler says they approach chamfering-deburring "as two completely different processes. Deburring is most commonly a functionality issue, where a burr being present could cause issues with assembly, mating surfaces, meshing issues, etc. There is also a safety concern for both handling as well as once the gear is put into the field. In most cases, a loose burr being introduced into a working assembly can cause catastrophic failure. Chamfering (when not used specifically for deburring) is beneficial to eliminate and reduce stress points for many applications. A sharp corner will fail before a chamfered corner will fail. Chamfering can also simplify the assembly process in certain applications or allow for smoother operation of an assembly by providing necessary clearance." United Surface Solutions' Bagdasarian adds that "All manufactured and machined parts require some sort of deburring. With the addition of surface refinement, the friction on parts is reduced, allowing for smoother operation, increased load capabilities, and increased life cycle.

United's centrifugal barrel finishing (CBF) systems will yield 99% consistency once a process has been developed and part dimensions are set. The CBFs generate upwards of 30Gs, which reduces the deburring and chamfering process down to minutes. The edges are radiused to precise dimensions without inconsistencies (Photo courtesy United Surface Technologies).

We asked our contributors what they thought about chamfering/deburring being sometimes considered an afterthought? At Abtex, they turn that around and make lemons into lemonade. "For years, Abtex CEO Mark Fultz has (like perhaps his customers) called deburring a 'necessary evil' that's becoming more necessary all the time," says Saner. James' Richards points out that, "In the past it was an afterthought, but now it is engineered into the part. What is still often an afterthought is other areas of parts like snap ring grooves that have sharp edges that need deburring or edge breaking to allow assembly, and were not seen or anticipated prior to manufacturing."

"Absolutely (it's an afterthought), but it's getting better all the time," says Mutschler. "Manufacturers are starting to realize the need for deburring at the beginning of the project as opposed to making it an afterthought. Due to the number of variables involved, a burr can sometimes be hard to predict and even harder to quantify or define." "Most manufacturers are conscious of the need to chamfer and deburr, says Bagdasarian. "However, they are not aware that such high standards can be reached by CBFs, (which) causes them to avoid taking on certain manufacturing jobs and leaves a void in the industry."

Meanwhile, given robotics' increasing prevalence in manufacturing, chamfering-deburring has made strides to keep up in one area or another. "Chamfering and deburring is about positioning the tools in a specific 3-dimensional envelope in relation to the part being chamfered and deburred, which is what robots do very well," says James' Richards. "The correct question (regarding robotics) is what differentiates a robot from a MAX? Robots have great strengths, but showing what they are great at and why our machines' address a void in the market is a standalone article by itself." Abtex's Saner flips the question: "I'm not sure about deburring's role in robotics, but robotics' role in deburring is becoming more common all the time as manufacturers seek greater efficiency. When we bought Nihmble (a robotics company) in 2015, it was with the idea that automation would play a greater role in deburring, and that prediction has definitely come true. Our customers are now looking to automate deburring operations just as they do other manufacturing operations, and we've been able to develop robotic handling systems that help — especially by turning parts that have multiple surfaces to be deburred."

Is there an effective alternative to chamfering-deburring? If so, what?

Richards states that "Every alternative to grinding chamfers and brushing edges, to date, have had their own issues that manifest into cost-restraints-per-part, or absolutely huge initial cost, and have not become effective alternatives." Bagdasarian believes that "Robotics may be an alternative to manual deburring; however, even robots have limitations. The tools used by robots cannot reach into tight areas with small recessed sections. CBFs can utilize abrasives as small as 1,000 grit, which can effectively deburr the smallest recesses." CDMC's Mutschler's take: "I do not believe so — at least not yet. There are many steps taken in today's manufacturing world to reduce or eliminate burrs, or to ensure that if a burr is present that it will not cause a functionality issue (e.g., burr traps in powder metal components). While these are effective at reducing and eliminating *some* burrs *some* of the time, if material is being removed or changed in manufacturing there will be a burr present at some level."

Not yet mentioned in this discussion — powder metal (PM) and plastic gears. Is chamfering-deburring a player? If so, how big?

"Huge," Richards flatly states. "Plastic and powder metal parts have one thing in common — they both have multi-part dies. The interaction of these moving parts, which opens the die letting the part out then reclosing and either pressing or allowing high pressure plastic to be forced into the die, causes the edges of the die parts to, over time, regress and allows material to form "flash" on the edges of the part. This process needs to be dealt with in a deburring or chamfering process. Traditionally this has been addressed by mass finishing processes. But when it comes to PM gears the mass finishing degrades the operation tooth face to the point that many PM gear manufacturers are looking for alternate methods, hence traditional gear chamfering and deburring."

"PM is a huge part of our business and one of our primary focuses," affirms Abtex's Saner. "PM companies continue to push the envelope in geometry and form and we work hand-in-hand with some of the best in the world to develop an appropriate deburring solution."

Also of interest, how if at all, has the arrival in recent years of especially high-grade steels and other metals affected the chamfer-deburr process? On one hand, Richards says, "Generally, not at all. We have seen the toughest of materials in the aerospace industry forever."

But at CDMC, "The cost associated with scrapping a part that is made from these materials is much more significant. (On the other hand), these materials are also very well-suited to ceramic abrasive grain, which has become extremely popular in abrasive brushes over the last few years. The ceramic is slowly taking the place of silicon carbide abrasive grain, as it has a higher cut rate and material removal rate. This is especially true when the material is an exotic alloy or a very hard material."

"In recent years," says United Surface Solutions' Bagdasarian, "more exotic materials have been introduced in the industry. These materials are harder, creating a huge issue for the industry. Standard deburring methods no longer work on these materials as they destroy deburring tools. CBFs are un-phased by these materials; on the contrary, they seem to work even better on such materials."

And what of ISO and AGMA standards. What or how big a role do they play regarding specifications?

Not tipping his cards, Richards says, "I won't select any organization specifically, but specifications over the years, and what can actually be done, have traditionally had a disconnect. I have had countless conversations with aerospace engineers in particular who have acknowledged the specification on the drawings was not technically possible to perform by technologies at the time. We would joke that the specification-writing engineers needed to actually talk with the engineers that are trying to create machines to perform their specification requirements. The MAX is the first and only machine I know of that can perform the more elaborate aerospace requirements fully in one cycle. This process will be debuted later this year. Sayner's simple take on it is that, "We are held to the edge callout on the print. It is different for everyone."

CDMC's Mutschler says "Absolutely," to the ISO/AGMA relevance. "Several years ago, we saw many applications for deburring gears that had been shaved. While many gears are still being made this way today, we have seen many gears that are now being ground. This both changes the requirement and increases the need for deburring. Since the grinding process is typically done after heat treatment, a burr could cause excessive wear on the grinding wheels (very expensive). We have also seen a more defined and precise requirement for the size and angle of the chamfer to be applied."

So where does this leave things? Is there a long-range future for chamfering and deburring?

Richards, James Engineering: "As automotive and trucking remove weight from drivetrains to improve efficiencies requiring smaller, higher-strength gearing, chamfering, deburring, and *surface finishing* will become mandatory in these industries — just like aerospace. With aerospace adding gear reductions, as Pratt & Whitney has for the large primary fans, that has had a significant energy savings so far. Soon, all will follow — which means a lot more aerospace gears needing processing. Electric car companies — especially Formula E — are only now realizing gear transmissions improve the efficiencies of their product. So hold on… more gears coming."

Saner, Abtex: "As manufacturers become more creative in machine and part design, it's incumbent on us to develop even more innovative solutions that will allow our customers to move quickly, efficiently, and economically. We have a unique advantage in being able to design our deburring systems in direct partnership with customers' engineers. As soon as they know what they need from us, we jump in to design the solution that will best meet — and often surpass — their needs. We need to excel by continuing to innovate even more effective brush designs and even more efficient parts-handling technologies. Fortunately, we're playing to our strength in both of those areas."

Mutschler, CDMC: "I think that there are new things being developed all the time. The future will likely continue heading toward more automation, less operator involvement and higher production rates. This has always been the case, and things have continued to evolve accordingly. Every day there is a new program launched for production, and there is an older program that is phased out of production. As we watch these changes occur, it's important to note the different technology being used in gear manufacturing in today's world. The future of gear deburring and chamfering will be directly dictated by the future technology used in gear manufacturing. After all, we are in the business of removing what this equipment creates. I once heard a customer say the following: 'Just like any other process that this part goes through, unless the part is properly deburred, it's still a scrap part.' This gives me hope that the last step in manufacturing is beginning to get the respect that it deserves."

Bagdasarian, United Surface Solutions: "(We have) been on the forefront of innovation for decades. We are constantly challenged to develop processes to reduce costs and increase throughput. United has been designing and engineering the most advanced and automated systems available anywhere. All of United's machines are proudly designed and manufactured in the USA."

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The Evolution of Gear Chamfering

The latest technological solutions help keep chamfering and deburring operations in-line—often without increasing cycle times

Gottfried Klein, Gleason Corp.

Many gear manufacturers recognize that premature transmission failure, less-than-optimal efficiency, or unacceptable noise can result from application of transmission gears operating with anything less than a flawless tooth flank. For these manufacturers, generating a chamfer to precise customer specification for size, shape and angle is of critical importance in order to minimize the potential for sharp, brittle edges after heat treat, as well as to avoid material plus conditions in the tooth flank prior to the hard finishing operations.

Chamfering and deburring are particularly critical in advance of hard gear finishing processes. This is especially true of honing, where excessive stock and hardened burrs can greatly diminish honing tool life and, as a result, significantly increase cost per piece. These conditions can occur as well when the finishing process is threaded wheel grinding.

Chamfer size and angle according to customers' specification.

An additional benefit of chamfering and deburring is to help reduce the health and safety risks that can result from operators handling parts with sharp burrs.

Gleason offers manufacturers several highly desirable chamfering and deburring solutions that are just as easy to apply as the primary soft and hard processes. With the latest series of Gleason hobbing and chamfering machines, users now can apply the optimum chamfering technology for their particular application using forming or cutting technologies — up to and including truck-size gears.

Chamfer rolling on vertical 210HiC for burr free flank with a sequential hob-chamfer-hob process.

Chamfer Rolling

Chamfer rolling is ideal for planetary pinion applications requiring particularly fast cycle times (10 seconds or less chip-to-chip) or for gears on shafts with little or no clearance below the root diameter. In wet machining operations, this process delivers the lowest possible tool cost per workpiece. Chamfer rolling is a forming process applied mostly for smaller gears up to module 5 mm, which creates chamfers along the tooth edge by pressing material. The pressed material forms a burr on the face side of the gear and a smaller one on the tooth flank. While the gear face burr is removed by single blades, deburring discs or file discs, the flank burr requires special chamfer rolling tools with burnishing functionality or removal by an additional hob cut downstream in

Gleason's 100HiC horizontal hobbing machine with integrated chamfering and robot loading cell.

advance of a subsequent hard finishing operation. Chamfer rolling today can be integrated into shaving, power skiving and hobbing machines and performed either in parallel or sequential to the main gear process. Where shortest cycle times are required, chamfer rolling is integrated parallel to the hobbing process on machines such as the horizontal Gleason P90CD Hobbing and Chamfering Machine or the ZSE150 Shaving Machine. When a second hob cut is necessary to remove the flank burr, a horizontal 100HiC or vertical Genesis 210HiC is available. The latest tool design developments increase chamfer rolling tool life significantly, especially with dry operation.

As alternatives to chamfer rolling, several new cutting chamfer technologies are of increasing market interest. Applications can range from the high volume production found in the automotive industry to job shop gear manufacturers with small batches but a large variety of gears. Gleason's two new chamfer cutting technologies respond to this wide range of needs: highly flexible Chamfer Contour Milling for smaller batches of medium size gears and Chamfer Hobbing for higher volume, shorter cycle time production.

Chamfer Hobbing for Lower Cost Per Workpiece

While chamfering with hobs has been known for decades, Chamfer Hobbing takes the process to a completely new level. Chamfering is performed using a Gleason Chamfer Hob, with diameters similar to a gear hob, made with the latest high-speed steel materials like G30 or G50 and featuring AlCroNite Pro coating for exceptional tool life in dry cutting conditions. Gleason Chamfer Hobbing employs one Chamfer Hob for each tooth flank, with a tooth profile which is specifically designed for the particular chamfer form to be realized.

This design delivers greater flexibility: comma or parallel-chamfer forms are possible as well as chamfers along the tooth edge only, or including the root area. Similar chamfer angles like those commonly produced in the chamfer rolling process are also easily achievable.

In the Chamfer Hob design process, Gleason technology software is used to simulate the required chamfer and identify and avoid all potential collisions of the tools with the counter flank and with interfering contours above and below the actual gearing.

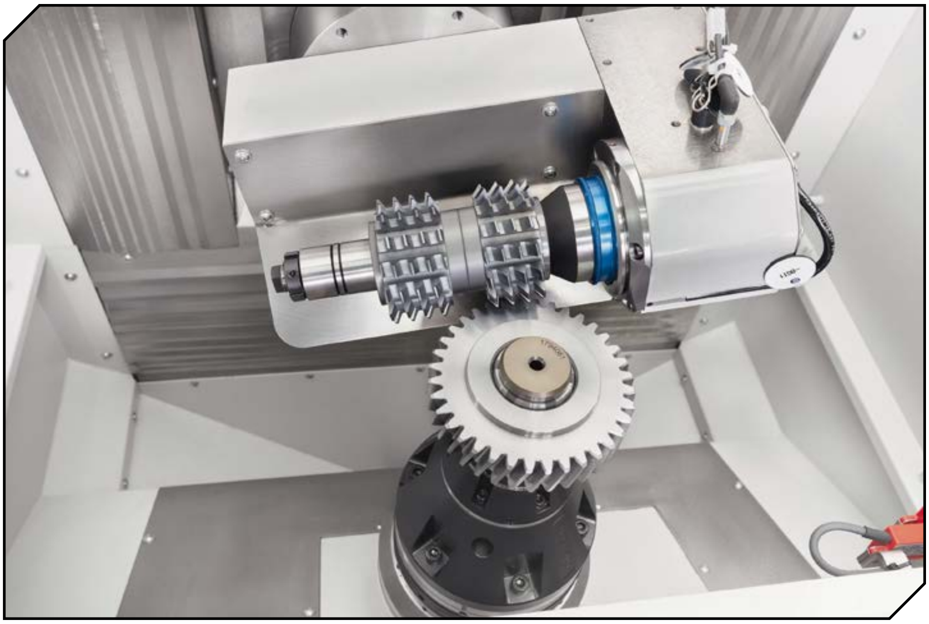
By cutting into the gap, burrs are avoided on the face side of the gears. With chamfer angles such as those produced by the chamfer rolling process, there are no noticeable burrs on the flank that require removal downstream.

Finally, the Gleason Chamfer Hobbing process offers tool shifting, which delivers increased tool life, minimal change over times and, ultimately, lower cost-per-piece. Additionally, the existing grinding capabilities for gear hobs can be used as well for Chamfer Hobs.

Cutting the chamfer with a chamfer hob.

Chamfer Hobbing in Parallel

The new-design Genesis 160HCD combines the proven Genesis vertical hobbing platform with an integrated chamfering/deburring station to perform the new Chamfer Hobbing process in parallel to hobbing, and thus achieving cycle times to satisfy the requirements for dual-clutch or electric drive transmissions. A high-speed, 2-position NC-gantry loads the workpiece for hobbing, transfers the workpiece to the chamfering station and then delivers the finished workpiece to the parts conveyor. In addition to shorter cycle times, change-over procedures are optimized as well, since the machine includes a new-design operating software to make setup and change-over easier.



Two chamfer hobs for independent chamfering of left and right flanks.

Countour Milling: Mastering Chamfers on Larger Gears

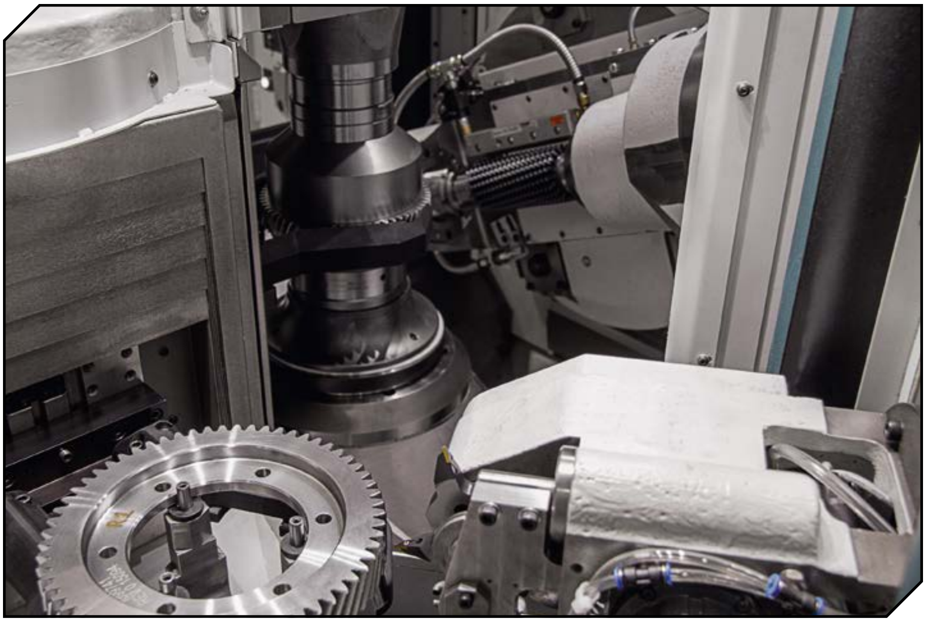
While chamfering gets increased focus with automotive-size gears, equally effective solutions for larger, 'truck-size' gears are becoming nearly as important — and more readily available.

With larger gears, requirements are changing. Smaller batches, larger variety of parts and longer cycle times are typical. Therefore chamfer rolling and Chamfer Hobbing with dedicated tools may not be the best fit since tool investment could be significant. A more flexible solution is necessary, but it should be just as easy to use and deliver low tool cost per part.

The continuous 'fly cutting' process offers significant advantages for improving chamfering flexibility as well as reducing machine and tooling costs as compared to other chamfering processes. This process, called Chamfer Contour Milling, generates a chamfer along the gear edge contour by synchronizing fly cutter and workpiece rotation such that the fly cutter — generally a star-shaped body with four standard, replaceable indexable carbide inserts — contour mills the chamfer with the desired characteristics.

The Chamfer Contour Milling process is continuously indexing and creates a cutter path that envelopes the tooth geometry from the outside of the part in. All six axes in the chamfer unit are used during generation of the tool path, and the tool seeks to use the straight side of the indexable blades to optimize the process and tool life. Since each edge of the tooth is done separately and the chamfer

Gleason's Genesis 160HCD: small footprint, parallel hobbing and chamfer hobbing.



Chamfer Contour Milling and gear hobbing in parallel, interlinked with 4-station ring loader.

size and angle depends on machine movements and not on the tool design, the process is quite universal. It can, with only a few sets of indexable carbide inserts, cover parts ranging from module 2.5 mm to the maximum machine capacity of module 8 mm. The process enables just a relatively few different standard insert blade sets to accommodate a wide range of gear sizes, geometries and chamfer requirements. Due to the size of the cutter, some clearance below the root diameter is necessary to avoid collision. This requested clearance depends on chamfer angle, root chamfer requirements and tool diameter. Therefore best results with this chamfer contour milling process can be expected with disc-type parts or shaft-type parts with some distance between the root diameter of the gear and the shaft itself.

Genesis 400HCD Hobbing and Chamfer Contour Milling Machine

While fly cutter chamfering has long been successfully employed on bevel gear cutting machines, it has just been adapted for the first time as a viable chamfering process for cylindrical gears on Gleason's new Genesis 400HCD Hobbing Machine, designed for workpieces up to 400 mm outside diameter and module 8 mm. The optional Chamfer Contour Milling station, positioned at 90 degrees to the main hobbing work area, allows parallel hobbing and chamfering processes to increase productivity. A four-station ring loader transfers workpieces between the machine's central worktable and the chamfering/deburring station, which is equipped with the aforementioned fly cutter. The new operating software allows an easy and fast learning experience for smooth set up and operation.

While available for wet cutting, the 400HCD is also optimized for dry hobbing and chamfering. A machine bed with steep angles and large openings directs hot chips away from machine components. Additionally, hob head and workpiece spindle speeds can accommodate the latest tool materials like G50 or even G90 with AlCroNite Pro coatings for high performance cutting.

Designing the machine for dry hobbing also enables the chamfer process to run dry without limits.

In Summary

Manufacturers now have a variety of integrated and automated chamfer/deburr options available, whether the well-proven chamfer rolling process for shortest cycle times, these newest Chamfer Hobbing process for precise and burr free operation with lowest tool cost per part, or the Chamfer Contour Milling process for highest flexibility and low tool investment even with a large variety of gears.

BONUS VIDEO: Watch and listen to the author give a live interview about chamfering and deburring technology in our new ***Revolutions*** segment on *Gear Technology TV.*

www.geartechnology.com/tv/.

Gottfried Klein is Director of Product Management for hobbing, chamfering, shaving and rack manufacturing at Gleason Corporation

Gleason's Genesis 400HCD: Hobbing and flexible chamfer contour milling in one machine.

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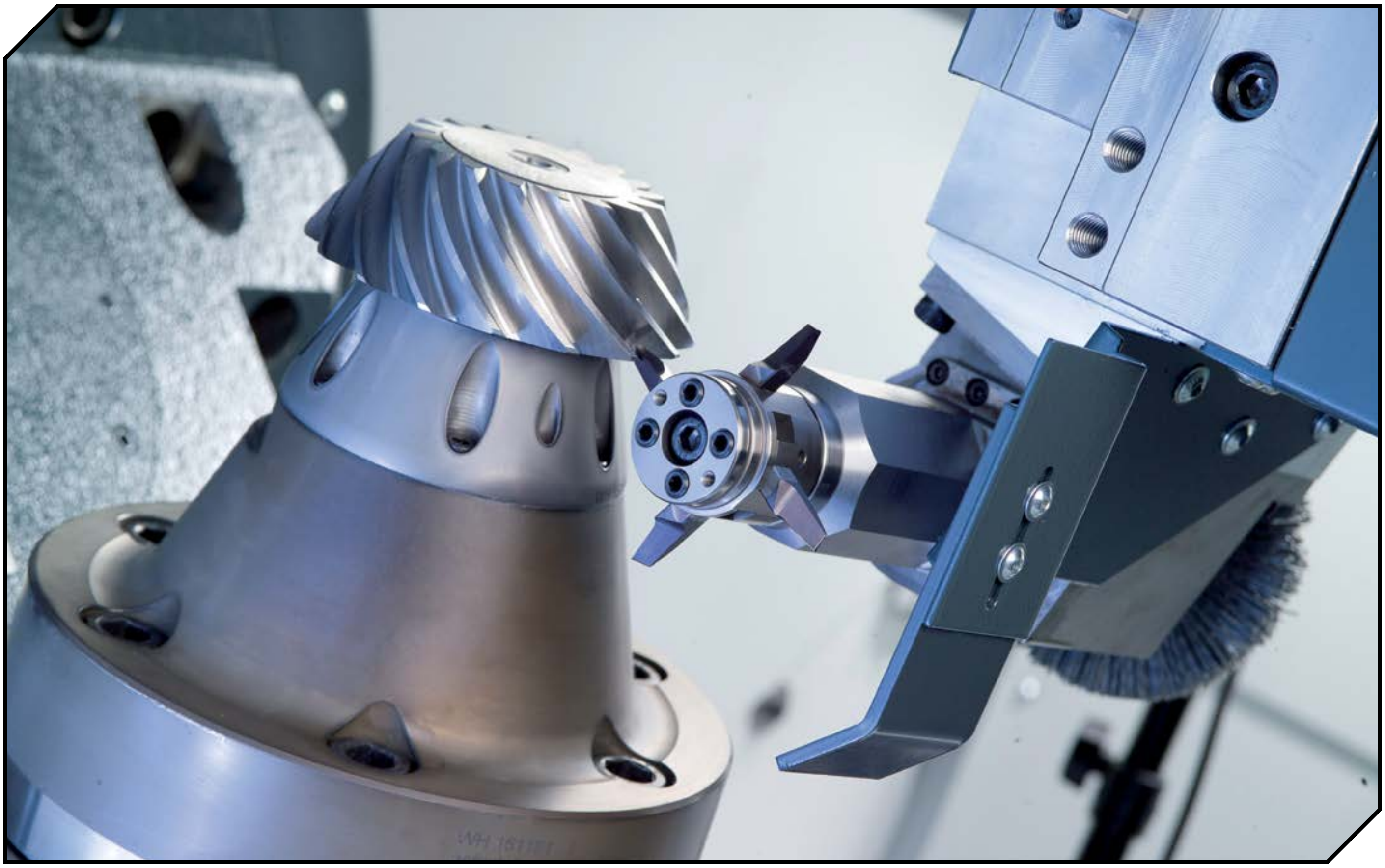
Deburring – The Underestimated Task

Karl-Martin Ribbeck, Klingelnberg GmbH



Deburring or chamfering of gear teeth is gaining attention in practical settings. And with a view to make the production sequence as efficient as possible, it is becoming increasingly important to be able to implement the deburring tasks directly on the cutting machine after spiral cutting. Read on to find out how complex this seemingly simple task can turn out to be, and how a new deburring concept provides for enhanced efficiency.

Figure 1 Deburring tools.

Why are bevel gears deburred or chamfered? The reasons vary greatly. In bevel gears, the edge area between the concave flank (gap) and the component's outer contour must be deburred in every case. That is where the bevel gear cutting tool normally exits the material and leaves behind a more or less conspicuous burr. This area is extremely sharp-edged and must be chamfered to avoid the risk of injury. As wear on the bevel gear cutting tool increases, a burr can also develop in the cutting area between the convex flank (gap) and the component's outer contour. This area should therefore also be taken into account and deburred as necessary.

How complex the task of deburring is depends significantly on the outer contour of the component, as well as on the area to be deburred, in accordance with the user's specifications. The outer contour can be straight in the area of the edge to be deburred, but it can also comprise a number of contour elements. A straight chamfer can usually be processed easily in just one cut using a deburring tool. Complex deburring edges typically do not allow this. In these cases, several deburring tool positions and cuts must instead be considered.

Deburring Directly on the Cutting Machine

Deburring outside the cutting machine (in a second clamping) always entails additional component handling, in which the reference of the position of the deburring edge must again be established for the deburring task. Manual deburring, by contrast, involves a risk of component damage, in addition to a significant time factor, and is therefore avoided in most cases.

It is therefore noticeably more efficient when deburring takes place directly on the cutting machine. In this case, component clamping is already quite stable, and the position of the gaps after cutting is known and does not change even in the event of multiple setups.

Accordingly, the gap position does not have to be reassigned for repeat production, which significantly decreases the work involved in setup. If several different deburring positions are defined for an extremely complex component contour, their assignment remains stable and they can be sequentially executed in the familiar clamping. The processing times and thus the competitive capacity can be optimized in this way. Modern bevel gear cutting machines make high-productivity cutting processes feasible – with extremely high, reproducible gear cutting quality. These machines also allow complex deburring tasks to be realized. The chamfer generated here can be accurately represented, and the deburring tools have a long tool life.

Simulating Highly Complex Requirements

In bevel gear production, deburring directly on the cutting machine is already being required – and performed – with increasing frequency. The implementation can have varying degrees of complexity and therefore suitably adapted, and varying technological approaches, all of which must satisfy one condition: Avoiding collisions. The risk of collision can occur between the deburring tool and the gap, where the opposite flank can become damaged. However, the collision situation between the deburring tool and the clamping device must also be considered. This collision situation is usually less critical for deburring of ring gears. For deburring of pinions, however, collision analysis is often particularly important.

A simulation of this complex task makes it possible to also analyze the penetration of the component/clamping device with the drive of the deburring tool. Such a simulation includes three different elements. These three elements must be made compatible in advance with the capabilities of the specific cutting machine:

1. The simulation starts with a definition of the deburring tool geometry. The deburring tools consist of carbide stick blades that are clamped in a holder. The stick blades can have a variety of profile shapes, with the technological angles specifically adapted to suit requirements. To minimize setup costs on the machine and reduce tool costs, as many deburring tasks as possible are executed with the same deburring tool.
2. The second element includes definition of the suitable exit angle for the deburring tool cutting edge, from the material to be deburred. An exit angle must be selected that will prevent another (secondary) burr from developing as a result of the deburring task, which itself is also a chip-removing operation. Both the deburring tool geometry and the movement executed by the tool in the space play a role here. To thoroughly analyze the deburring task, testing is necessary to determine how many different cuts are required to completely capture the area to be deburred. The exit angle of the cutting edge must be checked for each of these tool positions.

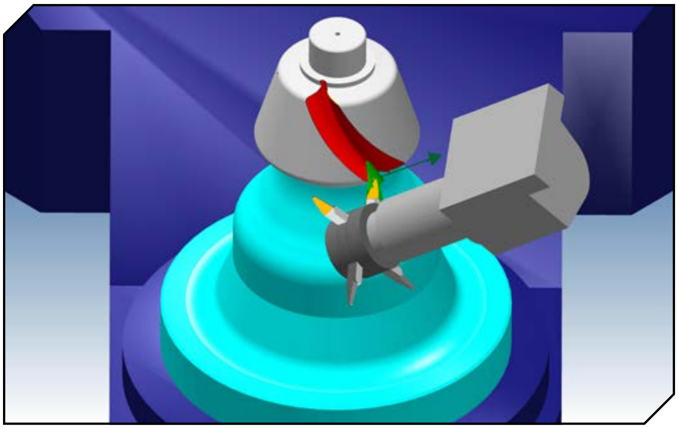


Figure 2 3D view of all components involved in the deburring task.

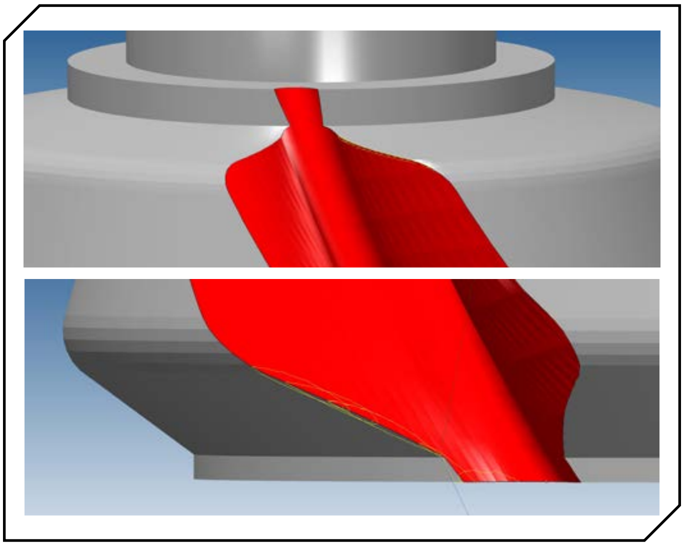


Figure 3 Edges to be deburred, resulting from the cutting area between the component envelope and the component gap.

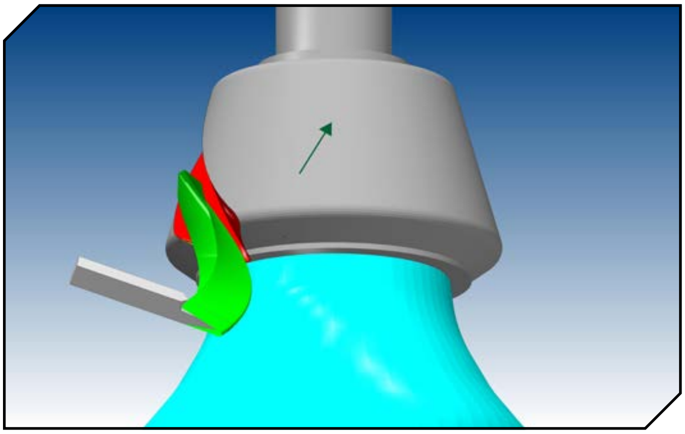


Figure 4 Component clamped in device, deburring tool trajectory in green.

When the component contour description is as precise as possible, it facilitates targeted optimization of the deburring tool positions. Turned part descriptions are increasingly available in digital format. This component contour can be imported into the simulation as a contour element frequently in the form of a Drawing Interchange file (DXF).

3. The third element is a collision and traversing path test for the specific cutting machine. Collision testing is required with reference both to the opposite flank in the gap and to the clamping device used to hold the component in the cutting machine. For this test, the deburring tool trajectory is represented in an adequate spatial expansion. When the clamping device description is done precisely, it facilitates targeted optimization of a collision-free deburring tool position. This clamping device contour is generated automatically for Klingelnberg clamping devices and can also be imported as a DXF element.
   Testing of this deburring task and the collision check can be tailored to suit the circumstances, such as, machine concepts and machine sizes of individual machine types.

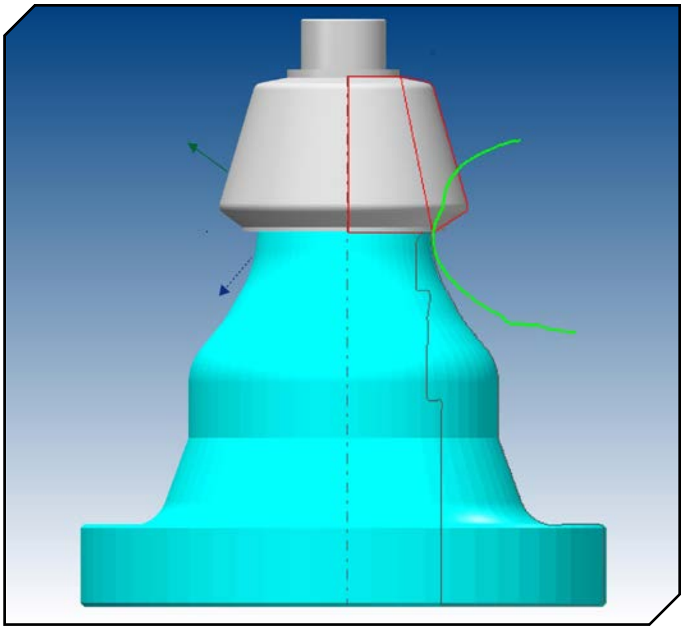


Figure 5 **Envelope contour of a clamping device and component (red); collision range of all deburring positions (green).**

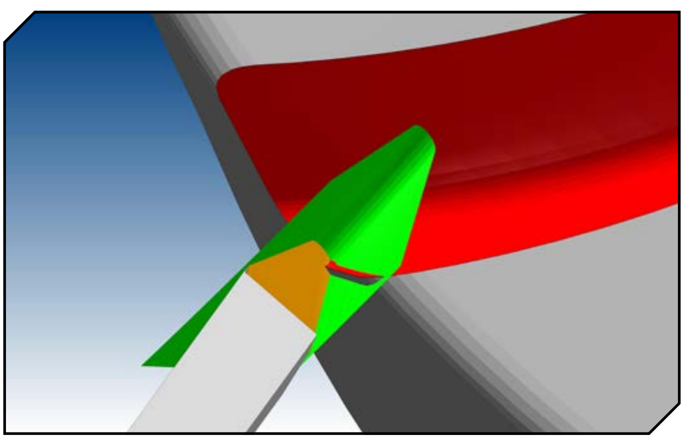


Figure 6 **Action of the deburring blade cutting edge at the tooth root and final shape of the deburring edge after a single cut.**

Machine Axes Determine Flexibility

For spiral bevel gear production, there are different machine designs on the market. Various deburring options are available, depending on the design. In terms of deburring versatility, the number of available machine axes always plays an important role. Depending on the component size and clamping device concept, the available traversing paths also influence the deburring task options. Compared with older models, new machine generations have a significantly increased range of functions with regard to deburring. This development is reflected in the fact that in modern concepts, great emphasis is placed on the capability to thoroughly implement deburring tasks.

A Variety of Methods for Component Deburring

Deburring facets can be generated in different ways – and combinations are also possible. These include:

- For Klingelnberg's horizontal cutting machines with only four axes available for the deburring task, the single-cut method is used. The tooth root can also be deburred by turning the component in the final position of deburring.
- The numerable-cut method can be employed on Klingelnberg machines with a vertical machine concept and the capability

Figure 7 **Contour generated with five different positions of the deburring tool.**

Figure 8 **Contour generated with many different positions of the deburring tool.**

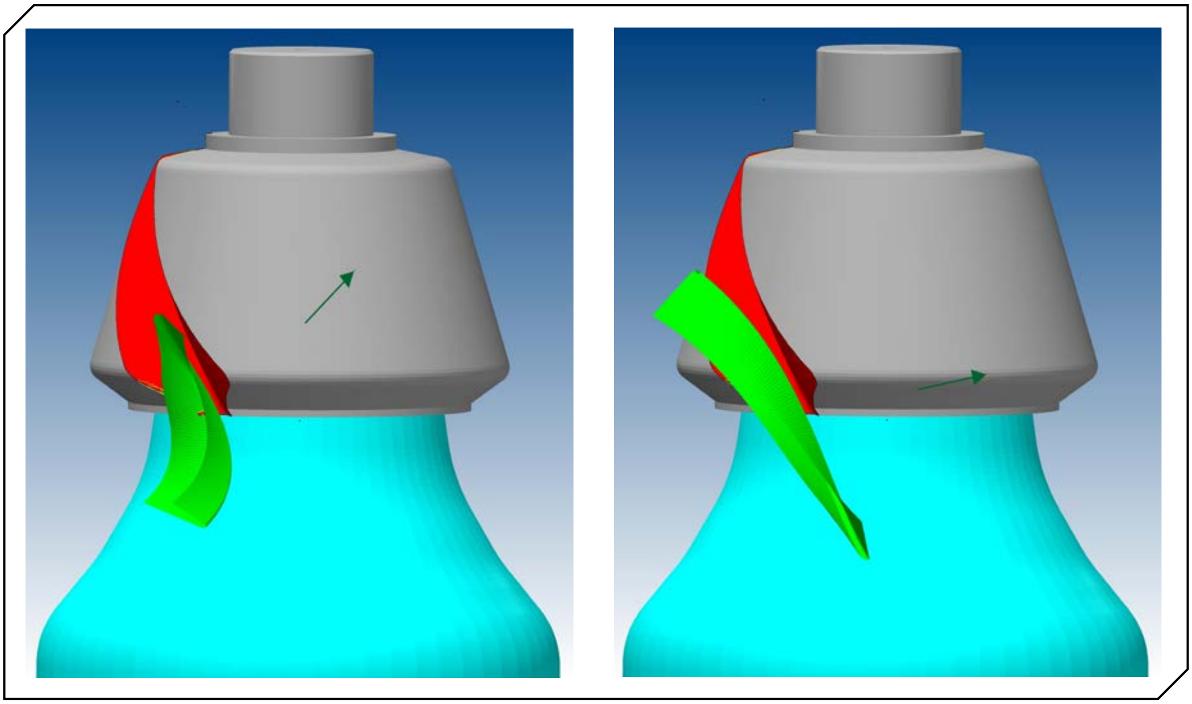


Figure 9 Comparison of the two possible coupling situations for the same deburring task.

to use six simultaneously controlled NC axes. Here a contiguous edge is deburred through several cuts located one after the other in the heel area. Figure 7 shows the result of five selected positions. These are necessary because the tooth flank has an extremely pronounced curvature in the profile direction, which is offset by three cuts, and because there is a peculiar contour change on the back cone of the component. This requires an additional, extremely steep cut. Lastly, the gap root is deburred with a tightly-turned final cut. Between each deburring position, the tool is withdrawn from the gap and re-situated for the next position with a feed movement.

- The many-cut method can also be employed on Klingelnberg machines with a vertical machine concept and the capability to use six simultaneously controlled NC axes. A contiguous edge is deburred through innumerable cuts located in close proximity to each other. The special thing about this method is that the deburring tool does not lift out from one position to the next – rather, it executes every deburring position along the edge directly with a rapid feed movement. The cutting is performed primarily by the tool tip radius.

New Coupled Movement Optimizes the Collision Curve

All of the component deburring methods presented are based on a principle of continuous motion. This has the advantage of extremely short auxiliary times, and therefore a short deburring time overall. This continuous operation principle requires a coupled movement of the rotation of the deburring tool axis and the component axis.

All familiar coupled movements used so far for deburring are set up in such a way that the component flank moves toward the deburring blade. This movement requires a specific spatial expansion relative to the trajectory of the deburring blade. In a number of deburring tasks, however, this spatial expansion of the trajectory relative to the collision situation is a key challenge.

Klingelnberg has therefore developed a way to create this coupled movement so that the component flank moves away from the deburring blade. The spatial expansion of the trajectory for this coupling relationship has a significantly different form and requires considerably less space. Collision-critical tasks can therefore be performed with much better results using this deburring principle.

Conclusion

The seemingly simple task of performing deburring tasks on a cutting machine can turn out to be quite complex. This is evident in the variety and diversity of ways deburring can take place on a cutting machine – and also in the difficulty of reliably determining process parameters such as risk of collision. Simulation provides valuable support in this respect: The machine settings determined during the simulation can be loaded directly on the cutting machine, removing all obstacles to manufacturing real, burr-free components.

The fact that more versatile solutions are being offered and demanded with increasing frequency reflects just how important the capability to implement the deburring tasks directly on the cutting machine after spiral cutting has become for customers.

Dipl.-Ing. Karl-Martin Ribbeck is Head of the Bevel Gear Competence Center at Klingelnberg GmbH.

Everything-Friendly Lubricants

Lubricant experts are doing more than ever to make their products less toxic and harmful to everything from the environment to the people using them — which comes with plenty of extra benefits for productivity, too!

Alex Cannella, Associate Editor

Of the dozens of different challenges lubricant specialists have to weigh and consider, you might not think that their impact on the surroundings would be a priority. Most thoughts would immediately jump to matters of grave import such as manufacturing efficiency, productivity, cost efficiency, and so on. But the environment, and just as importantly, the people existing in it, is rightly an important consideration right alongside the usual suspects that's been on the minds of a lot of lubricant manufacturers. And they've been doing a lot lately to improve their products on that front.

Lubricants are getting friendlier than ever. More environmentally friendly, more user friendly and more machinery friendly. Across the board, you can find evidence of all kinds of different ways coolants and cutting oils damage their surroundings, from the environment itself to the individual people working with them. But across the board, you also see lubricant specialists thinking about these problems and making adjustments to minimize them. The process is still ongoing, but it is going somewhere, and we're seeing the fruits of those labors today.

The most well-known industry shift you've probably already heard of is the advent of hydro- and vegetable-based oils that break down more easily and don't fester as toxic waste, but there's so much more going on behind the scenes. Anti-misting and foaming measures. Reducing toxicity and removing chemicals that are flammable or harmful to the skin. Even the materials a cutting or grinding machine are made of and how coolants interact with them is a consideration.

> **"We've found our most environmentally friendly products also work extremely well for gear manufacturing and gear hobbing."**

That last one might sound surprising,

Lubricants typically have many toxic properties that can damage everything from the environment to a machine operator's skin, but suppliers are finding new ways to tackle and eliminate their products' capacity for harm.

Caption: "Oelheld regularly tests machinery components to see how their materials interact with the company's cutting oils."

but for Oelheld, it's an important issue that they've devoted significant effort and time towards. Oelheld has developed its own entire system for testing those materials, and there are a surprising number of considerations when just focusing on this one small aspect of designing lubricants.

A prime example is a silicon-based lubricant that is sometimes sprayed on a machine's wiring. Oelheld's found that over time, that silicon can wreak havoc with cutting oils when exposed repeatedly. As it's weathered off, the silicon itself gets into the cutting oil, creating a reaction that causes massive foaming, and that foaming in turn spirals into a whole host of other issues and can even leak out of the machine and start flooding your work space with cutting fluids. Silicon can actually be used as a defoaming agent, but only when used in very minute amounts. Just like with medicine, a little bit can help, but too much is a poison, and over time, wash off from silicon coatings becomes too concentrated and achieves the exact opposite of its intended effect in a cutting oil.

"We go to many machine manufacturers and say 'listen, why don't you use, for example, a synthetic PAO to coat the wires in?'" Stephan Hecht, CEO of Oelheld, said. "It's a good lubricant, just as good as silicon, but it's compatible with any oils."

And that's just one example. Oelheld has an entire lab set up to test the effects of lubricants on other components' materials, and they're regularly tapped by machine manufacturers to test their machines' materials and see how they react to Oelheld's products, or to discover the root cause of why another company's lubricant isn't playing well with their machines.

While it might sound like such a minor thing, Oelheld's efforts on this front can actually have a big impact by preventing unexpected costs during production. Once the silicon gets into your lubricant, your only course of action is to just replace it. Entire barrels of lubricants can get ruined in this fashion, which not only affects your bottom line as you have to replace the spoiled cutting oils, but can be disastrous for the environment if said lubricant can't be broken down easily.

"When the silicon gets in, it's over for the oil," Markus Munde, global technical support at Oelheld, said.

In its own roundabout way, reducing or eliminating reasons to prematurely dump lubricants is a primary method that manufacturers are using to improve their footprint on the environment. After all, the fewer lubricants that need to be dumped before they're used, the less harm they'll do. And the number of ways different lubricant experts are finding to do that are extensive, from smaller efforts such as pointing out and addressing potential ways lubricants can be compromised such as Oelheld's work with machining components to more obvious ones such as just improving a lubricant's shelf life.

But all of that only treats a symptom. Taking soft measures to lessen lubricants' environmental imprint is all well and good, but the root cause — that many lubricants do not play well with the ecosystem — still remains. So while we might be mitigating the issue, how do we solve it?

Luckily, there are a fair number of lubricant manufacturers that are tackling that exact question, and the best way they've found is those hydro- and vegetable-based oils I mentioned before.

Blaser utilizes an ester base for many of their cutting oils, including their Vascomill and Vascomill MMS lines. Ester is significantly more biodegradable than mineral-based oils, making Blaser's Vascomill lines far gentler on the environment. But Blaser was also pleasantly surprised to discover that the switch to ester-based cutting oils was actually a win all around. It turns out that there are numerous side benefits to using ester that directly improve manufacturing efficiency for gear manufacturers.

"We've found our most environmentally friendly products also work extremely well for gear manufacturing and gear hobbing," Randy Templin, vice president of Blaser Swisslube Inc., said.

Using an ester-based lubricant provides plenty of additional benefits that are appealing to gear manufacturers. Primary among them is increased lubricity, and increased lubricity in turn means more parts can be machined with less oil. They also have a high flash point, low misting and vaporizing and a low

drag out on parts, all beneficial traits that just naturally come with using ester-based lubricants. And in addition, many of Blaser's cutting oils also offer wear protection and low discharge rates.

"The consumption is low and the performance is also very high, so it's the best of both worlds," Templin said. "You have high productivity on the machine and also low consumption of the cutting oil, which is also renewable."

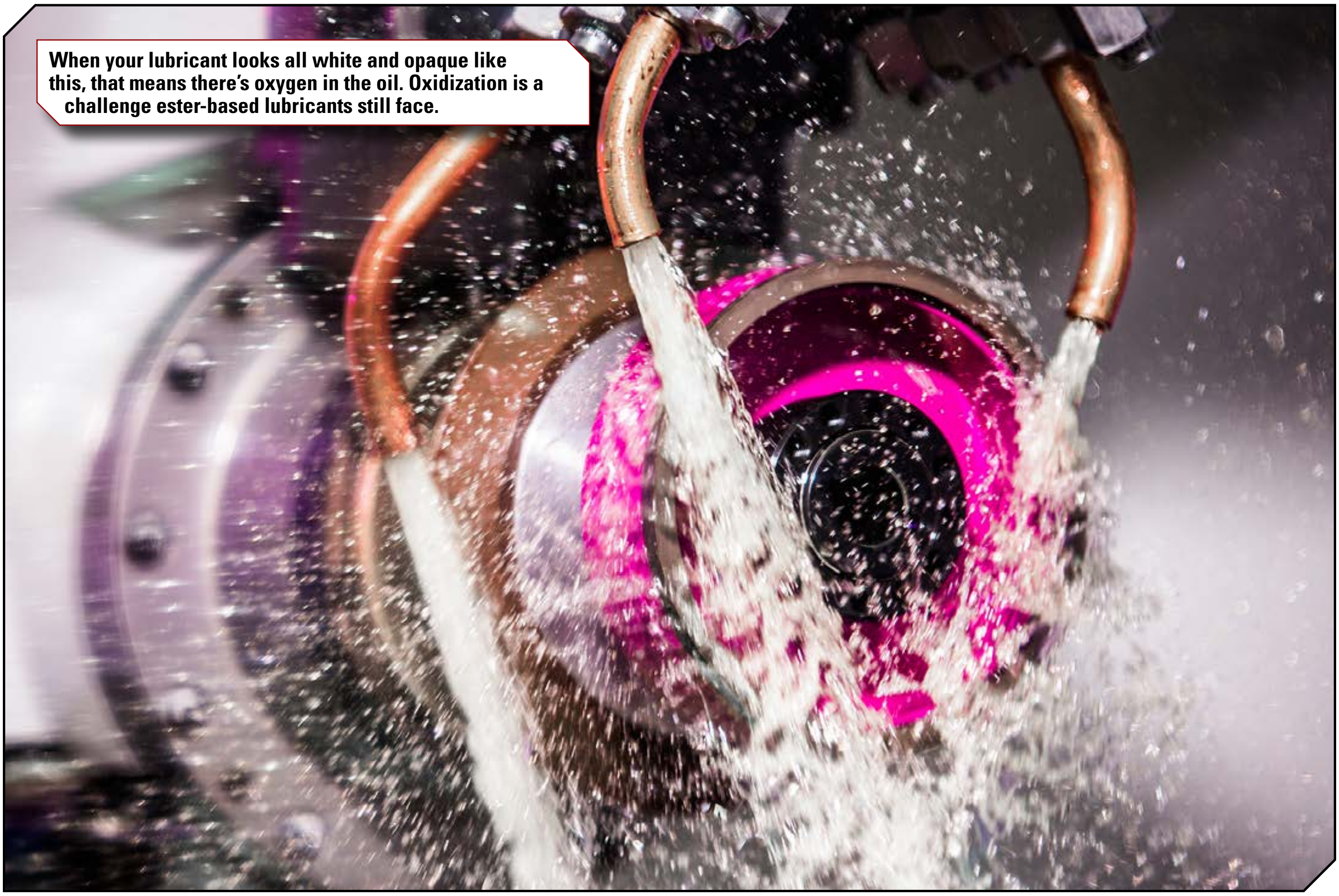
But according to Templin, if there's one issue Blaser's run into with their ester-based cutting oils, it's oxidization. This can be an issue for many cutting oils, but is a little more pronounced with ester-based ones.

Blaser's answer to that issue is their GTL (gas-to-liquid) products, primary amongst them being Blasomill GT and Blasogrind GTC 7. While they're both mineral-based products and thus not all that biodegradable, they do offer an alternative that covers the Vascomill line's primary weakness. The primary advantage of utilizing GTL is that even if air gets into the cutting fluids, they release it drastically faster than other lubrication products might.

"In the end, even though they might pay more with one of our products, they should be paying less overall once you look at the total cost of operation because the product benefits outweigh the extra cost."

"When oil comes back to the machine, the air comes out of it, so by the time the pump [delivers the oil], it's air free," Templin said. "You're delivering nothing but oil to the cutting zone or the grinding zone."

Lubricant suppliers can also run into another unexpected challenge with ester-based lubricants if they operate globally. One of the primary sticking points of making the jump over to biodegradable vegetable-based lubricants is the availability of the vegetable oil itself, as Houghton International discovered when they found out how expensive it would be to transport their lubricants. Between the cost of transporting vegetable oil in bulk halfway across the world and import regulations in some parts of the world such as Europe, Houghton International found that it was actually cheaper to develop individual copies of the same lubricant for each major region of the world they serve, each redesigned to work with locally available vegetable oils. It was an unexpected hurdle, but one



When your lubricant looks all white and opaque like this, that means there's oxygen in the oil. Oxidization is a challenge ester-based lubricants still face.

that Houghton International was able to overcome.

"We try to develop our new products with global markets in mind, and so one of the challenges is that vegetable oils come from different sources around the world, different crops, and even the different environmental conditions impact the vegetable oil," Mike Smith, technical director of new product development at Houghton International, said. "So you get different properties from the different vegetable oil sources, and a lot of our work goes into making appropriate adaptations to regional needs."

One final issue that might tempt manufacturers to not buy in for vegetable oils is the cost. As with most products on the leading edge of technology, it's going to cost a bit extra to get an ester-based cutting oil. But remember that some of the natural benefits that come from using that ester base are increased tool life and lubricity. And according to Dave Slinkman, senior vice president of research and technology at Houghton International, those natural benefits can actually help you save money in the long run when you switch.

"The approach that we take, the product might be a little bit more expensive due to a vegetable oil or some other improvement, but typically that benefit is going to be seen in the fluid lasting much longer than it typically would or providing much better lubricity so that they increase the number of parts they can make per tool," Slinkman said. "And in the end, even though they might pay more with one of our products, they should be paying less overall once you look at the total cost of operation because the product benefits outweigh the extra cost."

That cost can still make both lubricant suppliers and their customers look the other way, however, even when it's disadvantageous to do so. The chemistry behind lubricants can get complicated fast when you consider just how many different needs a coolant or cutting oil manufacturer has to cater to. You need to be efficient, clean, and have a long shelf life, low misting, low foaming, and low oxygen absorption. To say nothing of individual considerations that certain products need to weigh like chip removal. When faced with all that, "secondary" concerns like the environment can often take a backseat instead of being added to the considerations to be balanced when concocting a new lubricant.

But the environment shouldn't be a secondary concern, and your own workers that have to interact with these lubricants definitely shouldn't be, either. And there are a lot of lubricant suppliers out there now going the extra mile to nullify the hazardous nature of formerly toxic, damaging products, to the benefit of pretty much everyone. The only question now is how many gear manufacturers will go that extra mile, too.

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Ester-based lubricants may be a little more expensive, but most often, they'll save you money in the long run by enhancing tool life.

NVH Potential of PM Gears for Electrified Drivetrains

Dr. Gerd Kotthoff,
Director Advanced Gear Technology & PM Processes, GKN Sinter Metals Engineering GmbH, Germany

Introduction

Electrification has already started to have a noticeable impact on the global automotive industry. As a result, the drivetrains of hybrid (HEV) and full electric vehicles (EV) are facing many challenges, like increased requirements for NVH in high speed e-Drives and the need for performance improvements to deal with recuperation requirements. Motivated by the positive validation results of surface densified manual transmission gears which are also applicable for dedicated hybrid transmissions (DHT's) like e-DCT's, the GKN engineers have been looking for a more challenging application for PM gears within those areas, [1]–[3]. As a result of this, the following case study describes the successful validation of a powder metal (PM) gear for an e-Drive application. Starting with initial engineering discussions on the system requirements, a complete process development of a surface densified PM intermediate gear for an electrified axle gearbox has been executed, followed by system tests related to durability/performance and NVH behavior. Further development insights on ongoing optimizations to increase the benefits in performance and NVH behavior are given, like the improvement of the damping behavior by PM tailored gear bodies and designing an NVH tailored micro-geometry for a surface densified PM gear. Finally, the strong need for an early collaboration between customer and supplier to drive future innovations in drivetrain technology efficient and fast will be discussed

High Variety of Electrified Drivetrains

The current transmission developments show, in particular by the different types of hybridizations, a high variety. Figure 1 illustrates this with reference to the arrangement of the electric motor(s) in the drivetrain. Depending on the allocation of the e-motor, the different concepts are classified, from hybrid drive concepts up to the battery-powered vehicle BEV.

In the power-split hybrid drive (PS), the mechanical power of the ICE is split into two paths (mechanical and electrical) and reunited to drive the vehicle. The parallel hybrid powertrains (P) are distinguished by the location of the electric motor (0: belt starter generator, 1: on the crankshaft, 2: at the gearbox input, 3: at the gearbox output, 4: on the axle). The P1 hybrid arrangement is characterized by a relatively low electric power of the hybrid vehicles, in which no purely electric drive is provided. If the electric motor is located at the transmission input with an upstream clutch, this is referred to as a P2 arrangement. In this arrangement, the electric motor can be decoupled from the engine and it is a purely electric ride possible. At the P3 arrangement, the electric motor is located at the transmission output. The power during the electric drive and recuperation must not be passed through the transmission. The e-machine is subject to the transmission output speed and thus a much wider speed range. For the future BEV's favored P4 arrangement, the ICE and the electric motor act on different axes. With this concept a four-wheel drive can easily be realized.

Figure 2 shows some transmission designs for HEV's and BEV's. The so-called "Add-On Hybrid Transmissions" are a combination of an e-machine with existing transmission concepts, like "Dual Clutch Transmissions" (DCT's) or Automatic Transmission (AT's). These transmissions have full functionality even without the operation of the electric motor. Furthermore, "Add-On Hybrid Transmissions" offer the advantage for both OEMs and transmission manufacturers that the majority of the transmission components used today can continue to be used.

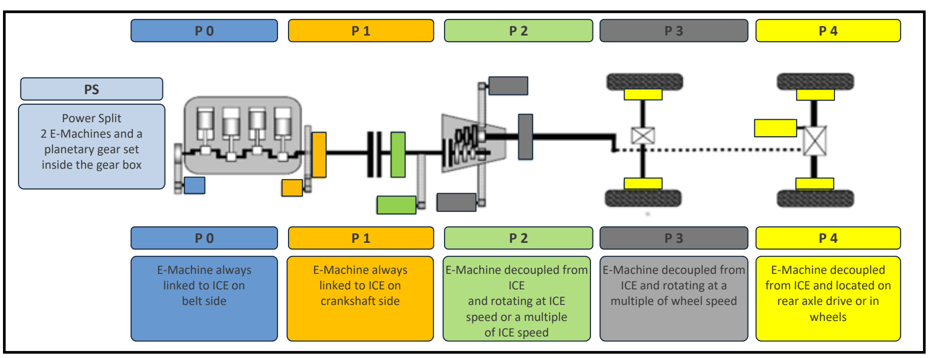

Figure 1 High variety of hybrid and BEV architectures.

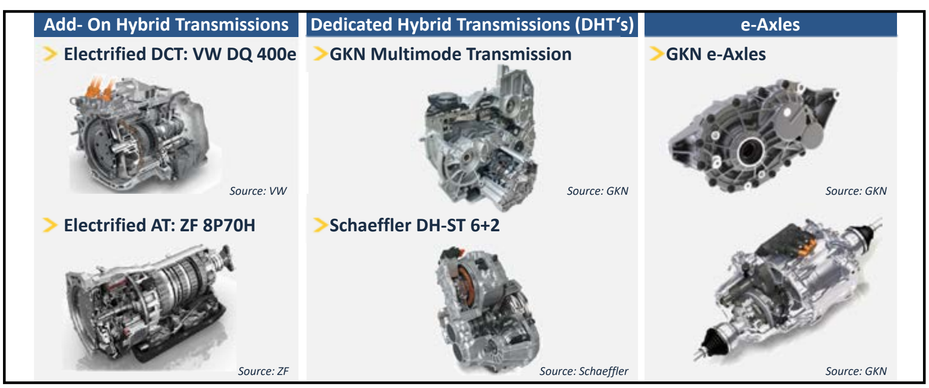

Figure 2 Electrified transmissions with potential for PM gears.

The so-called "Dedicated Hybrid Transmissions" (DHT's) are transmissions with a fully integrated the power source for the electric drive. Their functionality depends entirely on the integrated electrical components. Figure 2, middle, shows some actual examples of electrified DHT's. Finally, the Figure 2, right, shows electrified axles which are available on densified PM transmission gears could be applied. The arrangement of the transmissions on the second vehicle axle allows e.g. the realization of a four-wheel drive without the use of a prop shaft. However, high rotational speeds up to 16.000 rpm, up to 30.000 rpm are already under development, lead to challenging requirements related performance and NVH (Noise Vibration Harshness) behavior.

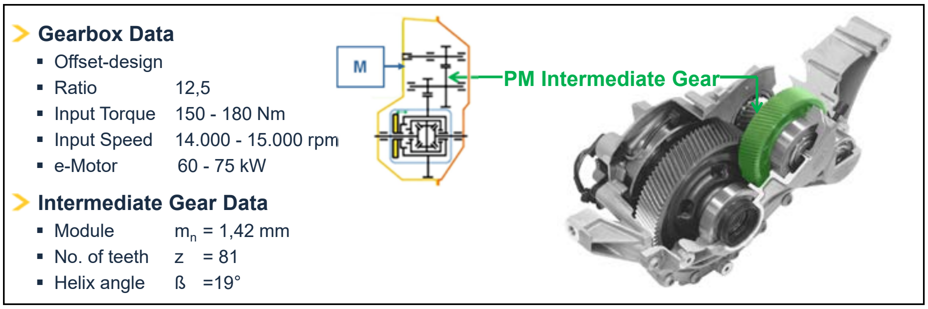

Figure 4 Selected E-Axle gearbox for PM technology validation.

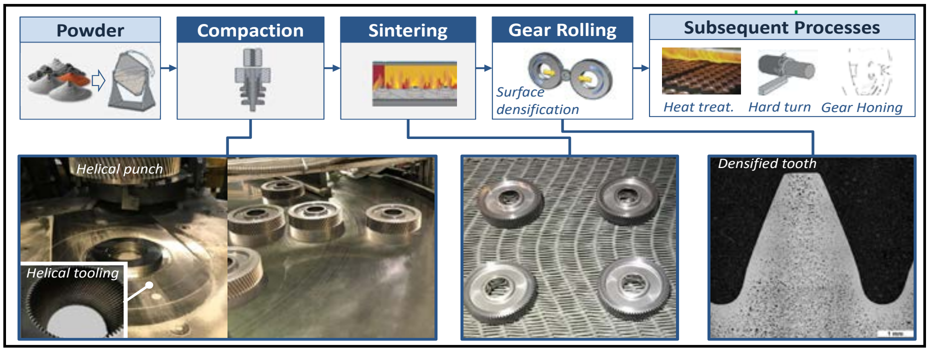

Figure 5 Off-tool production of PM intermediate gears.

Validation of Surface Densified PM-Gears for E-Drives

While surface densification technology of PM Gears has been validated with a ß = 34° helical transmission gear for 6-speed manual transmission [1], [2], the motivation of our engineers was high to proof the technology and implementation readiness also for e-Drive applications. However, one main challenging requirement is the increased sensitivity related to the NVH behavior needed to be addressed and answered positively as part of a product validation program, Figure 3.

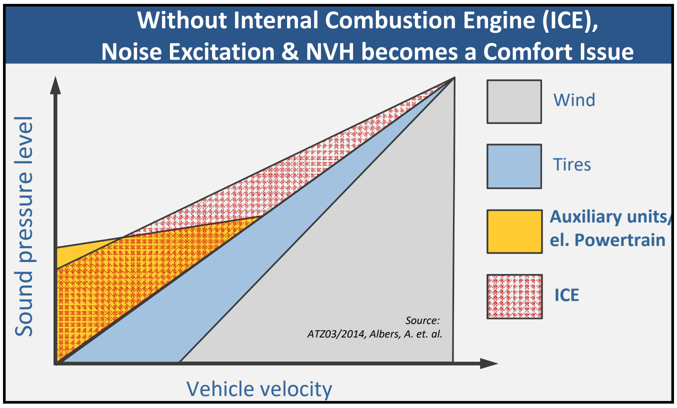

Figure 3 Sound sources depend on vehicle velocity.

Looking back into 2016, the potential of the NVH improvement has been shown on a generic e-axle system as used currently in serial production by changing the steel intermediate gear into a PM gear. At that time, the PM gear was machined from blanks with a core density of 6,8 g/cm³ and has been tested on a test bench up with rotational speed to 6,000 rpm, which is comparable with car speeds up to 50 km/h (city mode), [1]. Having shown the potential of NVH improvement within this first test of machined blanks, it was clear to the team that the performance of the PM intermediate gear needed to be proven, while at the same time working on measures on improving the NVH behavior of surface densified gears in a systematic approach. The gearbox, as it is used for the current system validation of the PM intermediate gear, is shown in Figure 4.

Consequently, the development of off-tool and surface-densified (rolled) gears has been carried out in order to execute a complete system validation based on a customer defined load-collective test. The core density of the PM gear had to be moved up to ~7,15 g/cm³ to be on the safe side regarding durability. The production steps of the off-tool and surface densified PM Gears are shown in the following Figure 5.

The process route starts with the powder manufacture, followed by compaction and sintering of a gear preform, a transverse rolling process and finally a case hardening and gear honing operation. A GKN owned design for the helical compaction tooling was applied. On the bottom right, the picture shows a cross sectional cut of a surface densified tooth with the performance tailored densification zone. The densified layer is quantified after metallographic preparation of a cross sectional cut of the teeth, Figure 6. In order to properly quantify the densification depth, an approach similar to the hardness curve evaluation has been applied. The surface densification depth SDD 98%, describes the depth with 98% density of the "fully dense PM material" and is 0.36 mm on the flank and 0.19 mm in the root section.

Following to the surface densification by gear rolling, the PM intermediate gears have been heat treated. Figure 7 shows the results of the heat treatment runs. From the experience on the densified manual transmission gears it was known that no specific heat treatment process needed to be developed. This is beneficial e.g. if a densified PM gear shall be heat treated and hard finished within an existing production environment. Two serial case carburizing programs for steel gears have been applied and the program *CONV2* was selected for the carburizing of the gears to be validated in the system tests.

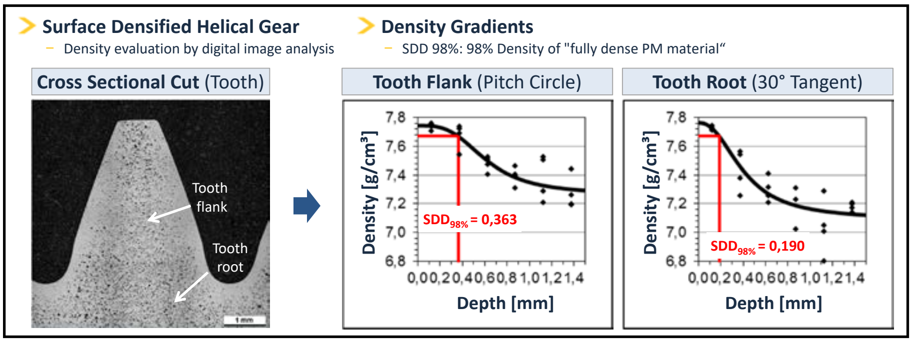

Figure 6 Result of surface densification.

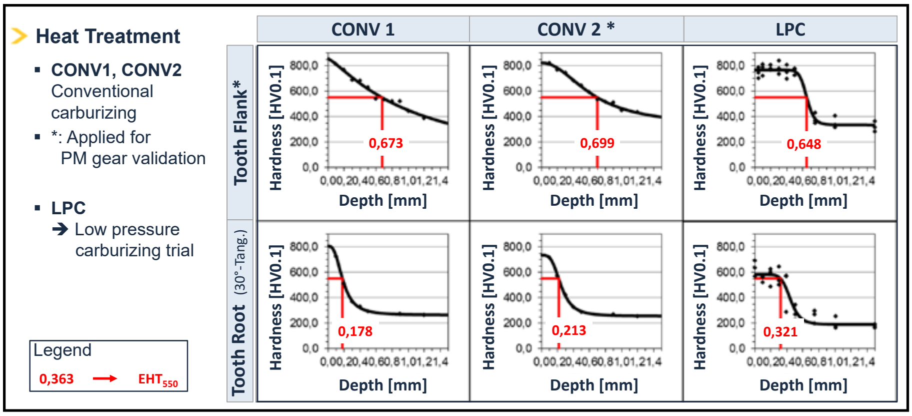

Figure 7 Result of heat treatment runs.

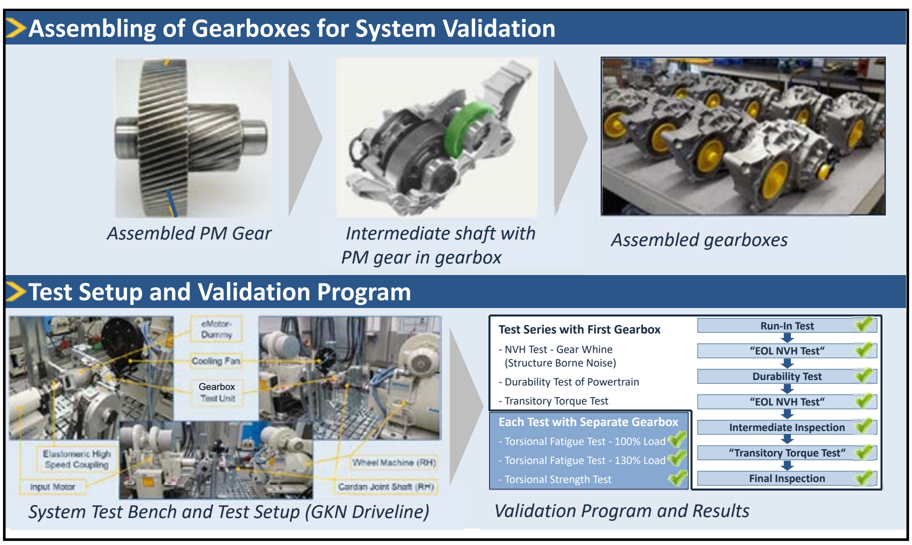

Figure 8 Assembling of gearboxes, test bench setup (GKN Driveline) and results.

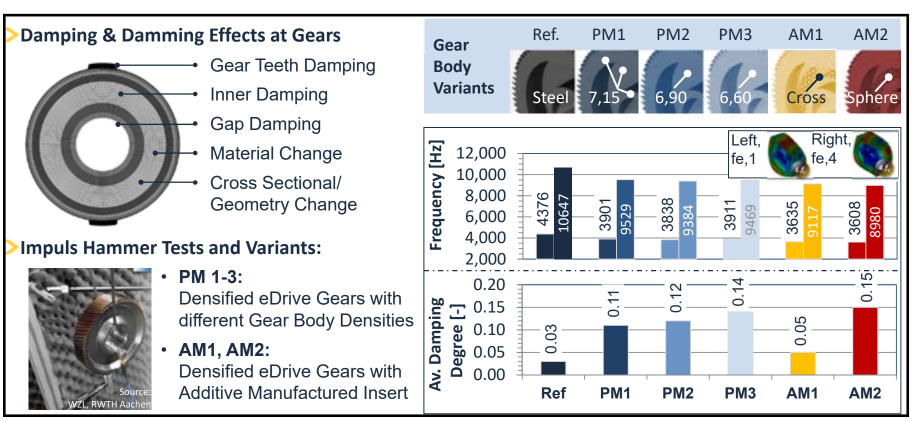

Figure 9 Potential of PM technology to tailor the damping behavior of gear bodies.

In addition, the potential of low pressure carburizing was analyzed within the heat treatment development. The low pressure carburizing tests show that a more flexible adaption of the hardness curves is possible, Figure 7 right. Further evaluation on this process is ongoing.

Following the successful manufacturing of the surface densified intermediate gears, the PM gears have been assembled on the intermediate shafts and the test gearboxes have been built for the validation tests and adapted on the system test bench, Figure 8.

In summary, the PM gear successfully passed all steps of the extensive validation program, achieving at least the same level of reference gear in terms of strength, wear and NVH [4]–[6].

NVH Potential of PM E-Drive Gears

Damping and damming effects

As PM Technology gives a high freedom with regard to the design of the gear body, a series of basic investigations related to the influence of the gear body on the structure-borne noise transfer has been started. In order to get a basic understanding of the influencing factors related sound damping and damming, differently produced steel and surface densified PM gears have been manufactured and experimentally tested by impulse hammer tests, carried out with the GKN parts at the WZL of the University of Aachen, Germany, Figure 9.

With regard to the fixed shaft hub connection of the gear, only the first and fourth Eigen mode (fe,1; fe,4) of the free oscillating behavior are relevant. The experimentally measured Eigen frequencies of these modes show a decrease in the range of 460 Hz for fe,1 and more than 1.000 Hz for fe,4 while decreasing the gear body density. In addition, the damping degrees of the different variants have been determined using the peak-picking method of the first five Eigen modes. In summary, an increased degree of damping while decreasing the gear density is observed — with an additional increase of the damping while decreasing even further the ring segment density or combining the PM densified gear with additively manufactured inserts.

Tooth microgeometry effects

Another important topic within the design process is the noise emission which is initiated by the gear mesh excitation. Target of these basic investigations was first to model the density gradient as input for the simulation and second to compare the measured and simulated transmission error of a densified PM and a steel intermediate gear ($z_2 = 81$). Due to setup conditions of the available test bench, instead of the original gear box input gear a modified input gear was designed, resulting in a test gear set of $z_1/z_2 = 41/81$, Figure 10, [7].

A good comparison between tested and simulated transmission errors of the test gear set could be observed. Following, the micro geometry of the densified PM gear has been simulated for the original gear set ($z_1/z_2 = 23/81$), considering the displacements of the real gearbox and targeting a reduced excitation at medium and high torques, Figure 10, right.

In summary it can be stated, that applying a copy of the original steel geometry to the PM gear ("original PM") leads to a higher excitation, while the optimized geometry shows a lower excitation at the targeted torque range. As a result of this, the micro-geometry optimization should be part of the design process for surface densified PM e-Drive Gears.

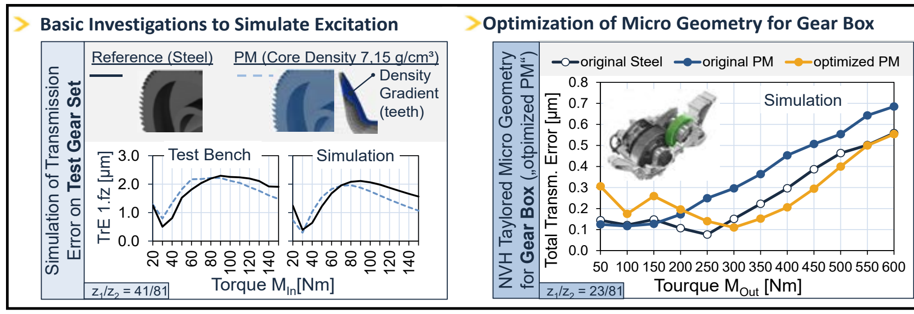

Figure 10 Approach to simulate the excitation of densified PM gears.

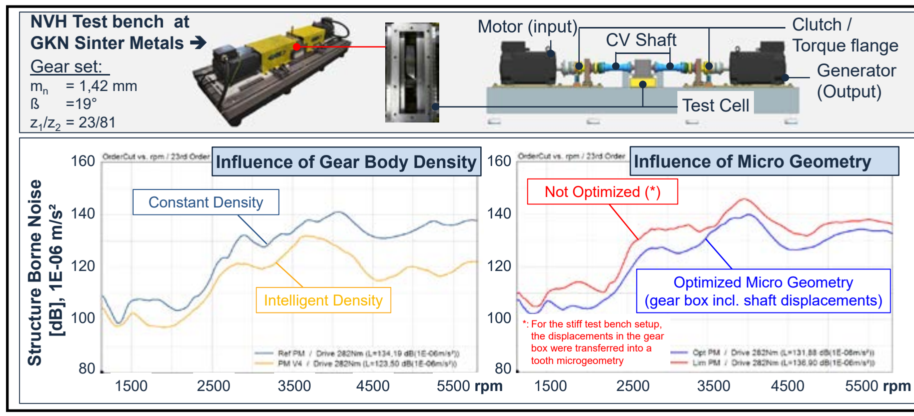

Figure 11 Influencing the NVH by gear body density and tailored microgeometry.

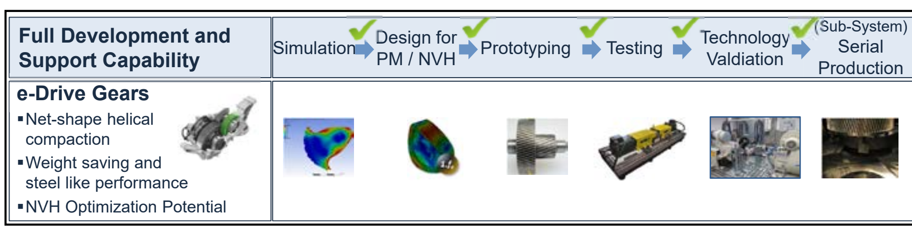

Figure 12 Driving product and system innovation with full development capability.

Quantifying the effects on component level

As part of the ongoing project, NVH tests on component and system level are carried out, e.g. at the NVH test bench at GKN Sinter Metals Innovation Center, Germany. Initial test results show the potential of the PM technology to improve the NVH behavior, considering the above mentioned effects, Figure 11.

Figure 11, left indicates the reduced structure borne noise emission for the surface densified intermediate gear by creating a gear body with a tailored density variation. Figure 11, right, shows the positive effect of a tooth micro geometry optimization. In order to evaluate the potential of the micro geometry optimization on the "ideal stiff" test cell, the displacements in the real gear box have been transferred to a modified micro geometry, characterized by a significantly increased crowning and reduced tip relief. It can be stated that these results just start to open more NVH optimization potential of PM Gears. However, in order to maximize the added value for a transmission system, a collaborative engineering approach on component and system level will be crucial.

Summary

The e-Axle PM Gear case study shows the potential to apply technological differentiated powder metal (PM) gears for electrified transmissions. Starting with a system engineering discussion on the eDrive application, a complete process development has been successfully executed, being now ready to apply PM Gears for eDrive applications. Additionally a holistic testing approach on component and system level to improve the NVH behavior opens further potential to integrate PM Gears in current and future transmissions. Figure 12.

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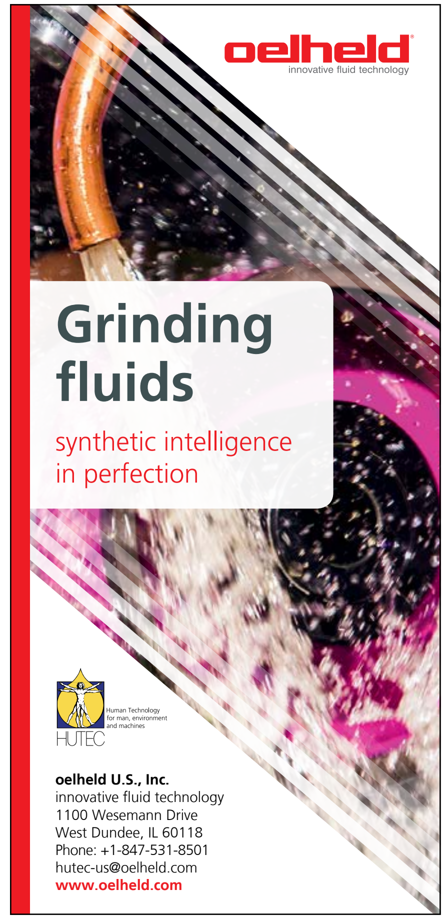
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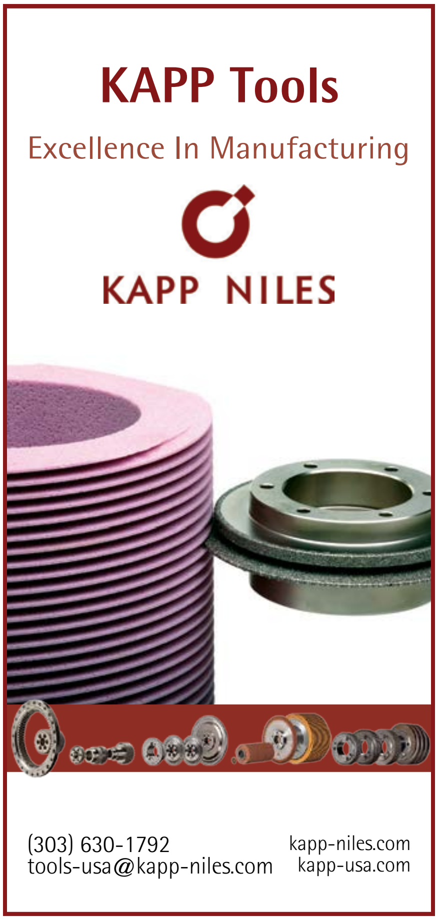
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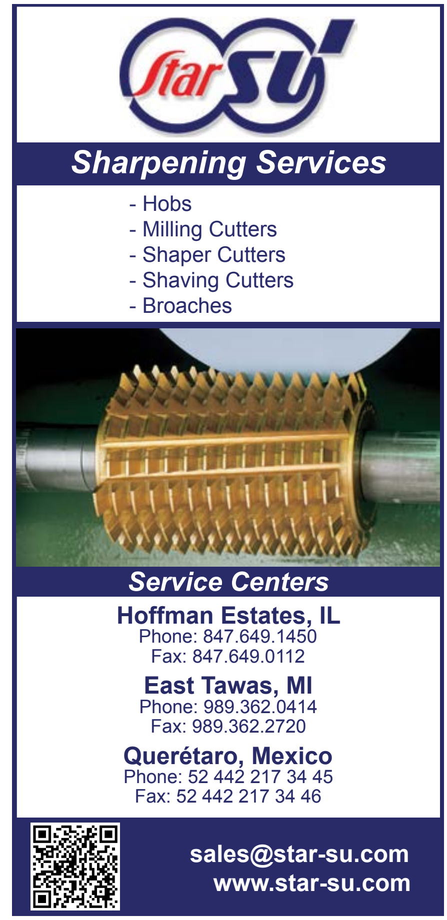
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Lubrication: Viscosity and Macropitting

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QUESTION

Is the ISO VG 320 adequate, or should a higher viscosity grade be used? How can we stop macropitting in gear teeth?

Expert response provided by Robert Errichello:

Given data

- Slowest speed gear in a gear train is 0.71 m/s pitchline velocity.
- Oil application is pressure-fed circulating system.
- Oil type is mineral (SERVOMESH EE 320).
- The product data sheet (PDS) for SERVOMESH EE 320 lists ISO VG 320, VI = 90, and pour point = –3°C.

Select oil viscosity

The first step is to ensure that the oil viscosity conforms to the requirements of ANSI/AGMA 9005-F16 (Ref. 1). Table 1 shows recommended viscosity versus operating temperature for a pitchline velocity of 1.0–2.5 m/s (lowest velocity given by ANSI/AGMA 9005-F16 (Ref. 1)). Table 1 applies to a mineral oil with a viscosity index (VI) = 90.

Table 1 Recommended viscosity (excerpted from ANSI/AGMA 9005-F16 Table B.1)

Operating temperature (°C)	Viscosity grade (cSt at 40°C)
50	320
55-60	460
65	680

Information provided courtesy of AGMA.

Definitions

- Ambient temperature is the dry bulb air temperature in the immediate vicinity of the installed gears.
- Operating temperature is the bulk oil operating temperature (temperature of the oil supplied to the gear teeth).

Discussion of viscosity

Table 1 shows that ISO VG 320 is adequate if the operating temperature is $\leq$50°C. However, such a low operating temperature will likely require a cooler. A more typical operating temperature is 65°C, which requires ISO VG 680.

Check pour point

The next step is to ensure that the pour point of the oil is at least 5°C below the minimum expected ambient temperature at startup. The PDS for SERVOMESH EE 320 lists pour points of –3°C for ISO VG 320 to ISO VG 680. Therefore, the minimum expected ambient temperature should not be less than 2°C. If lower startup temperatures are expected, you should use oil with the required viscosity but a lower pour point such as a synthetic polyalphaolefin (PAO), or use a heater to heat the oil prior to startup.

Reduce risk of macropitting

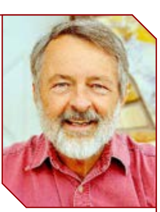
- ANSI/AGMA 1010-F14 (Ref. 2) recommends the following methods to reduce the risk of macropitting:
- Reduce Hertzian stresses by reducing loads or optimizing gear geometry;
- Use clean steel, properly heat treated to high surface hardness, preferably by carburizing;
- Use smooth tooth surfaces produced by careful grinding, honing, or polishing;
- Use an adequate amount of cool, clean and dry (free of water) lubricant of adequate viscosity;
- For surface hardened gearing, ensure adequate surface hardness and case depth after final processing. Note that excessive surface hardness may lead to other problems, such as risk of grinding cracks.

Other considerations

Be sure to consider other criteria that are affected by oil viscosity such as pumpability, efficiency, and operating temperature. See ANSI/AGMA 9005-F16 (Ref. 1) for further information.

References

ANSI/AGMA 9005-F16, "American National Standard- Industrial Gear Lubrication," AGMA (2016).
ANSI/AGMA 1010-F14, "American National Standard- Appearance of Gear Teeth- Terminology of Wear and Failure," AGMA (2014).



Robert Errichello, PE, is a founder of GEARTECH Software, Inc. A longtime contributor to Gear Technology magazine and a Gear Technology Technical Editor, he has for more than 30 years worked or consulted for several gear companies, and has taught courses in material science, fracture mechanics, vibration and machine design at San Francisco State University and the University of California at Berkeley. He is also a member of ASM International, STLE, ASME Power Transmission and Gearing Committee, AGMA Gear Rating Committee and the AGMA/AWEA Wind Turbine Committee. Errichello has published dozens of articles on design, analysis and the application of gears, and is the author of three widely used computer programs for the design and analysis of gears.

Powder Metal through the Process Steps

Anders Flodin

Powder metal (PM) gears normally sell due to the lower cost and their relatively high mechanical performance. The reason behind the lower cost is that most of the machining is omitted due to the net-shape forming process. So how net-shape are powder metal gears? In this article some hard-to-find information about the tolerances through the manufacturing steps will be presented.

The powder metal gear manufacturing processes are quite different from traditional-cut gears. The hard finishing process is identical, but heat treatment and prior processes are very different. For cut gears, the tolerances given by each process are well known — but for powder metal gears this is not common knowledge.

The powder metal process for the analyzed gear in this article is:

Compaction-sinter-case carburize-and grinding (threaded wheel)

Experimental background:

- Material composition: Astaloy Mo + 0.3% C-UF4 + 0.65% lube HD
- 10 gears were individually marked and measured as:
  - ¤ Green
  - ¤ Sintered
  - ¤ Case hardened
- Compaction pressure: 700 MPa, green density: 7.21 g/cm^3
- Sintering conditions: 1,120°C, 30 min 90/10 N_2/H_2 in a laboratory belt furnace Cremer CBS25-115/e; the gears were placed on flat Al_2O_3 trays during the sintering
- Case hardening by gas carburizing and oil quenching; carburizing at 920°C, Cp 1%, 40 min.; tempering at 180°C, 30 min
- Gears were finish ground by gear maker Swepart using a Reishauer threaded wheel gear grinder
- The ground gears were measured both by a Zeiss DuraMax 5/5/5 coordinate measurement machine (CMM) equipped with software "*GEAR PRO involute*" and by a Klingelnberg P40
- The green, sintered and case hardened gears were only measured by the Zeiss DuraMax 5/5/5
- Zeiss reports quality class for all parameters; only Klingelnberg reported quality class for lead profile parameters
- As compacted gears (and by that also the sintered and heat treated gears) have 0.1 mm grinding stock or protuberance added to the involute
- For measurement of the involute profile and lead profile, the highest number of four measured teeth is presented as a "worst-case scenario"
- In the measurement by the Zeiss "*GEAR PRO involute*," the same four teeth (front, left, back and right from the pressing direction) were measured after each processing step

Figure 1 PM-optimized pinion used in the investigation.

The compacted gear geometry is the 4:th drive gear in a 6-speed manual transmission (Fig. 1).

The right flank has a helix angle modification of-60 µm, which causes problems for the Zeiss CMM but is correctly handled by the Klingelnberg (Fig. 2). The traces in Figure 2 are the desired end result in the lead direction after grinding.

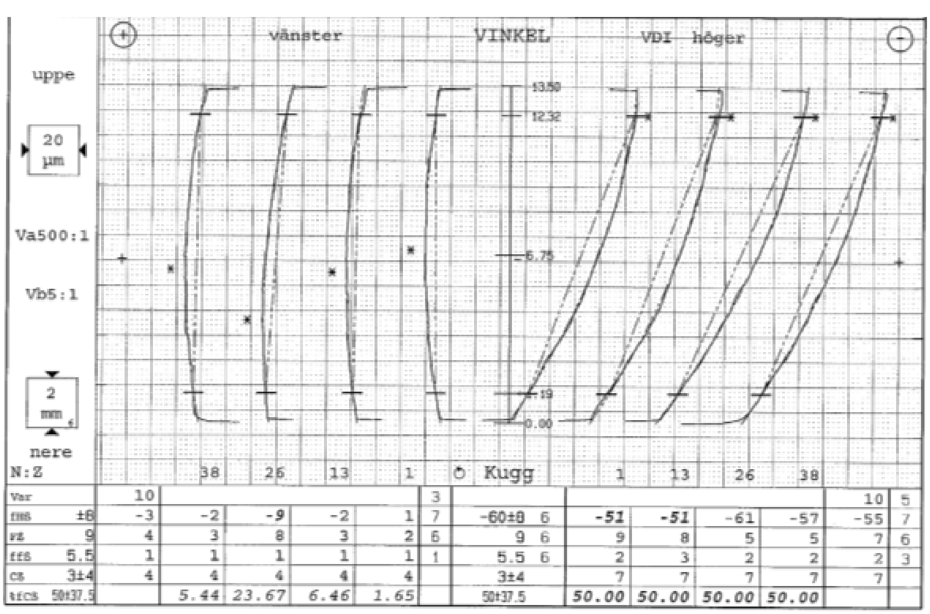


Figure 2 Measurement chart from the Klingelnberg P40; a 3 ± 4 µm lead crowning is also introduced by the grinding.

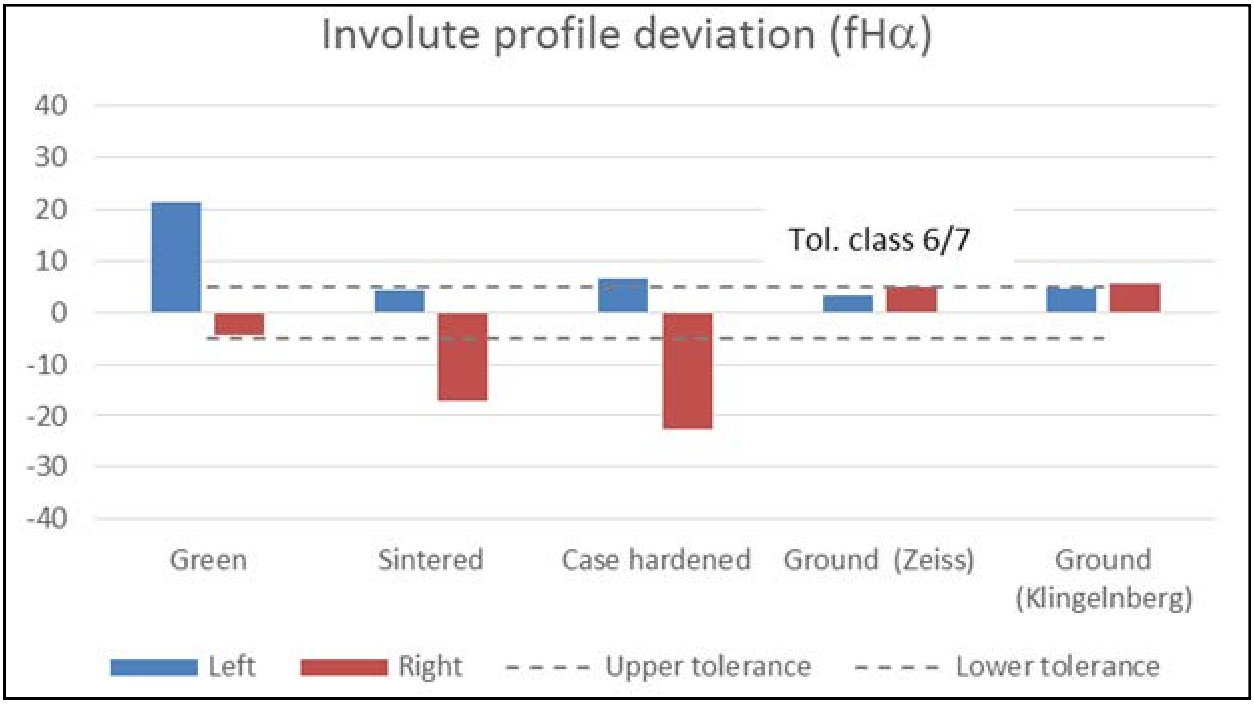


Figure 3 **Involute profile deviation.**

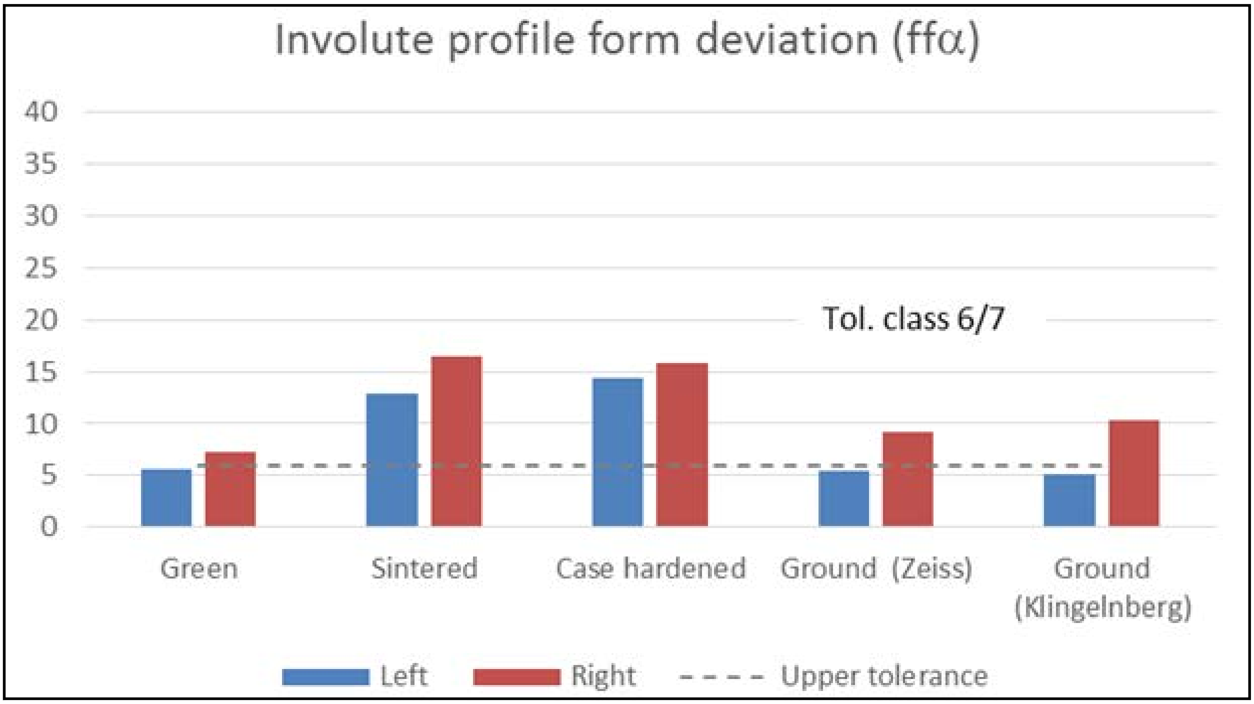


Figure 4 **Involute profile form deviation looks at the waviness of the surface; in this case the data is misrepresenting the waviness since powder particles got stuck on the surface before sintering.**

Result

The presented results use the ISO nomenclature. The worst results are presented in the following graphs, from 4 teeth on each of the 10 gears. This means that data in the bar diagrams are averaged over 10 gears; the worst of the teeth from every gear is selected. The numbers are chosen as a worst-case scenario so that an overly positive picture of the results are presented.

Involute Deviation

The involute profile deviation demonstrates a large movement going from green to sintered, while subsequent case carburizing does not change the shape nearly as much (Fig. 3).

The involute profile form deviation is very good in the green state, but the sintering deteriorates the profile significantly. The reasons for that are complex, but, for example, stress relieving and phase transformations are two influencers.

However, in this study it is actually powder particles that stuck to the flank,

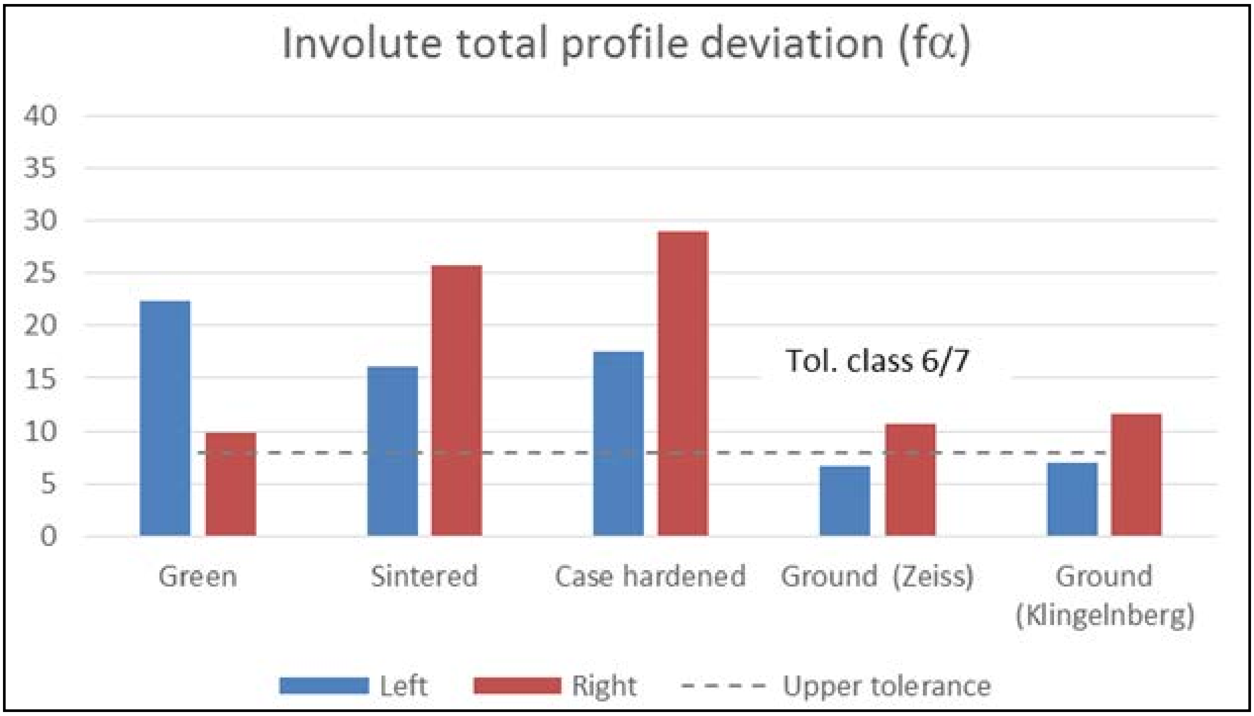


Figure 5 **Involute total profile deviation is the combined angular error and waviness error in Figures 3 and 4.**

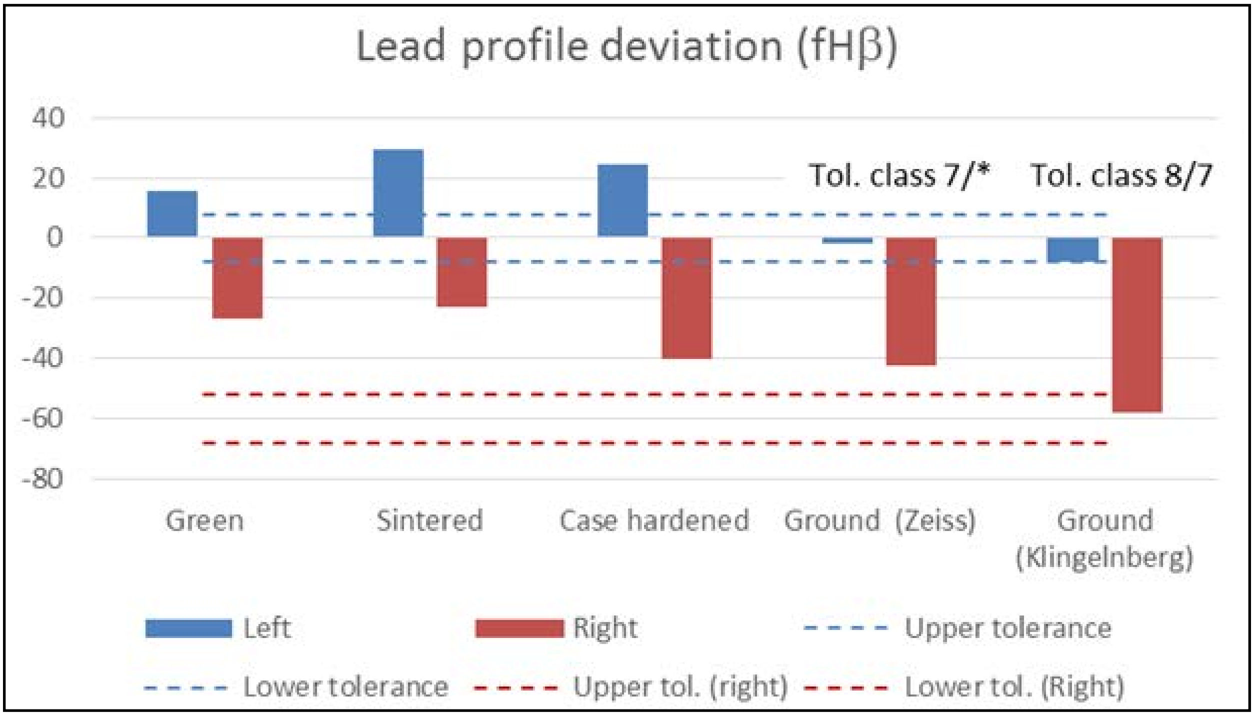


Figure 6 **Lead profile deviation.**

and the ball tip probe is bouncing off those particles. The carburizing does very little to the deviation, and any geometric changes that are contributed by the carburizing are masked by those powder particles on the surface. The right flank is actually out of tolerances after grinding — which can be remedied and should not be blamed on the material.

These two deviations are combined into the total profile deviation and displayed n Figure 5.

The errors on the profile form deviation influence the result in Figure 5, since it overshadows the profile error or waviness error.

Lead Deviation

The lead profile deviation parameter is the equivalent to the involute profile deviation error but in the lead direction. The right flank has a 60 µm modification which is not captured correctly by the Zeiss machine so the reader has to disregard that bar in Figure 6. The Klingelnberg can handle this modification and after grinding the teeth are within tolerances.

Figure 7 depicts the lead profile form deviations. Here as well is the result

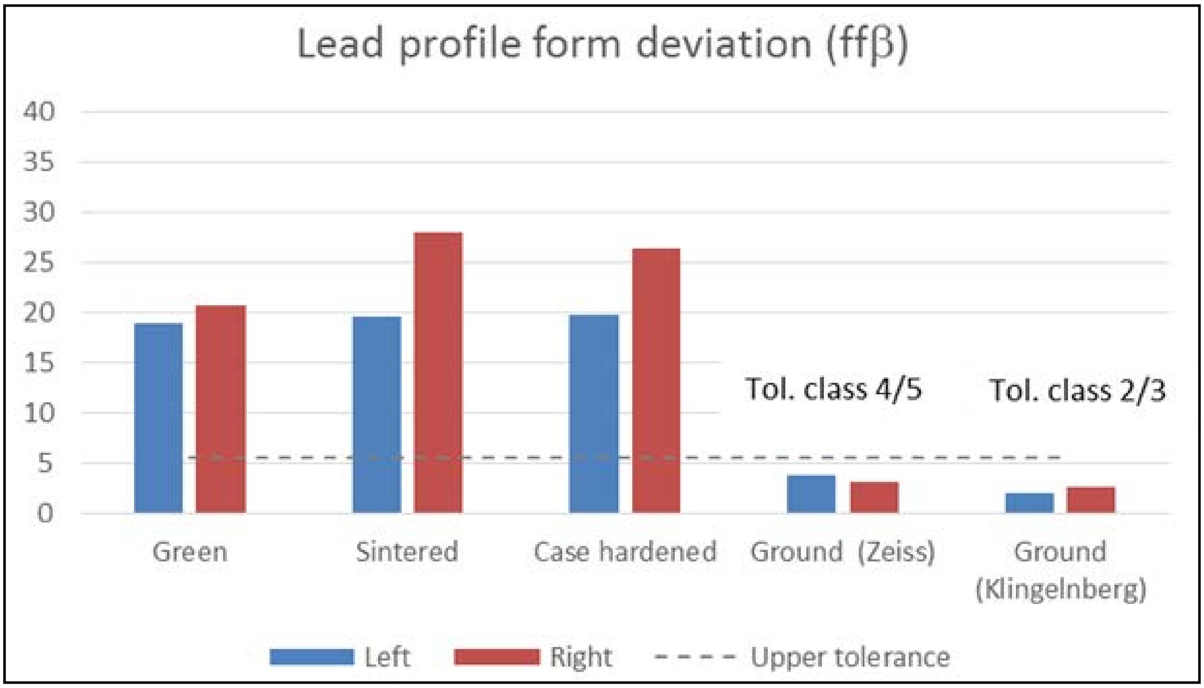


Figure 7 **Lead profile form deviation; the poor geometry in green, sintered and case hardened is an artifact created by powder particles stuck on the flanks.**

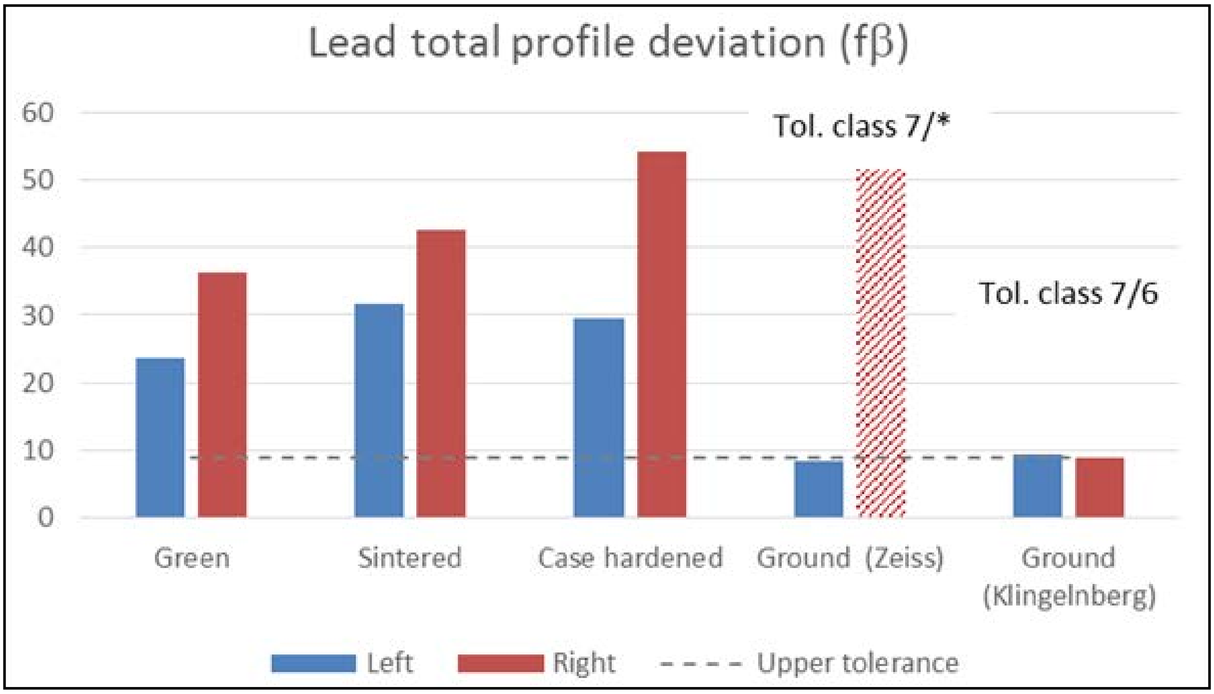


Figure 8 **Lead total profile deviation; within tolerances after grinding; deviations before grinding are partly due to powder particles stuck on the flank and not the actual error in the lead profile.**

influenced by residual powder grains on the flanks. After grinding the profiles are within tolerance.

When lead profile form and profile deviation are combined the total lead profile error is formed. In Figure 8 it can be seen that after grinding the profile is within specification. The bar measured by the Zeiss is hatched since it is incorrect.

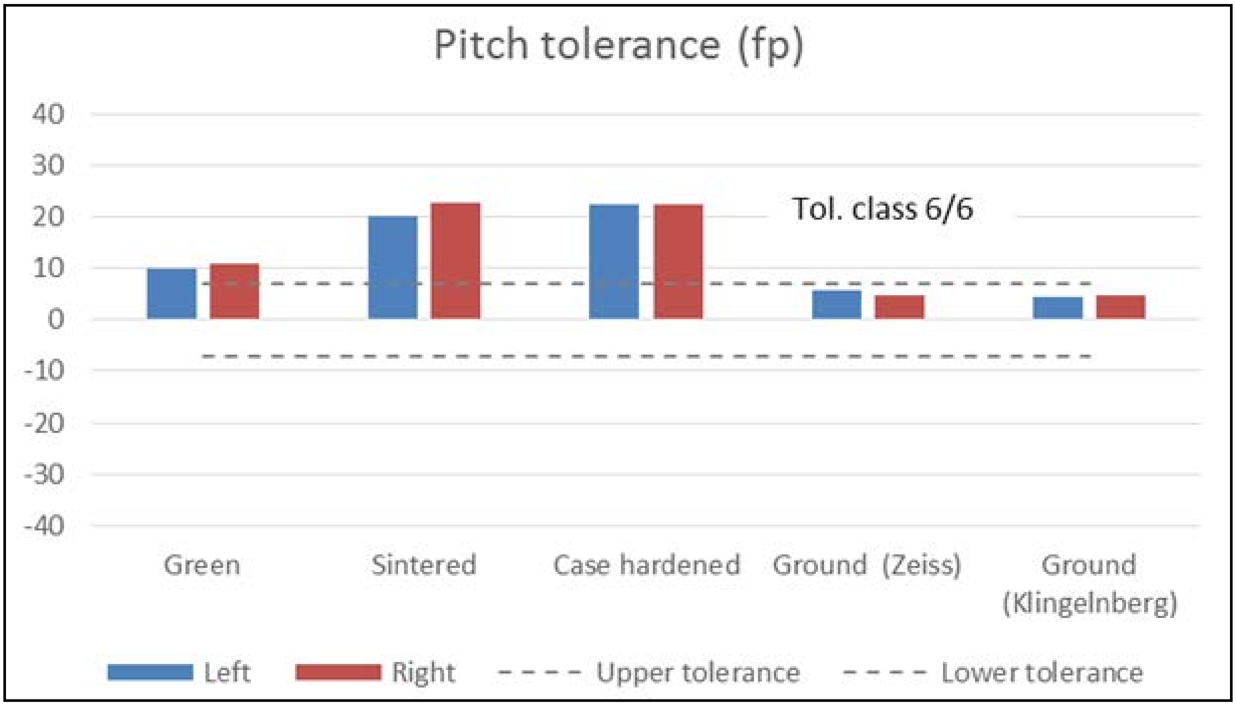


Figure 9 **Maximum single pitch deviation.**

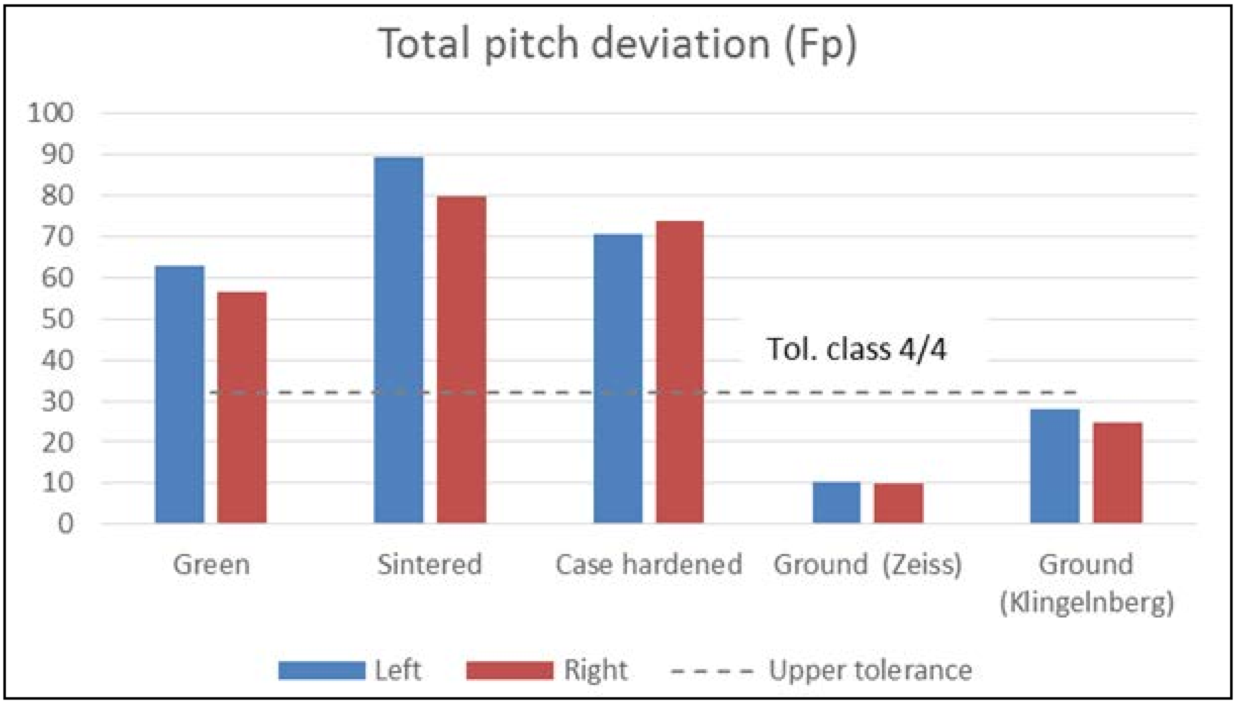


Figure 10 **Total pitch deviation.**

Pitch Deviation

The maximum single-pitch deviation is shown (Fig. 9). In the green state the deviation is very small; it grows predominantly during sintering and then less so in the following case carburizing process. After grinding, the gears are within tolerances. The total or cumulative pitch deviation is depicted in Figure 10; it follows the same pattern as the pitch tolerance in Figure 9.

The adjacent pitch deviation which measures the biggest pitch error between 2 teeth on the gear is shown in figure 11. The same trend as before can be seen with the biggest step in error being caused by the sintering process. Again, the grinding operation saves the day.

Runout

Radial runout and powder metal gears require some extra explanation. In a PM compaction tool there are a number of different parts. Since there is clearance in the radial direction between the different parts — or punches — there will be some play, and during the compaction stroke the different parts will be pushed in different directions. Here the worst-case scenario is that all the parts are pushed in one direction and the clearances line up radially — creating a large runout. In the gear under investigation (Fig. 1) there

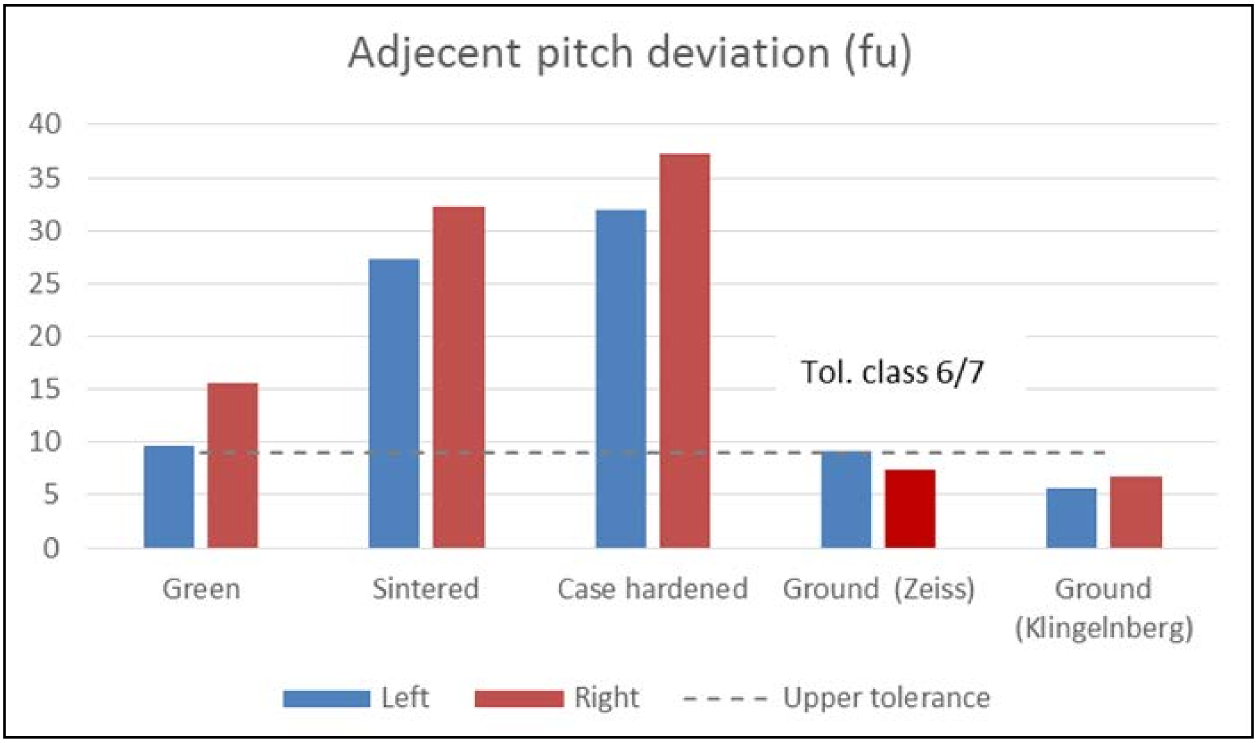


Figure 11 **Adjacent pitch deviation.**

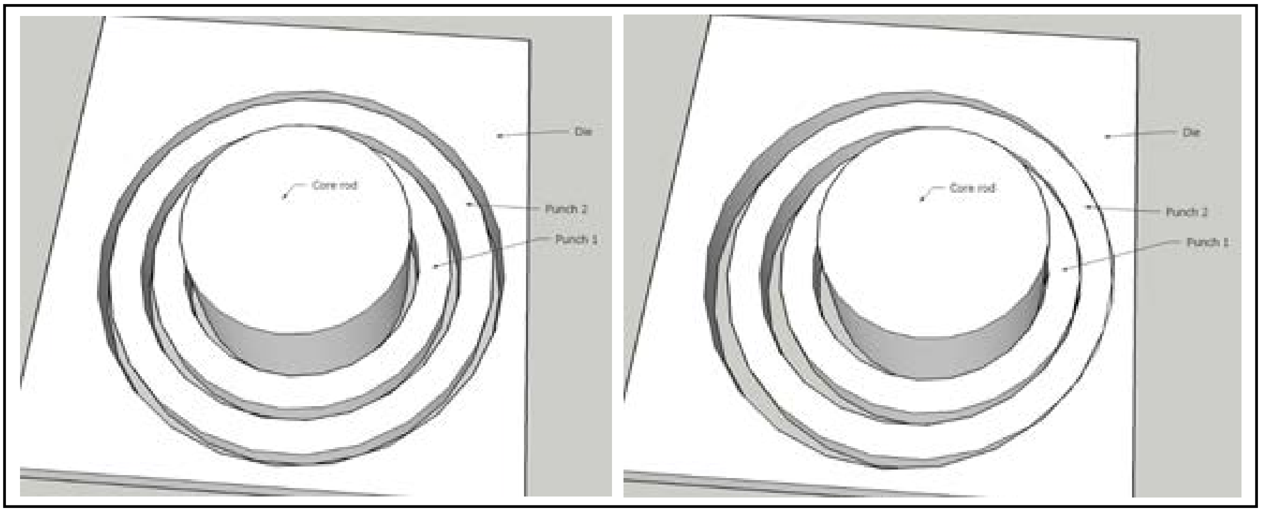


Figure 12 **Left: simple tool with concentric part; right: clearances stacked in one direction.**

are 3 punches plus the core rod forming the spline. This is a very advanced tool, as it creates the sum of 4 clearances — plus elastic spring-back and plastic deformation of the particles — as the theoretical run out. A very simple tool consisting of only one punch and no core rod will then have significantly less radial runout since it will consist of only the clearance between the one punch and the die (Fig. 12). In (Fig. 12, left) is a simple tool with core rod, 2 punches and a die. All tool parts are concentric, with tool clearances of course greatly exaggerated. In (Fig. 12, right) we see a worst-case where all the clearances line up and the core rod is offset with the sum of clearances creating runout and spacing errors in the measurement protocols. The maximum stacked clearance in the tool is 65 µm.

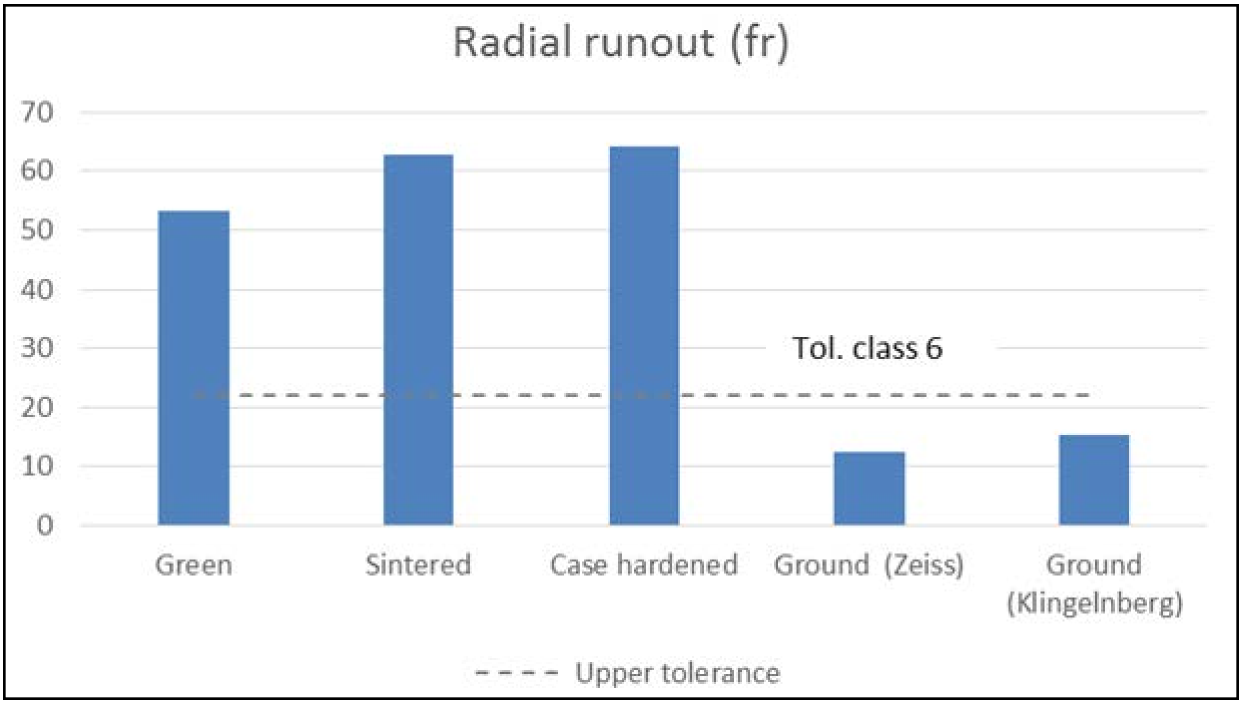


Figure 13 Radial runout.

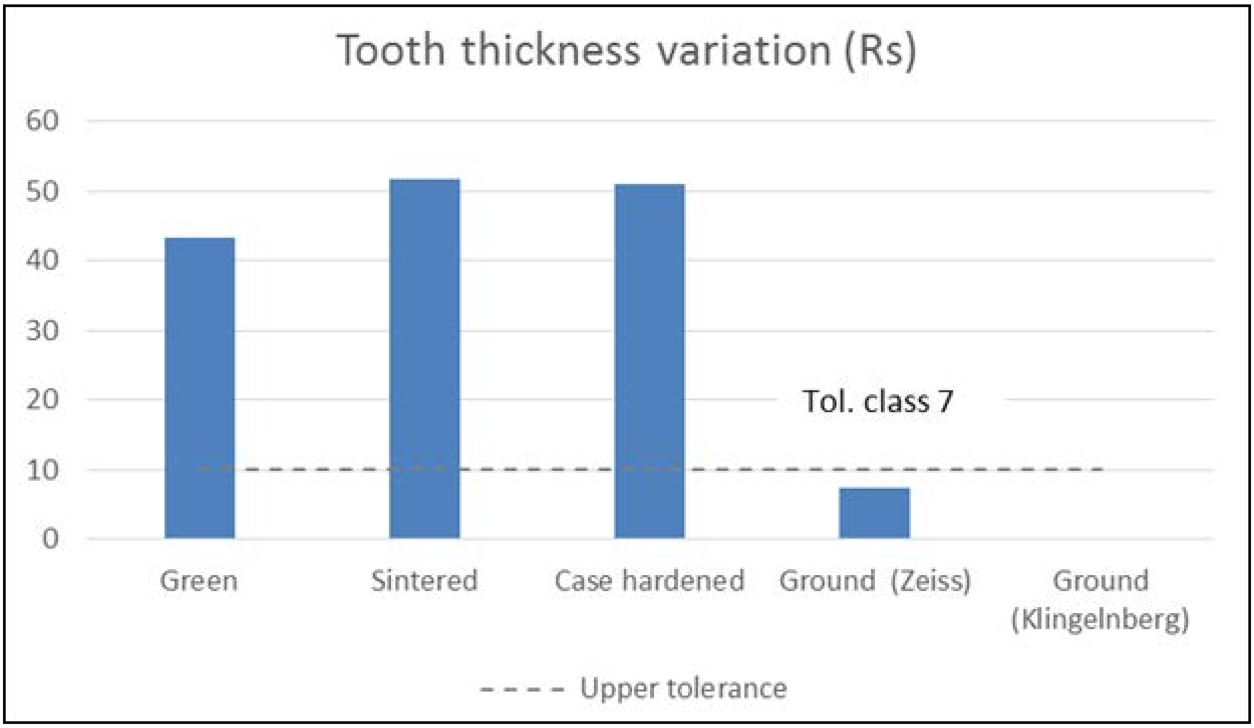


Figure 14 Tooth thickness.

Radial Runout

The radial runout follows the previous pattern of deterioration, with heat and the biggest drop in tolerance coming from the sintering (Fig. 13). However, the grinding will return the runout to within tolerances. One important fact is that this gear has a compacted internal spline and therefore can't be ground in the bore. Thus the runout is never worse than what can be repaired in the grinding. If that wasn't the case, then the net-shape capability of powder metal forming the spline would not be useful.

The tooth thickness deviation is also connected to the runout and how centered the bore is on the gear (Fig. 14).

The tooth thickness shows a similar development through the process steps, as the runout with an initially large discrepancy between actual and nominal value. With a simpler tool using less punches, the actual and nominal values would be closer.

The tip diameter changes as well during heat treatment. This parameter will also be influenced by the runout. As can be seen (Fig. 15) the diameter will be within specification after grinding. If the tip diameter is too low or too high,

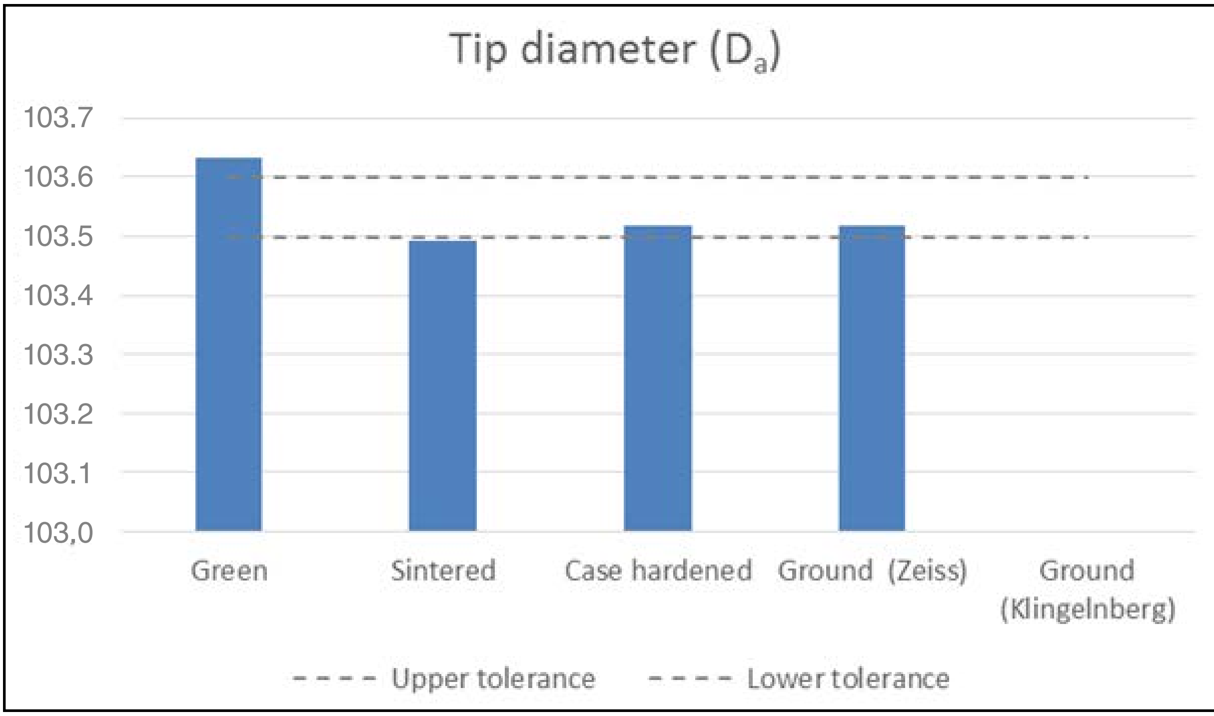


Figure 15 **Tip diameter; not measured in the Klingelnberg.**

there are ways to shrink and grow a part slightly in the sintering furnace. How this is done is not part of this paper, but one question that might come up is: If a die is cut and the gears turn out too small by a couple of tens of microns, does the die have to scrapped? The answer to that is no, there are ways using the material and sintering to correct such problems. Improving the runout without grinding is more difficult; it can be improved, but it can't be fixed all together.

Summary and Conclusions

An automotive gear in a 6-speed manual transmission has been manufactured using powder metal manufacturing technology. The tool consisted of 3 upper and 3 lower punches, plus a core rod and a die. The tool can be considered to be very advanced and, due to the number of punches and the core rod, it is also a tool where higher deviations can be expected. The goal of the investigation was to determine the tolerance classes after each manufacturing step, and if the deviation could be remedied with the final grinding without grinding the bore where a spline has been net-shape-compacted.

The findings are that the tolerances deteriorated predominantly in the sintering step. The case carburization using conventional oil quenching contributes further to the deviation — but not as much as the sintering. In some cases the case carburize process reduces the deviation, but no conclusions should be made from those observations where that occurred. The final grinding of the flanks returns the tolerances back to ISO 6-7 which is the nominal value. The data presented is taken as a combined worst case out of 10 gears. A combined low pressure sintering and case carburizing process using a controlled step quench is known to further reduce the deviations (Ref. 1).

(*The author wishes to acknowledge Mats Larsson and Mikael Dahlberg at Höganäs AB Sweden for performing all the experimentation, work, and documentation in this study — enabling this article to be written.*)

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1. Andersson, O. "Shape Distortion and Tooth Root Bending Fatigue Strength Obtainable with Various Hardening Process Routes of Ring Gears Made of PM Material," 2018, *Proceedings World Powder Metal Conference* (2018), Beijing, China.

Anders Flodin is Business Development Manager Powertrain at Höganäs AB. His background is in mechanical engineering, having received his Ph.D. in 2000 on the topic of simulation of wear on gear flanks. Since 2000 Flodin has worked on various gear-related assignments in the fields of aerospace, ship propulsion and automotive drivelines.

For more information.
Have questions or comments regarding this technical paper? Contact Hoganas AB's Anders Flodin at *anders.flodin@hoganas.com*.

First Part Right—Fiction or Reality?

Dr. Hermann J. Stadtfeld

Introduction

The manufacture of spiral bevel and hypoid gears is considered one of the most complex metal cutting operations in the industry. Many factors contribute to the accuracy of the flank surfaces. In the early 1980s, when the *G-AGE* correction software was introduced, it was possible, for the first time, to employ a closed correction loop. Before that, so-called proportional changes helped to make approximate changes, which after many trials resulted in a good part. But with the *G-AGE* closed loop correction software it was now possible—with basically one single correction step—to eliminate 80% to 95% of the practical influences from the machines, the workholding, and the cutting tool.

With the manufacturing of spiral bevel and hypoid gears in larger batches, it seems widely accepted that several development parts are required in order to match the theoretically developed geometry. If the once-developed gearset is repeated at a later time, the first-cut part in many cases does not reflect the theoretically developed geometry; the reasons in both cases are related to the cutting machines and the cutting tools.

Today's understanding of lean manufacturing—and the generalized quality teachings of "do it right the first time"—makes it difficult to accept that still some development parts continue to be required—especially for environmentally aware manufacturers.

This paper analyzes the different influences of the deviations between nominal and actual geometry for a first-cut bevel gear. In each section, the customary tolerances are quantified and the possibilities to reduce them are discussed.

The Influence of the Cutting Machine to Workpiece Accuracy

Gaging of the cutting machine like the Phoenix II 600HC (Fig. 1) is an important task that must be repeated after each incident on the machine between cutter head and part. Plunging with the wrong index position, prompting such blades into an aggressive first-cutting contact with the part, or worse—even situations where one or several blades breaking might require a re-gaging of the machine.

A gaged machine achieves axes positioning in the single micron range accuracy. Every part, based on its design specifications, is cut with axes positions that differ from the gaging position. All tolerances of machine components such as rails and trucks, bearings, ball screws and encoders, as well as the interface surfaces of frame and spindle housing castings, accumulate error commensurate with the distance of the axis position away from the gaging position. Six-axes, free-form machines also have kinematical deviations depending on the axes speeds and the combination of three linear and two or three rotational axes. The machine fingerprint commonly causes flank form errors between 0.010mm and 0.020mm.

The accumulated machine deviations that require specific corrections for one particular gear design are commonly called the "machine fingerprint." If the workholding and the cutting tool have no deviations from the nominal specification, then the nominal, actual deviation plot of the first-cut part from a CMM represents this machine finger print. Each CMM-based machine fingerprint is linked to a corresponding set of *G-AGE* corrections. The *G-AGE* corrections, which represent the machine fingerprint, could be stored in the respective machine

Figure 1 Influences to absolute part accuracy from the cutting machine.

and be superimposed on the theoretical settings of each new job.

In most cases, the final touches to the contact geometry of a bevel and hypoid gear development are made between roll tester and cutting machine. After such a "Gear-Lab" development is finished, the developed machine settings still include the machine fingerprint. If the machine fingerprint is known for a similar job, then this set of fingerprint corrections could be subtracted from the newly developed basic settings, which results in machine-independent settings. Those settings can be stored on the network and sent to any different machine at a later time for the repeated manufacture of this job. In this case the machine receiving the machine-independent settings will superimpose the newly received settings with the fingerprint for cutting this particular job.

Because each job has a unique set of fingerprint corrections, the basic data of a large number of gearsets must be stored in a database — together with the fingerprint corrections of every machine on which they have been cut; every new job sent to a particular machine will activate a data mining tool. Even though the new job has never been cut on any of the machines, the data mining tool will apply a list of similar criteria and find a set of fingerprint corrections for the new job in combination with the selected machine, thus assuring that the flank surfaces of first-cut parts fall within the specified tolerances.

Workholding influences. Workholding (Fig. 2) can introduce runout or part slippage. Influence to the flank surface geometry is basically limited to differences between the labeled arbor distance and the real value. It is possible that the axial draw, depending on the condition of an arbor, changes the effective arbor distance by small amounts.

Cutter head influence to work gear accuracy. Slot bottom radii of cutter heads have a certain tolerance that influences the actual point radius of the cutter head. Commonly, Gleason cutter heads are held in a tight tolerance band. The ability to measure the absolute radial blade position in a cutter head is limited due to a number of factors.

The following procedure is required to predict the radial location of the corner point between top width and blade distance (Fig. 3, left):

The tip of the blade must be captured — not at its high point — but at the blend of the tip edge radius to the top slope. Then the cutting edge must be scanned and approximated with a circular function. This function must then be extrapolated to intersect with the horizontal tangent to the blend point — between top slope and tip edge radius — because the corner point between top width and blade distance is virtual, as it physically does not exist (Ref. 1). The distance between the virtual corner point and the cutter axis is the point radius of the cutter head as it is specified in the summary. The possible measurement accuracy of a stick blade mounted in a cutter head in connection with the extrapolation can only deliver accuracies in the range of ±0.006 mm.

Stick blade seating. The seating between stick blade and cutter head slot introduces potential for radial errors that are minimized by the prismatic seating surfaces of the Pentac cutter heads. The blade seating can introduce radial

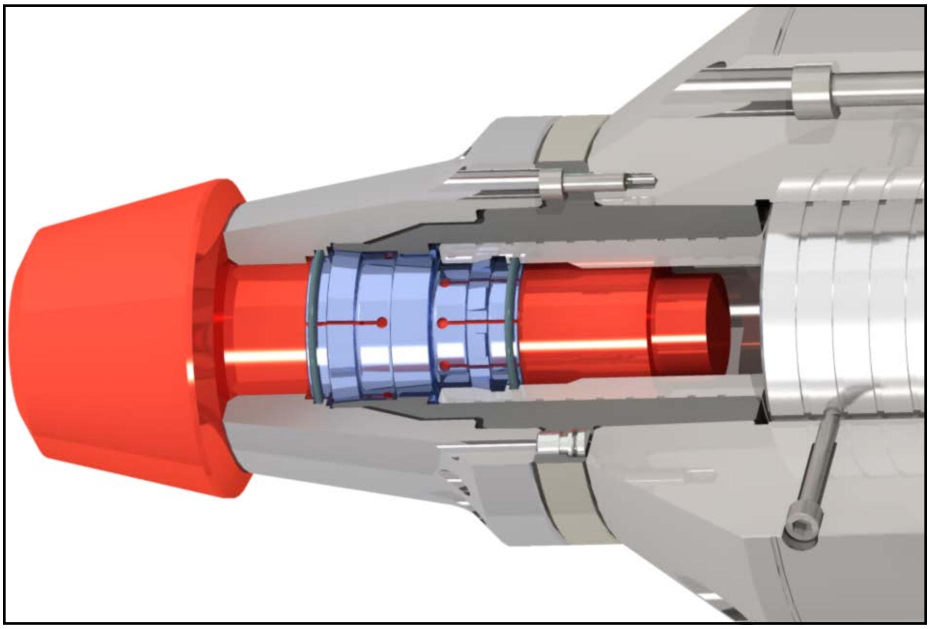

Figure 2 Influence to absolute part accuracy from workholding.

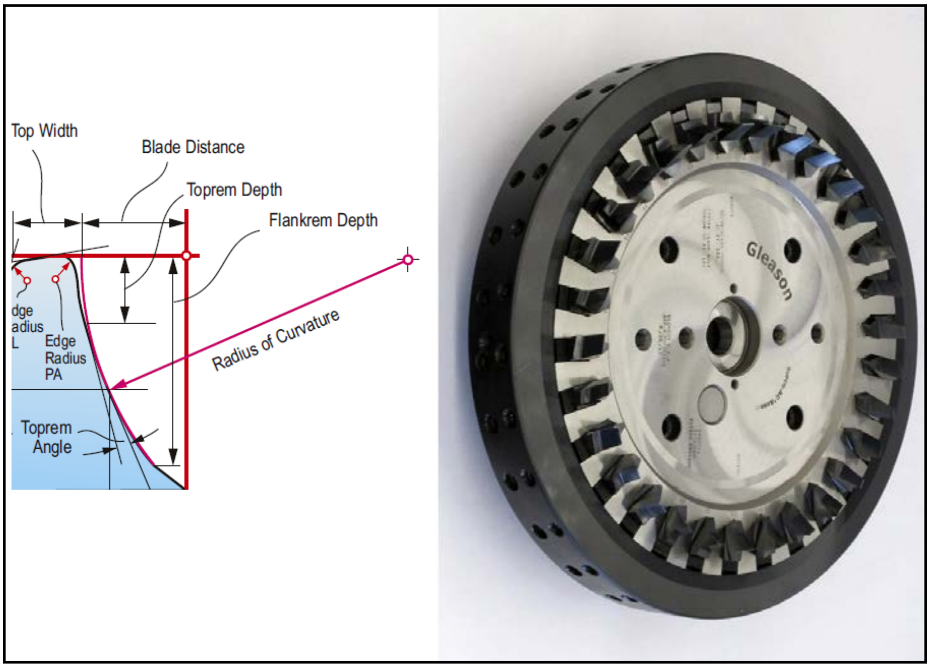

Figure 3 Influence to absolute part accuracy from cutter head.

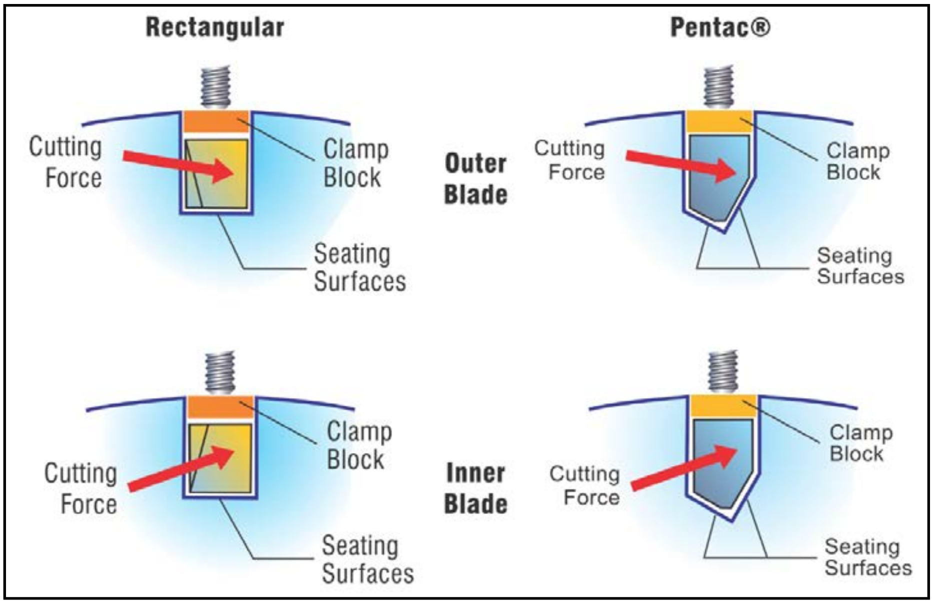

Figure 4 Influence to absolute part accuracy from blade seating conditions.

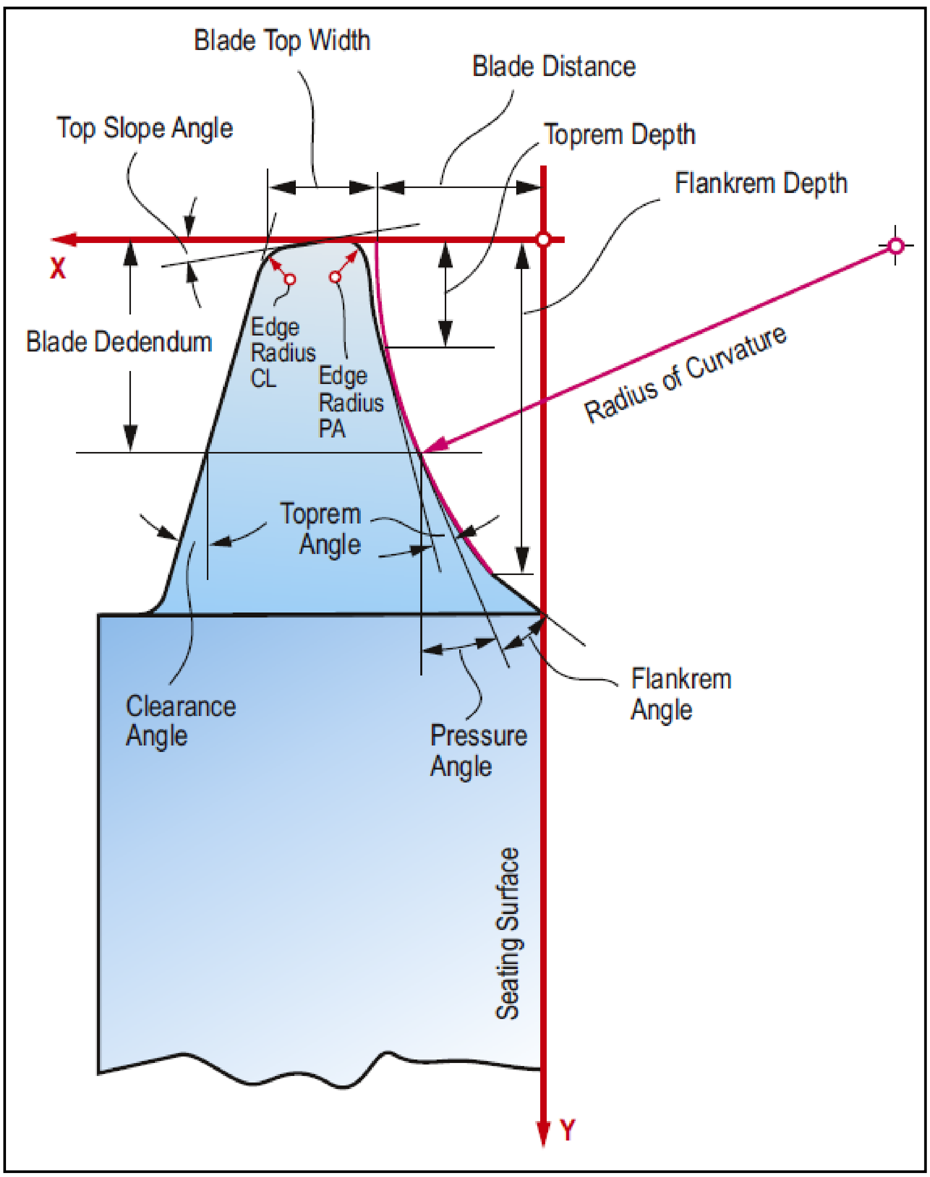

Figure 5 Influence to absolute part accuracy from blade geometry deviations.

dislocation of the blades in the single-micron range; often it is perceived to average out between all the blades of one set. In the case of Formate ring gears, this is incorrect because the "high blade" takes the last chip and leaves its influence on the entire flank form. Blades sticks are not perfectly straight, which causes the blade tips to vary. This variation can be eliminated with radial, truable cutter heads, which, however, will influence the cutter point radius in the 0.010 mm range.

Stick blade geometry. Regarding the blade definitions provided in Figure 5, the pressure angle and the blade distance are the relevant features that assure accurate flank geometry of the manufactured gears. Blade distance and pressure angle of ground stick blades have to be within a certain tolerance. In particular, in the case of curved blades, the deviations between the real blade and the theoretical blade have allowable deviations in pressure angle of 0.05° and in blade distance of 0.015 mm. The BPG blade grinding machine and the GBX measurement machine can assure finish deviations below this magnitude.

Blade grinding measurement and correction. Blade grinding accuracy is influenced by the frequency of machine gaging, grinding wheel dressing, and the condition of the blade clamping fixture. Also, if blades are close to their kill length, the accuracy of the blade geometry is reduced significantly. The closed loop in Figure 6 assures precise blades in the range of less than 0.005 mm — well below the tolerances specified in the last paragraph. However, there may be variations within one set in the magnitude of 0.015 mm and, as mentioned above, the "high blade" will dictate the final part geometry — especially in Formate (Ref. 2).

Blade measurement strategy. The question of measuring the blades on the GBX blade measurement machine on the cutting edge or below the cutting edge can be answered rather easily if geometrical conditions between cutting edge and the spherical tip of the probe in Figure 7 are observed. It becomes evident (Fig. 7) that a measurement between the cutting edge and the measurement sphere results in a metastable condition. This metastable condition degrades if an attempt is made to measure above the cutting edge (red dashed path in Fig. 7). Because of the tolerance of the front face, the effective path of the probe tip versus the cutting edge will be inclined, which is shown exaggerated (Fig. 7).

The path of the measurement sphere will never be able to follow the cutting edge precisely — even if the front face is measured before the cutting edge scanning. In the case of three-face blades, this is even more significant because of the slightly curved front face, which is approximated in the *GABE* software with a plane.

A measurement of 0.005 mm or even more below the cutting edge will provide stable contact conditions between the side relief surface and the measurement sphere. The small differences in blade distance direction due to the side relief angle are compensated by the *GABE* software.

Cutter building. Deviations in overall cutter height (Fig. 8) are the only obvious cause of part inaccuracies. Due to the procedure in cutter build machines like the Phoenix CB or the 500CB, inaccuracies in cutter head thickness are entirely filtered out. The blades are built to the overall cutter height, which reference the blade tip directly to the mounting interface between cutter head and cutting machine spindle.

Figure 6 Influence to absolute part accuracy from blade grinding and measurement.

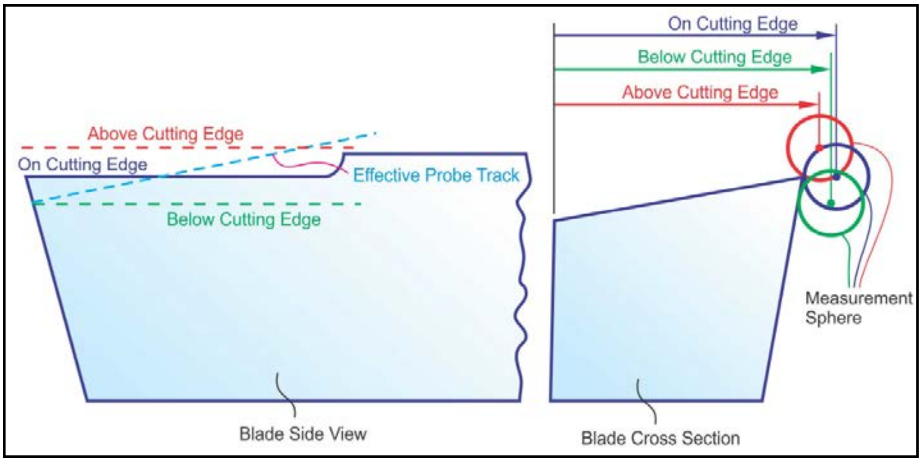

Figure 7 Influence to absolute part accuracy from blade measurement strategy.

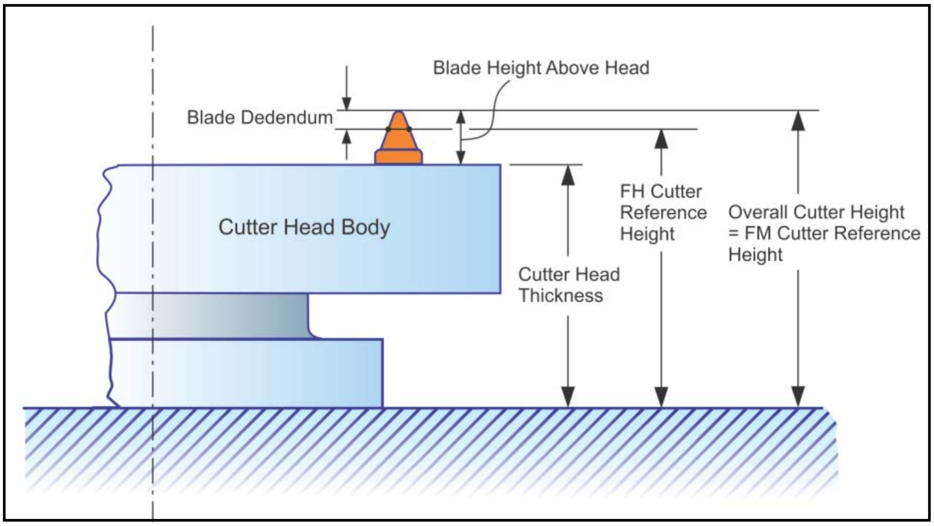

Figure 8 Influence to absolute part accuracy from cutter head building.

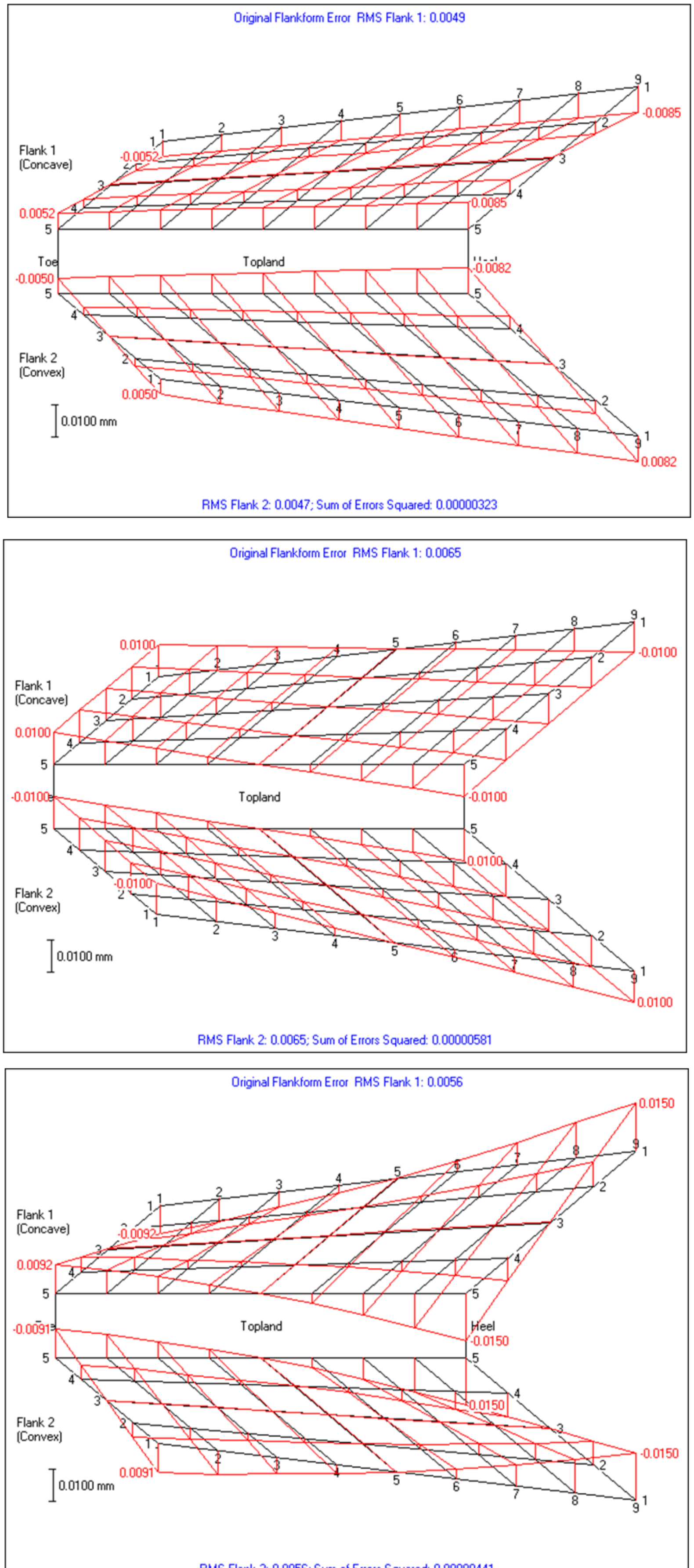

Figure 9 Flank form deviations resulting from machine fingerprint.

Summary of all Workpiece Accuracy Contributing Factors

In this final paragraph, the different flank form errors caused by the single deviations discussed above are modeled with *G-AGE4Win* order to quantify the different sources of deviations (Ref. 3).

Cutting machine errors can be expressed in components that lead to spiral angle errors, pressure angle errors and higher-order errors (Fig. 9).

The workholding can be neglected because — even after re-work — it is always possible to adjust the distance value to the actual number.

The blade pressure angle in the case of a deviation of 0.05° will cause a flank form deviation between 0.020 mm and 0.030 mm (Fig. 10).

The collective influence of the slot bottom radius tolerance and the blade distance deviation of blades ground within the recommended tolerance are shown (Fig. 11). Both the influence of the cutter head and the influence of the blade distance variation result in a length crowning error of 0.004 mm, as shown in the deviation plot.

In order to gain a statistically realistic overall deviation from nominal, caused by all machine and tool influences, the worst-case combination of the graphics in Figures 9, 10 and 11 are superimposed (which is an unrealistically high deviation) and then reduced to 60%. The result, shown in Figure 12, reflects the probable nominal-actual deviation if all elements of the manufacturing are within tolerance and no *G-AGE* correction has been made.

The graphics in Figure 12 show realistic results with a dominating pressure angle error on the concave side, and a dominating spiral angle error on the convex side. However, both sides contain elements of spiral angle error, pressure angle error and twist. The maximal corner point amplitudes are 0.029 mm and 0.026 mm.

If the manufacturing cutting machine is eliminated, then the remaining 60% deviation probability of the cutter head and blade influence are shown (Fig. 13); the maximal corner deviations are 0.021 mm for both sides.

One attempt to eliminate the cutting machine is to develop for a new design the ring gear and the pinion — each on a particular machine. However, the cutter head cannot be eliminated because, as shown above, even pressure angle errors can be caused by the cutting machine fingerprint. If the first part of a new batch (previously developed job) is measured against the nominal data in the theoretical CMM download file, then a certain "base load error" is already contained in the first-developed reference part; statistically, 60% of all occurring cutter deviation will add to the base load error of the development part. In other words, the cutter deviations were never separated from the machine deviations.

Philosophical or Rational Conclusion?

If it has been decided to always use the same machine for a particular pinion or gear, then the machine and cutting tool fingerprint is *partially* eliminated from the deviation graphic in Figure 12, because the developed machine summary contains both. This statement is correct if the last-developed summary — which was developed on the respective machine — is used to cut the first part of a new batch. Remaining errors in the nominal-actual CMM deviation plot are the only flaw. Those deviations are caused by the cutting machine, as well as by the cutting tool.

If a new cutter head with re-ground blades is used, the cutting tool fingerprint changes. Depending on the location of the developed blade geometry within the tolerance band, the next ground set of blades might fall at the opposite border of the tolerance band. Because the remaining nominal-actual CMM deviations contain part of the cutting machine fingerprint and part of the cutting tool fingerprint, the new cutter head and the new set of blades are confronted with this "base load error."

If a manufacturer permits ±2' of pressure angle error with a "base load error" of +1' and a tolerance of blade grinding of ±1.5', then the realistic likelihood of cutting a good first part is 50%. But it is more realistic that small, additional machine-inflicted deviations, plus additional deviations from the use of a different cutter head, will reduce the likelihood of a good first part to 25%.

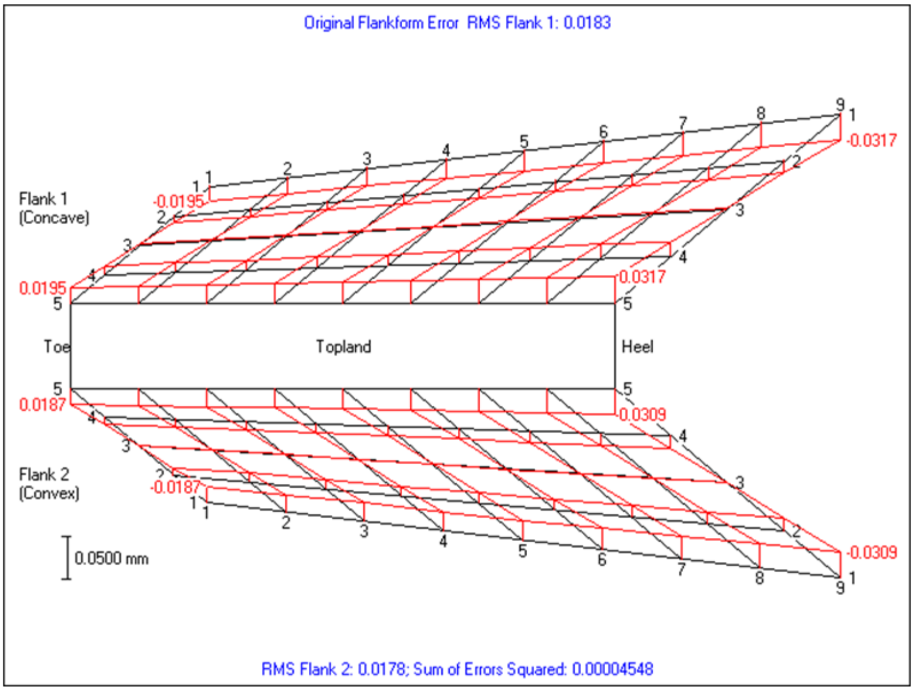

Figure10 Flank form errors resulting from blade pressure angle deviations.

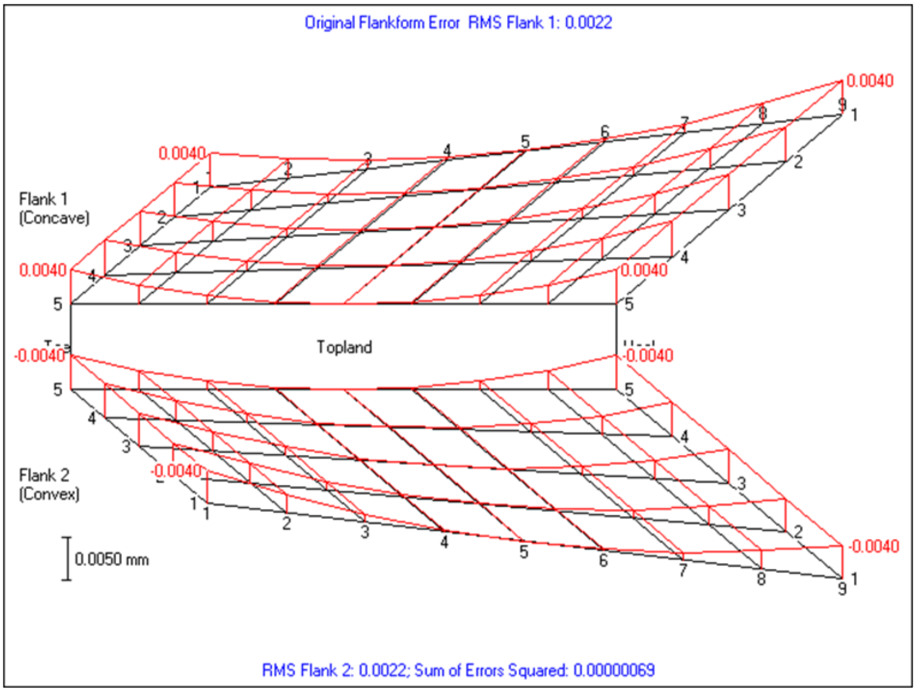

Figure11 Flank form errors resulting from cutter head and blade distance deviations.

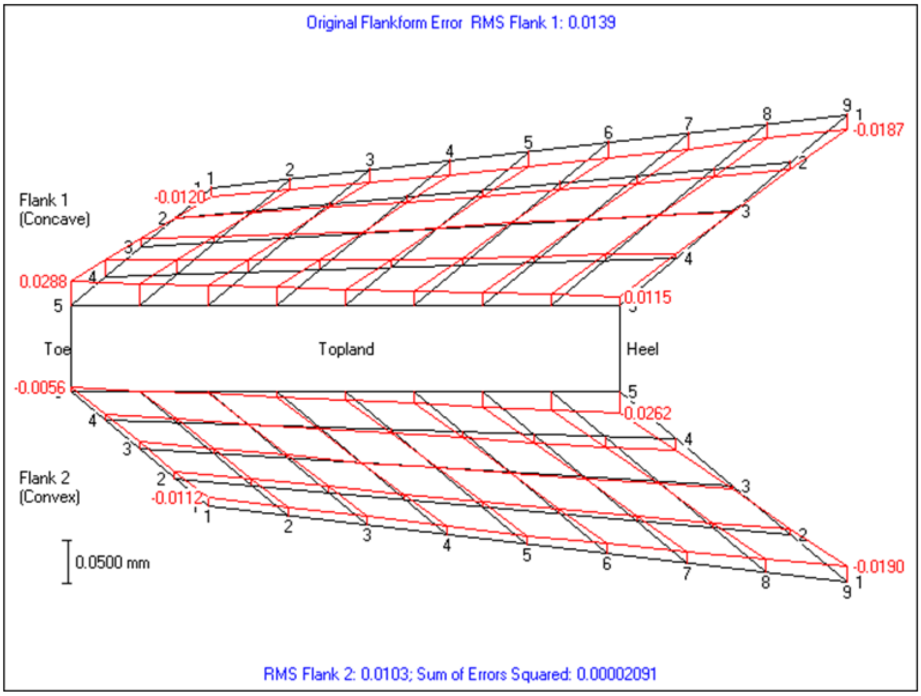

Figure12 Statistically probable total deviation in first part without any corrections.

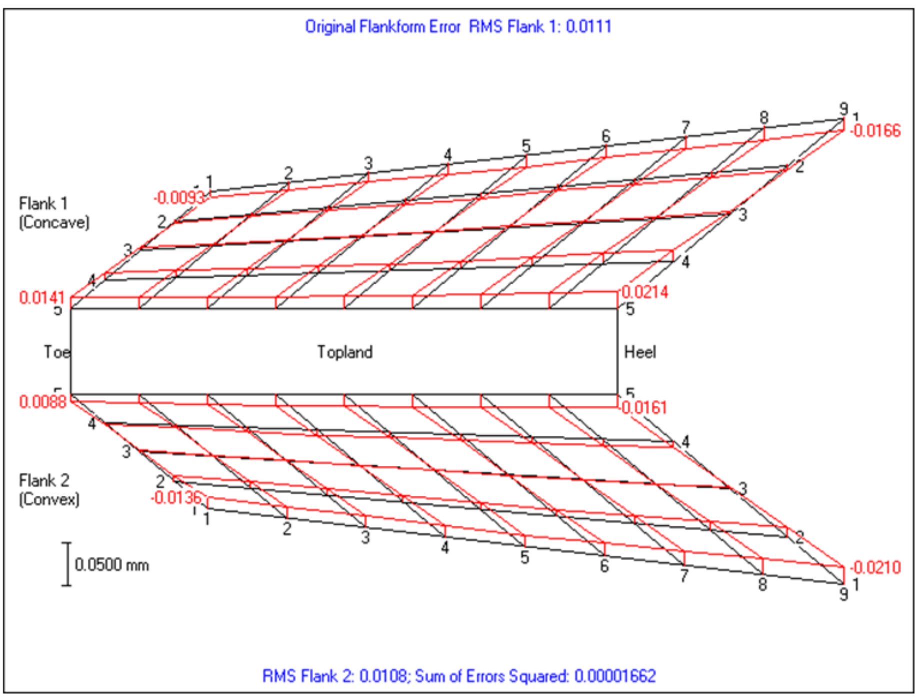

Figure13 Statistically probable deviation from blades and cutter head.

Dr. Hermann J. Stadtfeld received in 1978 his B.S. and in 1982 his M.S. in mechanical engineering at the Technical University in Aachen, Germany; upon receiving his Doctorate, he remained as a research scientist at the University's Machine Tool Laboratory. In 1987, he accepted the position of head of engineering and R&D of the Bevel Gear Machine Tool Division of Oerlikon Buehrle AG in Zurich and, in 1992, returned to academia as visiting professor at the Rochester Institute of Technology. Dr. Stadtfeld returned to the commercial workplace in 1994—joining The Gleason Works—also in Rochester—first as director of R&D, and, in 1996, as vice president R&D. During a three-year hiatus (2002–2005) from Gleason, he established a gear research company in Germany while simultaneously accepting a professorship to teach gear technology courses at the University of Ilmenau. Stadtfeld subsequently returned to the Gleason Corporation in 2005, where he currently holds the position of vice president, bevel gear technology and R&D. A prolific author (and frequent contributor to *Gear Technology*), Dr. Stadtfeld has published more than 200 technical papers and 10 books on bevel gear technology; he also controls more than 50 international patents on gear design, gear process, tools and machinery.

The solution of the problem is the RF30 of the flank surface deviation after finishing a development and creating the original reference set. The RF30 function sets all deviations between nominal and final development to zero, and with that produces a reference for all future gearsets of this particular design.

In many cases, duplicates of the reference gearset have been qualified in NVH and strength investigation. From this point on it is no longer desirable to manufacture parts with zero deviation versus the original theory, as the original theory has slightly different specifications than the qualified geometry of the reference parts.

The physical reference gearset, often with a rolled tooth contact, is used as the ultimate master for future batch manufacturing; it is good engineering practice to create the corresponding electronic master. The RF30 function after 3-D measurement of the reference gearset delivers the electronic masters. This procedure is applied by 90% of all bevel and hypoid gear manufacturers who use coordinate measurement machines for their gearset development and manufacturing control.

The argument that the theoretical basis (SPA-File) no longer exists as soon as the RF30 function is applied is false. Gleason-developed software allows backfeeding of the "nominal-actual" deviations of the final reference gear, thereby creating an effective/developed SPA-File.

Applying the RF30 function will promote the "first part right" strategy and establish a clean basis by which reference part, CMM electronic master file, and SPA-File are identical.

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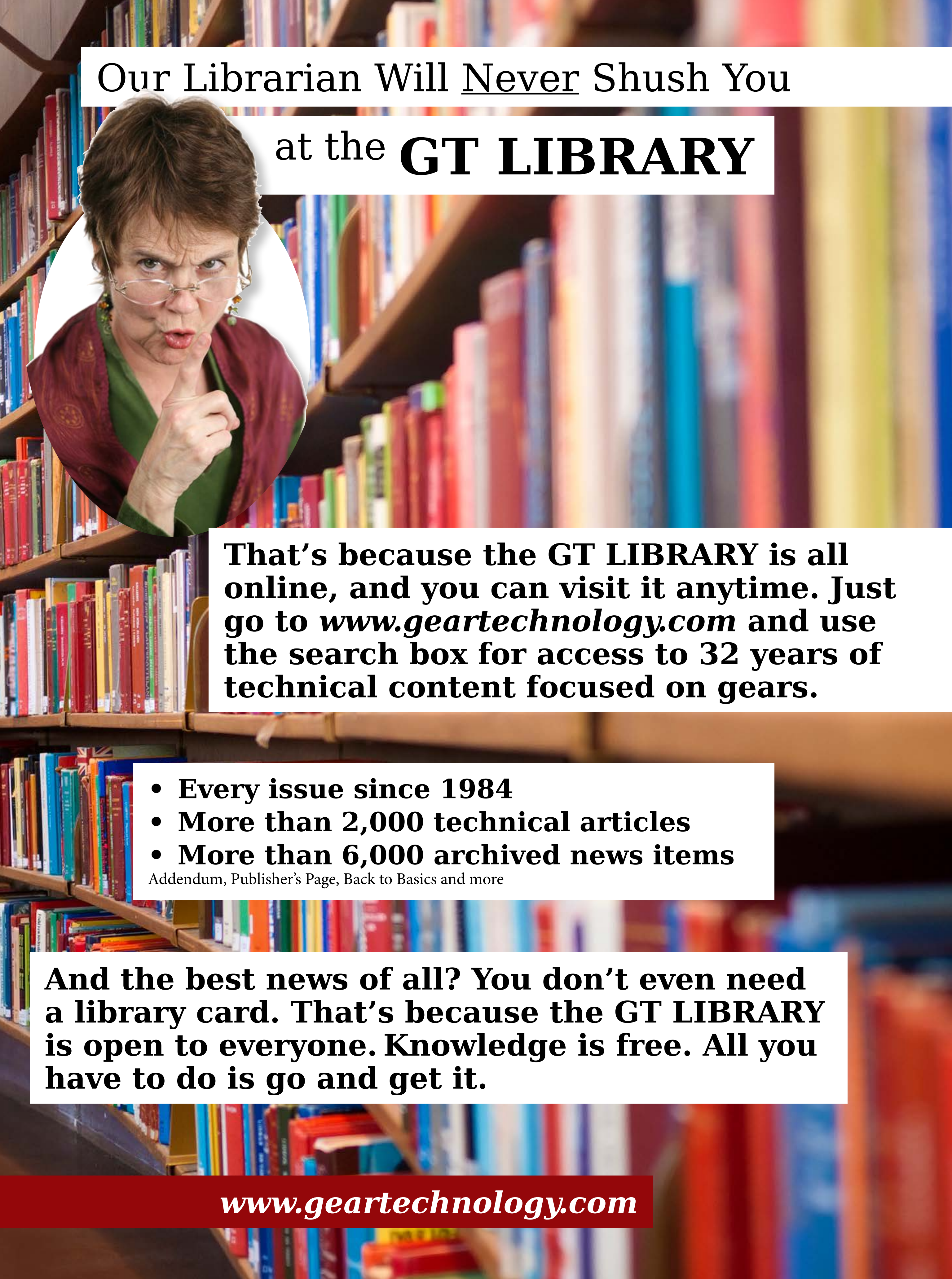
For more information.

Have questions or comments regarding this technical paper? Contact Gleason Corp's Dr. Hermann Stadtfeld at *hstadtfeld@gleason.com*.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Influence of Different Manufacturing Processes on Properties of Surface-Densified PM Gears

Tim Frech, Philipp Scholzen, Christoph Löpenhaus and Fritz Klocke

Introduction and Motivation

PM technology offers great opportunities for the reduction of the carbon footprint and improvement of the cost efficiency of gear production. PM gears can achieve flank load-carrying capacities comparable to wrought steel gears if the loaded volume is densified completely. Still, the tooth-root strength is of major concern. The tooth-root stresses can be minimized by optimizing the tooth-root geometry; this usually leads to a target conflict since fully optimized tooth-root geometries cannot be manufactured by generating processes such as hobbing, generating-grinding or rolling. To use the increase in tooth-root load-carrying capacity of a fully optimized root geometry on PM gears, a non-generating method for surface densifying is needed. The shot-peening process is used as an alternative densification process for PM gears. The properties of both shot-peened and cold rolled PM gears are analyzed and compared. To quantify the effect of both manufacturing processes, the tooth root bending fatigue strength will be evaluated and compared to wrought gears.

Today, the reduction of both material and energy consumption gains importance in gear production. A cost calculation of (Ref. 1) shows the potential for the PM process chain to substitute the conventional gear cutting process chain. A more precise calculation of (Ref. 2) specifies the cost distribution of the conventional and the PM gear manufacturing process onto the different manufacturing steps.

Figure 1 shows the distribution of process energy of the PM and the conventional process chain for a gear with the typical size of an automobile gear of module $m_n = 2$ mm. The conventional process chain contains the manufacturing steps of steel processing and forging, machining of the bore, and hobbing of the gear teeth. The PM process chain consists of the usual three steps of powder production, powder compaction, and sintering (Ref. 3). To increase the load-carrying capacity onto a level of conventionally produced gears, the sintered gears must be rolled to densify the surface. The comparison of the two process chains shows the advantage of PM gears, as less energy and material is needed for a single gear. Since the sintering process needs specific process chains, PM gears gain their benefits especially in large scale production. The advantage in energy consumption is mainly gained through the near-net shape production of the PM process chain. The near-net shaping process combines all formative processes, such as machining of the bore and hobbing of the gearing, into one process. Since no material needs to be cut, less material is needed to produce a PM gear than a conventional gear. To summarize, through near net-shape manufacturing PM gears offer an advantage in both material and energy consumption, which results in a cost advantage for this technology if applied in large scale production.

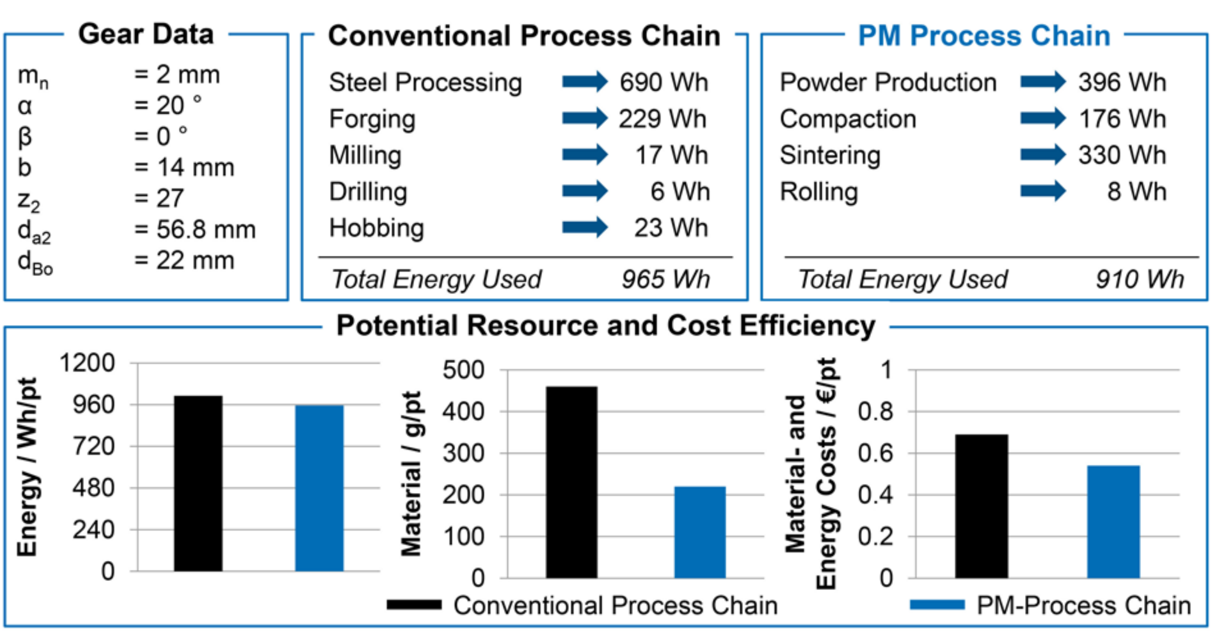

Figure 1 Cost and resource efficiency of PM gears.

State of the Art

The PM process chain offers a cost advantage for gear manufacturing. Furthermore, the process-related porosity of PM gears leads to a weight advantage of about 10% compared to forged and hobbed gears. Nevertheless, the remaining pores reduce the load-carrying capacity of PM parts. Figure 2 shows the density-dependent strength of powder metal, investigated by (Ref. 4). To achieve a strength comparable to normal steel, PM gears are densified at their surface. According to (Ref. 3), the material properties of PM steel can be calculated out of the remaining porosity in the component (Fig. 2, bottom left). Therefore the densified zone at the surface shows the highest Young's Modulus which decreases from the surface to the core. The Young's Modulus, as well as other density-related material properties, can be calculated with Equation 1, (Ref. 3).

$$E_{porous} = E_{\rho max} \cdot \left(\frac{\rho}{\rho_{max}}\right)^m \quad (1)$$

E_{porous}	[N/mm²]	Young's Modulus of the porous material
ρ	[g/cm³]	Density
m	[-]	Density exponent
$E_{\rho max}$	[N/mm²]	Young's Modulus at full density
ρ_{max}	[g/cm³]	Full density

As can be seen in Figure 2, the rolling fatigue strength of densified PM steels is comparable to conventional steels. Since the tooth root load-carrying capacity of PM gears is outperformed by conventional gears, the bending fatigue strength of the tooth root still needs to be optimized (Ref. 5).

The tooth root bending strength is determined by two characteristics — the nominal strength of the material, and the contact conditions that depend on the strain of the component. The nominal strength is characterized by material parameters such as Young's Modulus, hardness and defect size and quantity and, therefore, by the density of the material. In PM steels, each pore reduces the load-carrying cross-section and can be a crack propagator. The strain is determined by the geometric-functional properties of the gear pair, as well as by the time-dependent load distribution (Fig. 3, left) (Ref. 6).

The tooth root fillet weakens the bending fatigue strength of the gear. According to ISO 6336, the tooth root bending strength due to the geometry is determined by the chordal thickness S_f and the radius of the root rounding ρ_f (Ref. 6). Due to the reduction of the influence of the geometry on two the parameters ρf and S_f, a norm-based optimization of the tooth root is very limited in its design. As can be seen (Fig. 3, top right), the tooth root stress can be reduced by more than 10% when using full rounded standard profiles. Additionally, the tooth root stresses can be reduced further — up to 30% — when optimizing the tooth root free of norm-based restrictions (Ref. 7).

Meanwhile, the free optimization of the tooth root geometry without considering the manufacturing process is not productive. (Reference 7) showed that the optimal tooth root geometry cannot be manufactured by conventional processes. To minimize the notch effect of the tooth root, the highest possible tooth root radius is pursued. This leads to low curvature radii at the bottom of the tooth root so that the mathematical function describing the tooth root geometry cannot be continuously differentiated. Therefore, the tool cannot follow the optimized tooth root geometry in generating processes. As can be seen (Fig. 3, bottom right), already small changes in the tooth root lead to a significant reduction of the tooth root stress.

In addition to conventional densification processes such as cold rolling, further processes that can densify the optimized PM gears regardless of their geometry need to be qualified. The densification process determines not only the material parameters; e.g. — Young's Modulus — but also the surface and gear quality. Hence, the manufacturing process takes major influence on the running behavior and load-carrying capacity of PM gears.

As can be seen (Fig. 3, bottom right), already small changes in the tooth root

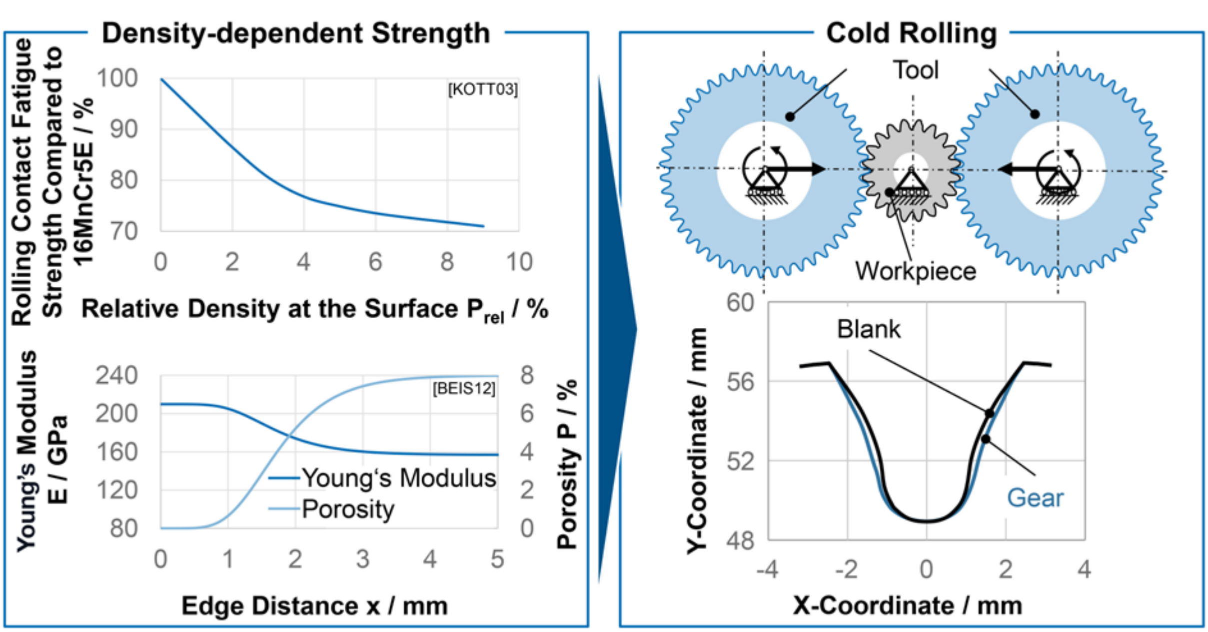

Figure 2 Density dependent material properties of PM gears.

lead to a significant reduction of the tooth root stress.

Densification Processes for PM Gears

PM gears are densified after the sintering process to ensure a proper load-carrying capacity. Furthermore, the densification process determines the density profile and the surface and gear quality and, therefore, the running behavior of PM gears.

Cold rolling. The most common and industrially established process for local densification of PM gears is the cold rolling process. As can be seen (Figs. 2 and 4), the PM gear is placed between two hardened tools and rolled between them to densify a stock on the flanks. The highest stock is located at the pitch circle. In this area the workpiece and the tool mesh with no slip, and so only normal material deformation can be found in this area. In the flank area above and beneath the pitch circle and at the tooth root, the workpiece and the tool mesh with slip. Therefore the material of the workpiece is not only deformed normally, but also tangentially and shoved from the pitch circle to the tip and the root of the tooth. The stock is relieved at the tooth tip and the tooth root to ensure the desired geometry after the cold rolling process. As can be seen (Fig. 4, bottom right), the porous PM gear is densified directly.

Shot peening. In shot peening, a sphere-shaped shot hits the material surface at great velocity. Shot material can be conventional steel-shot as well as ceramic- or glass-shot. The kinetic energy of the shot is transformed into deformation energy at the impact on the component surface. If the induced stress exceeds the yield strength, the material is deformed plastically. According to

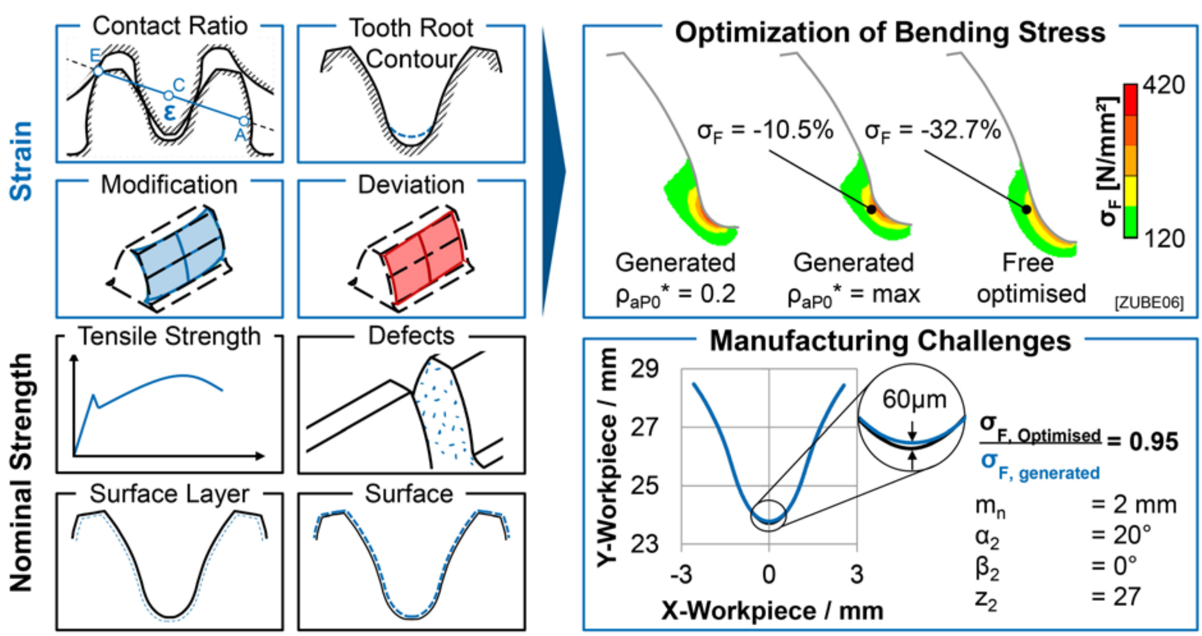

Figure 3 Challenges in optimizing the tooth root bending strength.

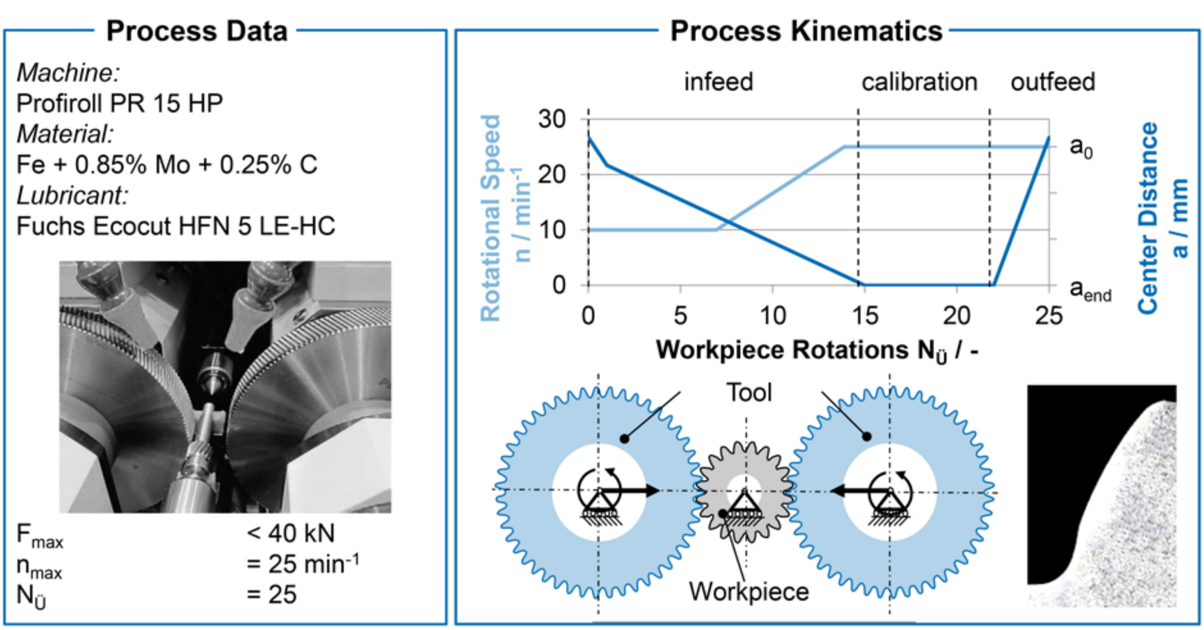

Figure 4 Cold rolling of PM gears.

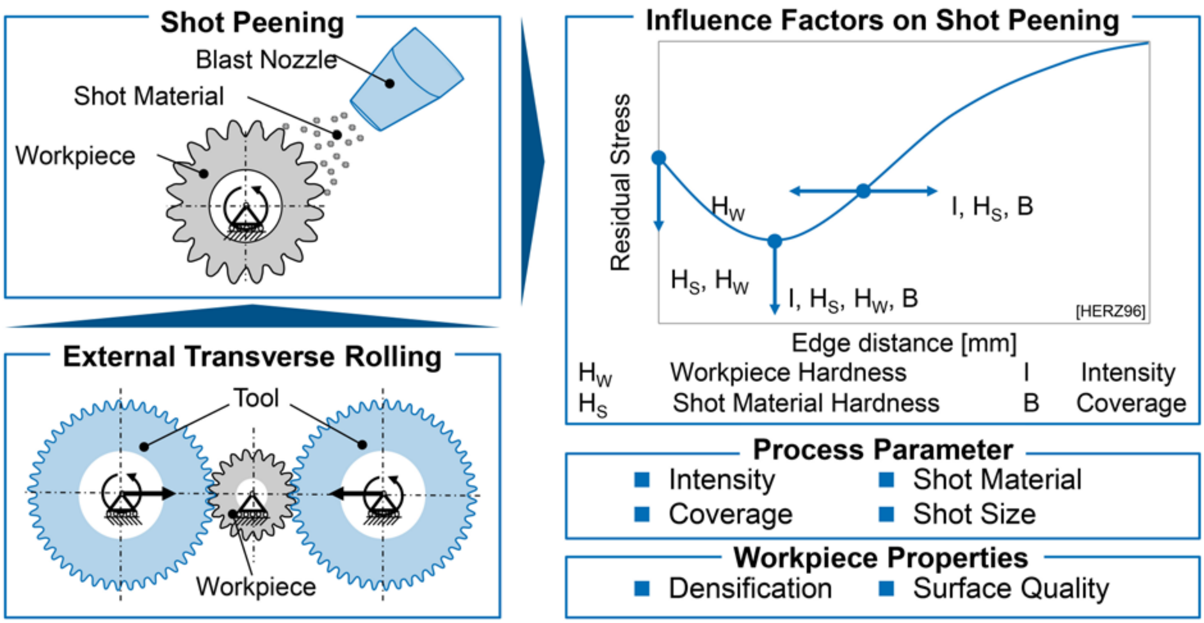

Figure 5 Shot peening of PM gears.

(Ref. 8), two model scenarios for the formation of residual stresses in shot peening exist:

- It can be assumed for low-strength materials that the impact of the shot deforms the surface plastically. Residual stresses build up through the bond of the surface layer to the core material.
- The residual stress in high-strength materials can lead back to the elastic theory according to (Ref. 9). Through the impact of the shot, the material is deformed and, therefore, compressive residual stresses are induced. The maximum of the induced residual stresses is located beneath the surface of the component.

Shot peening in gear production is used for cleaning purposes and to induce residual stresses after the heat treatment to increase the load-carrying capacity. Since residual stresses are induced by a plastic deformation of the material, it can also be used to densify porous materials. The induced stresses in the shot peening process and, therefore, the densification are influenced by the process parameters of the shot peening process (Fig. 5, right). The process parameters intensity, workpiece, and shot hardness — as well as the coverage — influence the induced stress profile in its depth and gradient. Additionally, the surface quality is mainly influenced by the process parameters of the shot peening process.

The shot peening process as a densifying tool was investigated by Iynen, Merkel and Molinari. Depending on the bulk density, densification depths in a range of $50 < t_d < 200\,\mu m$ can be reached (Refs. 10–12). The bending fatigue strength of the investigated specimen was increased by up to 30% (Refs. 11–12).

The achievable densification depths and resulting surface quality, as a function of process parameters intensity, shot material, and Young's Modulus of the shot, was investigated by (Ref. 13). The densification depth of Fe + 0.85% Mo + 0.25% C can be calculated by Eq. (1).

$$t_d = -314.4 + 281.3 \cdot I + 5.763 \cdot H - 0.000127 \cdot E \quad (2)$$

t_d	[µm]	Densification depth
I	[mmA]	Intensity
E	[N/mm^2]	Young's Modulus of the shot
H	[HRC]	Shot hardness

The shot peening process does not rely on specific process kinematics. As long as the shot can cover the whole tooth gap, gears can be machined regardless of their geometry. Therefore, not only normed designs but also optimized tooth root geometries can be densified.

Objective and Approach

The objective of this paper is the qualification of the manufacturing-related properties of surface-densified PM gears. The conventional and established cold rolling process will be compared to shot peening as a densification process. Shot peening allows for a densification without restrictions to the workpiece geometry.

In a first step, PM gears are cold-rolled with a conventional, standards-based tooth root design.

The influence of the tool geometry on the properties of the workpiece are examined and analyzed. Furthermore, the tooth root bending strength of these cold-rolled PM gears is evaluated and compared to conventionally manufactured gears.

Secondly, the tooth root of the PM gears is optimized to increase the bending strength. Since optimized tooth root geometries are not definitely manufacturable by generating processes, two variants are manufactured; i.e. — the first variant is densified by cold rolling while the shot peening process is used as a densification process for the second variant.

The different tooth root geometries can be seen (Fig. 6). The geometry for the cold rolling process can be seen (Fig. 6, left), and the geometry for the shot peening process can be seen (Fig. 6, right). The conventionally designed tooth root geometry is shown in light grey. The optimized variants show a significantly deeper tooth root and are displayed in red lines (Fig. 6). Furthermore, the stock for the different gear design is shown in black lines. For the cold rolling process, a maximum stock of $s = 0.15\,mm$ is used at the pitch circle of the gears. Since the workpiece and the tool are only in rolling contact, with no slip between the contact partners, only normal material flow can be found in this area. In all other areas on the tooth flank and tooth root, sliding occurs between the contact partners. Thus not only normal but also tangential material flow can be found in these areas. The stock is reduced continuously from the pitch circle to the tooth root to a minimum stock of $s = 0.1$ mm.

The contact conditions in the shot peening process are more uniform than in the cold rolling process; additionally, the process forces are lower. Thus a constant stock of $s = 0.013$ mm is used for the shot peened gears; the gears are shot peened at an intensity of $I = 0.3$ mm A at a coverage of B = 200% with ceramic shot Z425.

Manufacturing-Related Properties of Surface-Densified PM Gears

The different gear designs, as well as the manufacturing process, significantly affect the density profile and surface quality and, therefore, the strength of the gears. In the following chapters the surface and gear quality, as well as the density profile of the different gears, will be analyzed and compared. In the end the tooth root load-carrying capacity will be tested on a pulsator test rig to quantify the effect of the tooth root optimization and the influence of the manufacturing process.

Surface quality. The surface quality is influenced by the contact conditions of the compaction process. Furthermore, the surface quality affects the strength of the bending and rolling fatigue strength. The surface quality of the cold-rolled gears with, conventional and optimized tooth root geometry, as well as the shot peened gears, are shown (Fig. 7). The measurements of the surface of the conventional cold-rolled gears are shown at the top; the surface measurements of the optimized

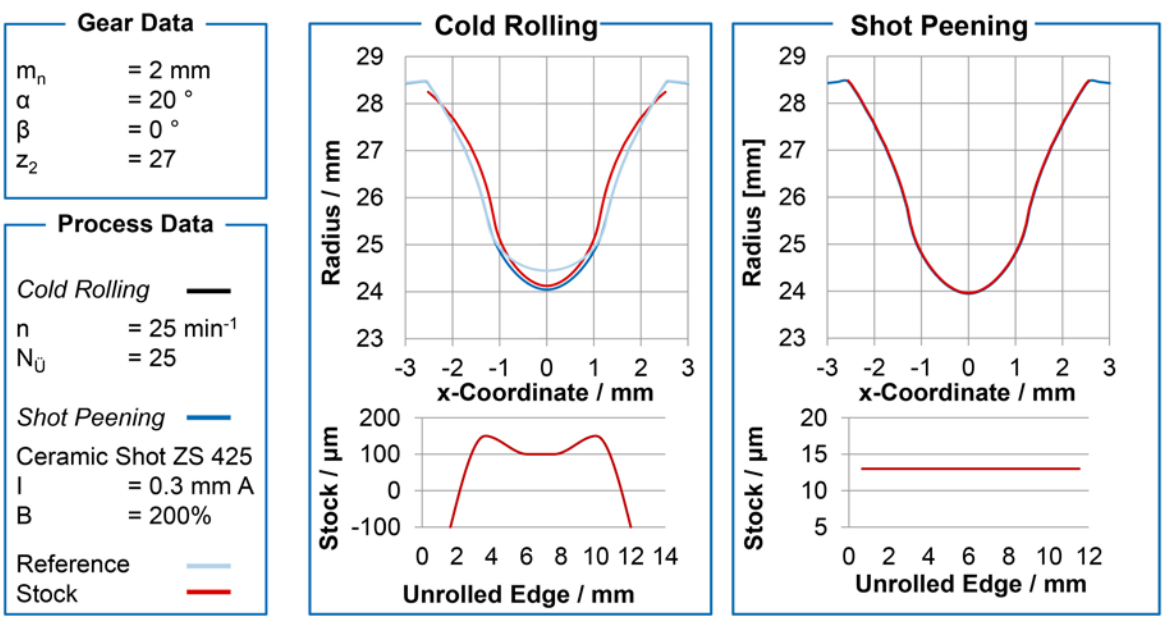

Figure 6 **Conventional and optimized tooth root geometries.**

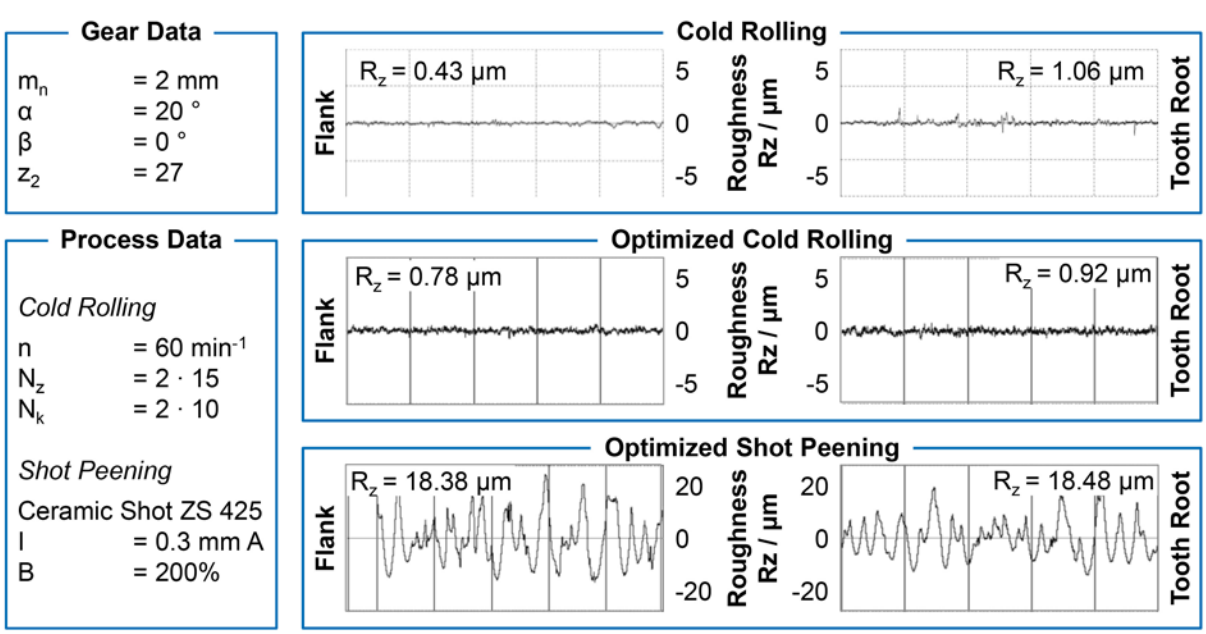

Figure 7 **Surface quality of surface densified PM gears.**

tooth root geometry that were densified by cold rolling and shot peening are shown in the middle and the bottom of Figure 7, respectively. For all variants the surface quality at the pitch circle, as well as at the tooth root, are shown.

Seen at the top and the middle section of Figure 7, the cold rolling process leaves a surface of high quality. At the pitch circle high surface qualities of $Rz = 0.43\,\mu m$ and $Rz = 0.78\,\mu m$ can be found. For both the conventional as well as the optimized gear, a slight decrease in surface quality can be detected in the tooth root. This can be traced back to the difficult contact conditions at the tooth root during the cold rolling process. The superposition of high slip between workpiece and tool with low contact radii in this area leads to distinctive tangential material flow in this area (Ref. 5). The surface of the shot peened gears is mainly influenced by the shot size and the intensity of the shot (Ref. 13). Since the shot can reach all areas of the tooth gap in the shot peening process, a uniform surface quality of about $Rz = 18\,\mu m$ can be found at the pitch circle as well as in the tooth root.

Density profile. The density profile resulting from the contact conditions of the densification process have a great impact on the load-carrying capacity and are, therefore, of high importance for PM gears. Thus the density profile of the unoptimized as well as the optimized cold-rolled gears and shot peened gears with optimized tooth root geometry are analyzed and compared.

The polished microsection of a tooth of a cold-rolled gear with conventional tooth root design is shown (Fig. 8). Additionally, the microstructure at the pitch circle and the 30° tangent in the tooth root are shown in detail. The densification depth $t_{d,99}$ is labeled in both detail sections and

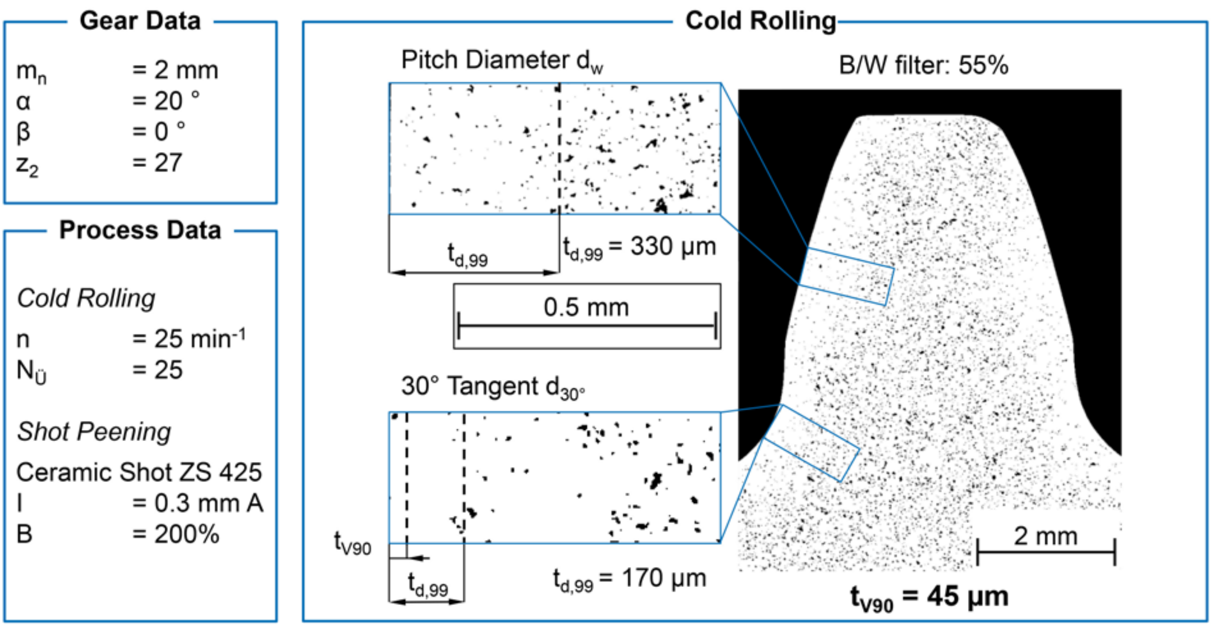

Figure 8 **Densification quality of cold rolled gears with conventional tooth root design.**

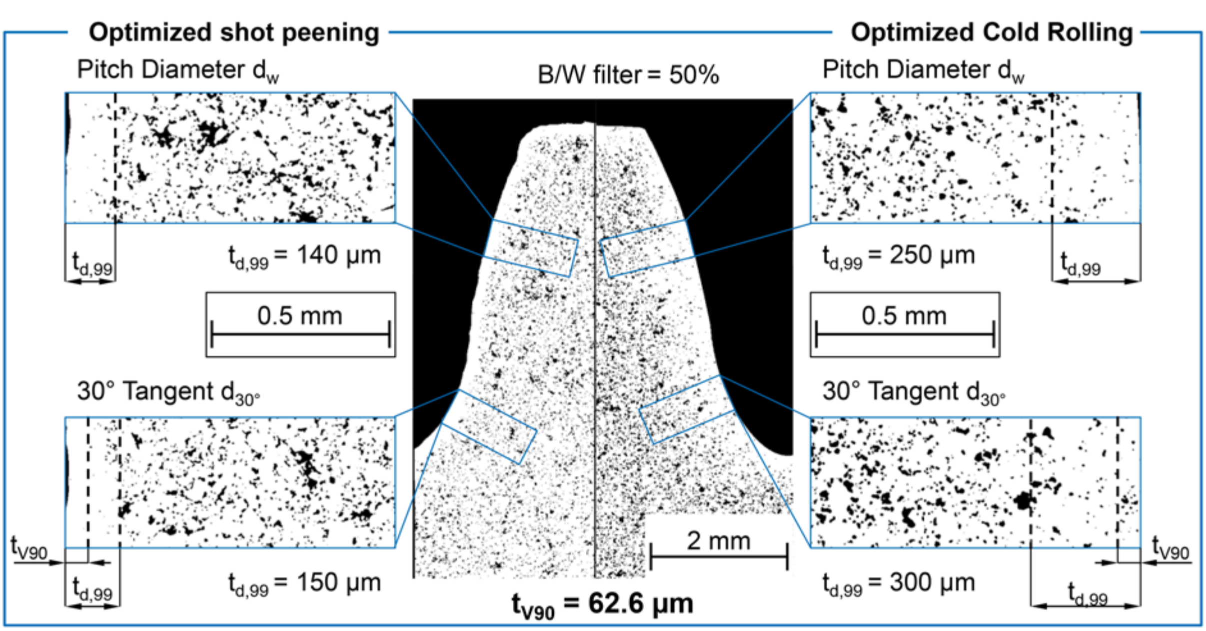

Figure 9 **Densification quality of cold rolled and shot peened gears with optimized tooth root design.**

marks the distance from the surface where at least 99% density can be measured.

At the pitch circle, a densification depth of $t_{d,99} = 330$ µm can be measured at the pitch circle while the tooth root shows a lesser densification at $t_{d,99} = 170$ µm. When meshing, the gear must withstand the abrasive contact as well as the stresses induced by the Hertzian contact at the pitch circle. Furthermore, the gear tooth needs to withstand the tensile stresses due to the deflection of the gear tooth under load. Therefore a full densification is needed in the highly stressed volume V_{90} in the tooth root. The highly loaded volume V_{90} is defined as the volume in which more than 90% of the stresses can be found. The highly loaded volume V_{90} reaches a depth of $t_{V90} = 45$ µm in the tooth root for the shown tooth root geometry, and is also labeled in the detail microsection at the tooth root. As can be seen (Fig. 8), a full densification of V_{90} can be measured. It can therefore be expected that the tooth root bending fatigue strength is not influenced by the porosity.

Figure 9 shows the metallographic sections of cold-rolled and shot peened gears with optimized tooth root geometry. The cold-rolled gear can be seen on the right, while the shot peened gear is shown (Fig. 9, left); as before, the microstructure at the pitch circle and the 30° tangent are shown in detail.

The cold-rolled gear shows a densification depth of $t_{d,99} = 250$ µm at the pitch circle and a densification depth of $t_{d,99} = 270$ µm at the tooth root. Since the shot peening process provides uniform contact conditions over the whole tooth, the densification depth for the shot peened gear can be measured to about $t_{d,99} = 140$ µm. The highly loaded volume is located in a depth of up to $t_{V90} = 63$ µm for this optimized tooth contour. Thus both the cold rolling process, as well as the shot peening process, are able to provide a proper densification of the highly loaded volume V_{90}; the greatest difference can be noticed in the density profile resulting from the different densification processes. The shot peening process causes a uniform densification over the whole tooth gap, with a sharp transition to the bulk density. The cold rolling process results in a more variable profile over the tooth height. The absence of slip between workpiece and tool causes a high normal material flow and, therefore, a high densification depth. The reduced densification depth in the tooth root results from higher slip between cold rolling tool and workpiece and, thus, in a more tangential than normal material flow.

Residual stress and hardness profile. The residual stress and hardness profile are other characteristics that are influenced by the manufacturing process, and affect the fatigue strength of the component. Therefore the residual stress profile, as well as the hardness profile of the case hardened gears, are measured and shown (Fig. 10). The profile of the shot peened gears is shown in blue while the profiles of the cold-rolled gears are shown in black.

The residual stress profile of both variants follows a comparable trend. At the edge, both residual stress profiles show a significant drop onto about $\sigma = -300$ MPa. The shot peened gears show a slightly higher drop, but less compressive residual stresses between the edge of the component and the core of the tooth.

The cold-rolled gears show a hardness plateau of about 850 HV 0.1 into a depth of about 200 µm, while the hardness of the shot peened gears decreases earlier at about 100 µm distance from the edge of the component. The hardness is mainly determined by the remaining porosity; therefore the different hardness plateaus can be explained by the different density profiles presented previously.

Both densification processes affect the porosity and, therefore, the hardness as well as the residual stress profile of the PM gears. Especially in edge distances of more than 100 µm, greater differences in the hardness and residual stress profile of the differently densified gears can be detected. The highly loaded volume V_{90} is located at depths of up to $t_{V90} = 63$ µm (see previous). In this depth, both variants show a comparable hardness and residual stress profile. As such, the effect of

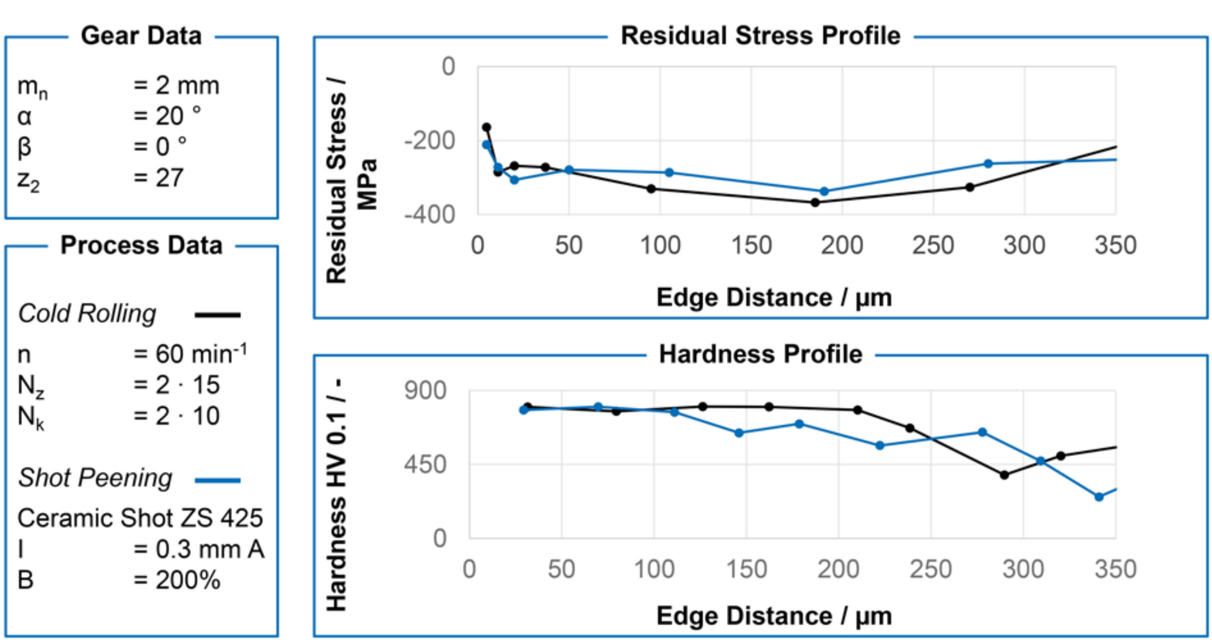

Figure 10 Residual stress and hardness profile of surface densified PM gears in the tooth root.

the hardness and the residual stress profile onto the tooth root bending fatigue strength is comparable for gears of both densification processes.

Tooth Root Load-Carrying Capacity of PM Gears

To study the effect of the different surface and structure qualities, as well as the different densification depths, the tooth root load-carrying capacity of the different tooth root designs and densification processes are tested on a pulsator test rig (Fig. 11). The gear is clamped between two clamps; force is applied from the right clamp and measured at the left clamp. These tests are not as application-related as trial runs, but faster and more economical (Ref. 14). The tests are evaluated using the staircase method by (Ref. 15) and are tested to load cycles up to $l_c = 3{\cdot}10^6$.

The bending fatigue strength of the different process and gear designs are shown (Fig. 12).

At the top of Figure 12, the test evaluation by (Ref. 15) is shown for the shot peened gears as an example. If the gear tooth reaches more than $l_c = 10^6$ load cycles, the load is increased, while the load is decreased when the tooth breaks before reaching the desired number of load cycles. Out of the spread in the test results, the mean bending fatigue strength can be calculated. Besides the PM gears, the test results of conventionally made gears are also shown.

The mean bending fatigue strength of the conventional cold-rolled gears can be calculated to μ = 6.63 kN; the optimization of the tooth root reduces the notch caused by the tooth root radius.

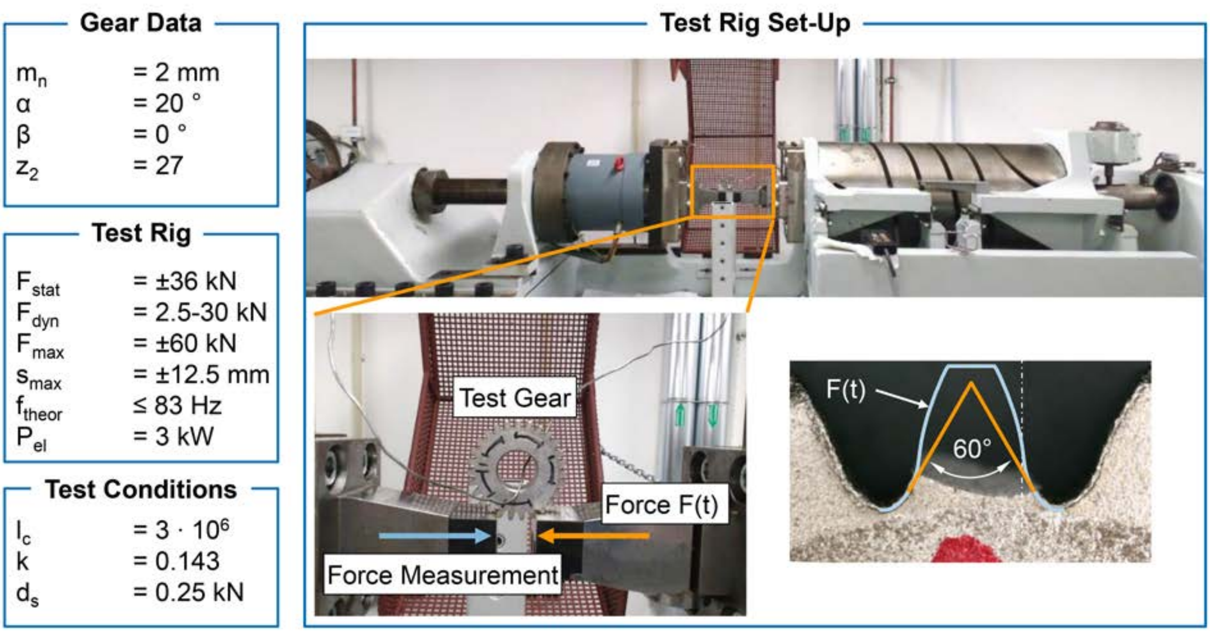

Figure 11 Pulsator test rig.

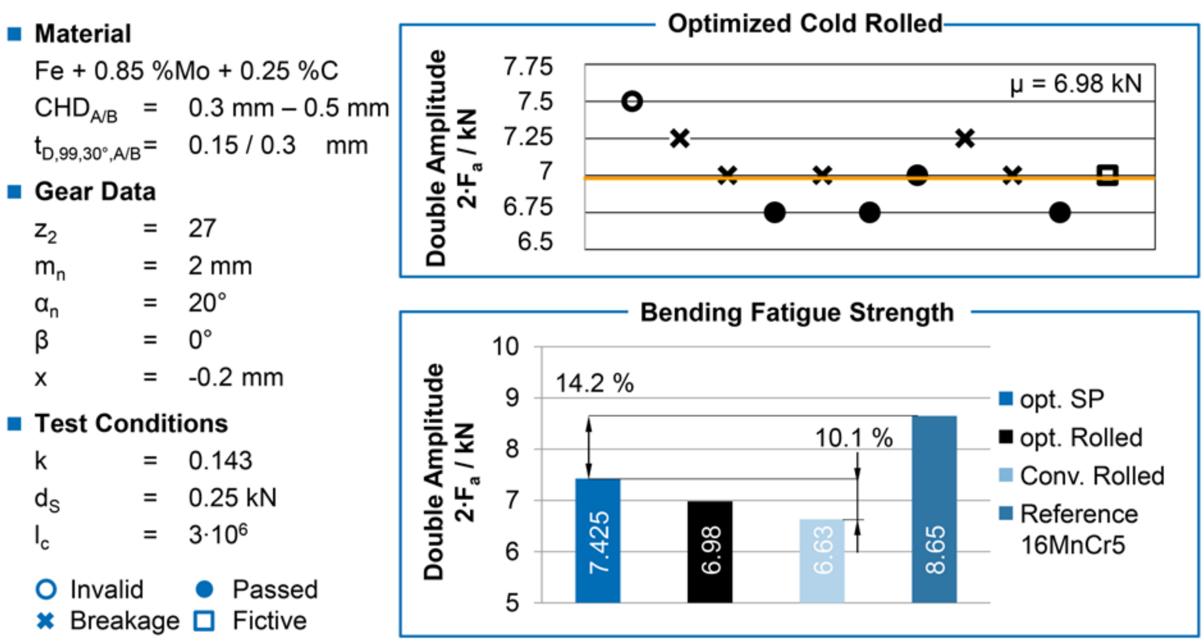

Figure 12 Bending fatigue strength of surface densified PM gears.

Therefore, lower tensile stresses are induced when the tooth is deformed, and so the bending fatigue strength of the optimized gears can be calculated to $\mu = 6.98$ kN for the cold-rolled gears and $\mu = 7.3$ kN for the shot peened gears. Hence, the optimization of the tooth root geometry leads to an improvement of the bending fatigue strength of up to 10%.

The differences of the achieved bending fatigue strength between the shot peened and cold-rolled gears cannot be traced back to the spread of the experiments alone; thus the differences in the density profile must be considered. The shot peened gears show a much lesser, but more even, densification when compared to the cold-rolled gears. Since the highly loaded volume V_{90} is densified completely, the lesser densification depth of the shot peened gears remains sufficient. The bending fatigue strength of the wrought gear is calculated to $\mu = 8.65$ kN. While the conventional PM gear has a 24% lesser bending fatigue strength, the strength of the optimized PM gear still remains more than 14% behind the unoptimized wrought gears. To provide a better understanding of this result, the influence of the density profile on the tooth root stresses is analyzed in detail.

Influence of the Density Profile on the Tooth Root Stress

The three-dimensional density profile in the surface zone of PM gears, as well as the material stiffness due to the porosity of the material, lead to a different tooth root load-carrying capacity of PM gears compared to steel. For the calculation of the tooth root load-carrying capacity of PM gears, it is necessary to consider

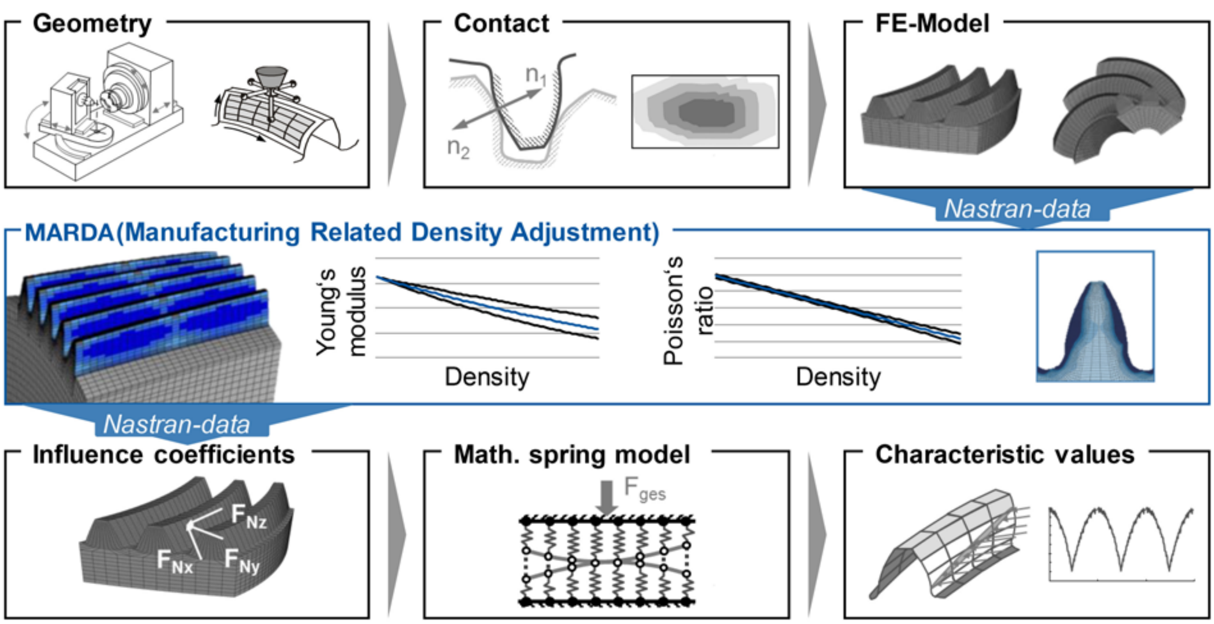

Figure 13 Consideration of the density profile in the FE-based tooth contact analysis.

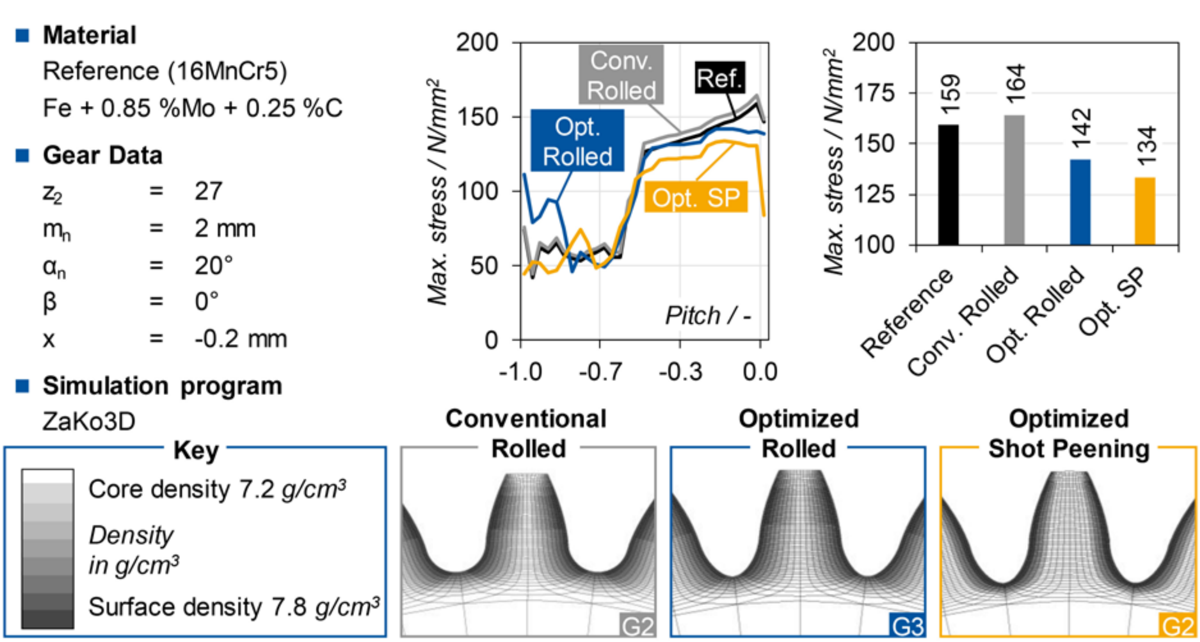

Figure 14 Simulation results: Tooth root stress of surface densified PM gears.

the density profile in the tooth contact analysis. Therefore the calculation program *MARDA* (*Manufacturing Related Density Adjustment*) was developed and integrated in the FE-based tooth contact analysis *ZaKo3D*. The general approach of the FE-based tooth contact analysis and the integration of *MARDA* are shown (Fig. 13).

The first two steps are the definition of the gear geometry and the calculation of the load-free characteristics of the running behavior. In the next step, the FE structure generator creates the FE model necessary for the loaded tooth contact analysis. The influence coefficients define the displacement of each FE node for the successive loading of the FE nodes with a unit force. Finally, the characteristics of the operational behavior of the gear set are calculated with a mathematical spring model.

The FE model generated by the FE structure generator contains all of the information needed for the loaded tooth contact analysis. According to (Ref. 3), the Young's Modulus and the Poisson's Ratio are functionally related to the density of powder metallurgical materials. This allows for the conversion of the density of PM materials into Young's Modulus and Poisson's Ratio and the adjustment of the FE model with regard to a defined density profile. Therefore, new materials are added in the Nastran file and assigned to the respective elements of the FE model. Regarding the adjustment, the material data of the FE elements successively change and the density profile of the PM gear is mapped for each layer.

Figure 14 shows the densified FE models and the simulation results of the tested surface densified PM gears. For the simulation the core density of the PM gears is $\rho_{core}=7.2$ g/cm^3, while the surface density is $\rho_{surf.}=7.8$ g/cm^3. To model the density profile in tooth height direction, the density profiles shown in (see previous) are used. The density profile of the material is defined by an s-curve density gradient. The result of the simulation is the maximum tensile stress in the tooth root over one pitch for $T_{Drive}=10$ Nm normalized torque (Fig. 14, left). To compare the different variants, the maxima of the curves are shown (Fig. 14, right).

The reference gear (Ref.) and the conventional rolled gear (Conv. Rolled) do not differ in the geometry, but in the material and the density profile. Nevertheless, the maximum tooth root tensile stress of the conventionally rolled gear is higher than the maximum tooth root tensile stress of the reference steel gear. The optimization of the tooth root geometry for cold rolling and shot peening leads to a decrease of the tooth root stress by 13.4% (Conv. Rolled to Opt. Rolled) and 18.3% (Conv. Rolled to Opt. SP). While the calculated maximum stress is lower for the optimized geometries (Opt. Rolled and Opt. SP), the tested bending fatigue strength of both gears is lower than the reference steel gear. To explain the results, the nominal strength resistance of the PM gears needs to be lower than for homogeneous steel.

The increased tooth root stress of a conventional rolled gear compared to the steel reference gear with the same geometry can be explained by the inhomogeneous material stiffness of densified PM gears. In the analogy view of the tooth bending by a bending beam, the densification of the surface layer of PM gears can be correlated to the resulting bending stress of a sandwich beam.

Figure 15 shows the stress distribution of two bending beams that differ in material stiffness and structure. On the one hand, the bending stress of a homogeneous (brighter line) and a sandwich beam (darker line) are plotted over the beam thickness (Fig. 15, top). On the other hand, the percentage deviation of the tensile stress of both variants is shown (Fig. 15, bottom). For the homogeneous bending beam, the resulting stress by shear force is divided and distributed linearly in the beam. It can be seen that the material stiffness of a homogeneous bending beam has no impact on the calculated stress distribution.

If a sandwich beam is loaded by a shear force, the inhomogeneous material

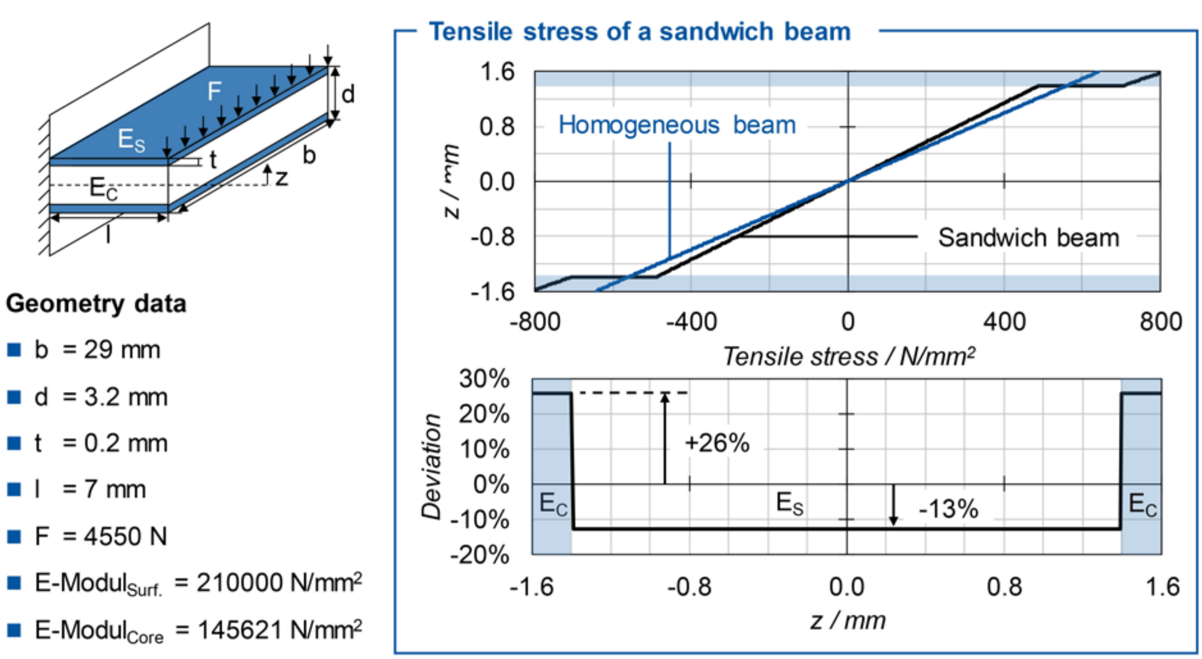

Figure 15 Stress distribution of a sandwich beam.

stiffness leads to a stress jump of the tensile stress distribution. If the material stiffness of surface layer of the beam is higher than the material stiffness of the core, like for PM gears, the bending stress in the surface layers increases during the material change. The percentage comparison of the resulting stresses of both variants shows a reduction of the tensile stress of the sandwich beam core by −13%, while the tensile stress of the surface layer increases by 26%. Hence, the analytical calculation results of the tensile stress in bending beams confirm the simulation results in the case of the increase tensile tooth root stress of Gear 2 compared to the steel reference gear. Due to the higher material stiffness of the surface layer of PM gears resulting from the densification process, the maximum tensile stress in the tooth root increases while the load is constant.

The comparison between the experimental results of the tooth root load-carrying capacity and the calculated tooth root stress of the gear variants show good correlation for the densified PM gears. While the calculated tooth root stress of the optimized PM gears (G3 and G4) is lower than the tooth root stress of the reference gear (Ref.), the experimental test shows a higher tooth root load carrying capacity. This deviation can be explained by a lower bearable tooth root stress of PM gears compared to steel (16MnCr5), which needs to be investigated in further research projects.

Summary and Outlook

The powder metallurgic process chain offers advantages in resource and energy consumption in mass production when compared to conventionally wrought components. The components are produced by compacting and sintering powdered metal into shape. After sintering, PM components show a process-related and unavoidable porosity. Since the pores reduce the load-bearing cross-section, while also being internal notches in the material, the mechanical properties of porous components are inferior to parts of full-dense material. Therefore highly loaded components are densified to increase their load-carrying capacity. Since gears are only stressed locally at and directly beneath the flank, gears are suitable for local densifying processes such as cold rolling.

Due to the densification in the cold rolling process, the flank load carrying capacity can be improved at levels of conventionally wrought gears. Still, the tooth root strength of PM gears must be improved. Therefore, the tooth root is optimized to reduce the stress in this area. Since optimized tooth root geometries cannot be densified by the industry-established cold rolling process in general, the shot peening process is an alternative. The densification process, either shot peening or cold rolling, has a major influence on the properties of the manufactured gears. The influence of the densification process on the surface quality, as well as the density profile, is analyzed in this report. Furthermore, the influence of the tooth root optimization, as well as the influence of the manufacturing process on the tooth root bending fatigue strength, is evaluated.

The contact conditions of the different manufacturing processes have a great impact on the surface quality. While the cold rolling process leaves high surface quality at $Rz = 1\,\mu m$, the indentations of the shot in the peening process cause a coarse surface at $Rz = 18\,\mu m$. The density profile is also affected by the different densification processes. In the cold rolling process, the contact conditions between workpiece and tool are changing over the tooth height and are, furthermore, influenced by the stock on the workpiece. Hence, the highest densification can be found at the pitch circle, while the densification in the tooth root is reduced. The even contact conditions over the tooth height in the shot peening process cause a constant densification depth over the tooth height. Since the highly loaded volume is completely densified for all process variants, the remaining porosity does not affect the bending fatigue strength. Furthermore, the residual stress and hardness profile for shot peened and cold rolled gears were evaluated after the heat treatment and are comparable for gears of both process variants.

To quantify the effect of the tooth root optimization and the different densification processes, the tooth root bending fatigue strength was evaluated and compared to optimized gears of both PM and wrought steel; optimization of the tooth root leads to 10% improvement of the tooth root bending fatigue strength. Nevertheless, the strength of the PM gears is 14% lower than the tooth root strength of conventional gears. To analyze these differences further, tension in the tooth root due to the different tooth root geometries and the density profile are evaluated.

In order to determine the influence of the density profile on the tooth root tensile stress, the calculation program *MARDA* was developed and integrated into the tooth contact analysis *ZaKo3D*. Due to the densification process, the resulting inhomogeneous density profile leads to a different tensile stress distribution in the tooth root that can be correlated to the stress distribution in a sandwich beam. The tensile stress in the densified surface layer of PM gears increases, while the tensile stress in the core material decreases. Still, due to the deviation between the calculated tooth root stress and the tested tooth root load capacity of densified PM gears, the bearable tooth root stress of PM gears needs further investigation and research.

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Liebherr and Wenzel

ANNOUNCE SALES AND SERVICE AGREEMENT FOR NAFTA

Liebherr Verzahntechnik GmbH, (LVT) Kempten, Germany, recently announced that Liebherr Gear Technology, (LGT) Saline, MI, will be the sole sales and service source for Wenzel GearTec (WGT) gear inspection machines and software for the NAFTA region effective immediately. The announcement was made by Dr. Christian Lang, LVT managing director and Frank Wenzel, WGT owner at the IMTS exposition in Chicago.

Dr. Christian Lang, Liebherr and Frank Wenzel, Wenzel GearTec at the IMTS exposition in Chicago.

LGT will import the Wenzel machines directly from the Wenzel GearTec factory in Karlsruhe, Germany, according to Frank Wenzel.

Gary Chatell, LGT president, said that Liebherr will provide full service support for all Wenzel machines currently installed in North America, including calibration services, training, parts, and applications assistance. Felix Scholz, service manager at LGT, will be adding dedicated staff to provide this customer support.

The agreement by Liebherr and Wenzel will result in improved service to customers in the market. Wenzel products cover applications from automotive, truck, off highway up to construction equipment and energy ranging up to workpiece diameters of 1600mm."This combination of the Wenzel gear inspection capabilities with Liebherr gear generation technology offers gear manufacturers a highly capable single source for advanced parallel axis gear production and inspection technology," said Scott Yoders, LGT vice president of sales.

(*www.liebherr.com*)

MPIF

RELEASES POWDER METAL STANDARD, ANNOUNCES CALL FOR PAPERS

The 2018 edition of Metal Powder Industries Federation's (MPIF) Standard 35-MIM – Materials Standards for Metal Injection Molded Parts has been released. This standard is a must-have document and provides the design and materials engineer with the latest engineering property data and information available in order to specify materials for components made by the metal injection molding (MIM) process. Each user-friendly section of the standard is clearly distinguished by easy-to-read data tables (Inch-Pound and SI units) and provides explanatory information for each material listed. Revised and expanded, this standard was developed by the metal injection molding (MIM) commercial parts manufacturing industry and includes new data for low alloy steels, MIM-4605 (HIP'D quenched & tempered) and stainless steels, MIM-17-4 PH (H975), and MIM-17-4 PH (H1025). This standard does not apply to materials for PM structural parts (SP), PM self-lubricating bearings (SLB), or powder forged (PF) products which are covered in separate editions of MPIF Standard 35.

In related news, an official call for papers and posters has been announced for POWDERMET2019, International Conference on Powder Metallurgy & Particulate Materials, to be held June 23–26, 2019, in Phoenix, Arizona. Topics include: Design & Modeling of PM Materials, Components & Processes, Particulate Production, General Compaction & Forming Processes, Powder Injection Molding (Metals & Ceramics), Pre-Sintering & Sintering, Secondary Operations, Materials Refractory Metals, Carbides & Ceramics, Advanced Particulate Materials & Processes, Material Properties, Test & Evaluation, Applications and Management Issues.

"The technical sessions provide the opportunity to stay current with today's technologies, but more importantly, the open sessions support learning to better prepare for future business improvements and growth opportunities," said Arthur "Bud" Jones, Symmco, Inc., and long-time conference attendee. "I have been able to apply what I have learned at this event to gain and improve business many times."

Additionally, an official call for papers and posters has been announced for the conference AMPM2019, Additive Manufacturing with Powder Metallurgy, June 23–26, 2019 in Phoenix, Arizona. This leading North American metal additive manufacturing (AM) conference will take place in the heard of Phoenix in the Sheraton Grand. Manuscripts are required, and qualified manuscripts will be eligible for the Metal Additive Manufacturing Outstanding Technical Paper Award. Topics include: Materials, Applications, Technical barriers, Process economics and New Developments.

"Presenting cutting-edge R&D at AMPM conferences, one of the world's leading forums on metal additive manufacturing, provides a unique opportunity for technology transfer between peers," said Joe Strauss, president, HJE Company, Inc., and former AMPM conference co-chair.

Submissions will be accepted through November 9, 2018. (*www.mpif.com*)

Gear Motions

ANNOUNCES NEW DIRECTOR OF OPERATIONS AND CORPORATE CONTROLLER

Gear Motions announces long-time employee **Dan Bartelli** has been promoted to director of operations of Nixon Gear, and **Anna Pastore** has been hired to the position of corporate controller.

This year Dan Bartelli is celebrating his 30th anniversary with Nixon Gear, a division of Gear Motions. This notable anniversary also comes with a well-deserved promotion; Bartelli has recently been promoted to director of operations.

Bartelli began his career at Nixon Gear in 1988 as a machinist where he distinguished himself as a quick learner and hard worker. He worked in a number of departments, and before long was promoted to lead machinist. From the shop, Bartelli moved to customer service where he demonstrated a natural talent for outstanding customer care. It was here that Dan established his skill for scheduling and planning and was promoted to master scheduler. In 2010 Dan was promoted to manufacturing manager and most recently to director of operations.

In his new role, Dan is responsible for all Nixon Gear Division Operations including manufacturing, quality, and engineering. He is an integral part of the management team,

providing leadership and direction to the entire Nixon Team. With his guidance, the Team will continue to deliver high quality products, meeting and exceeding customer requirements and industry standards.

Additionally, Gear Motions recently hired Anna Pastore to join the company as corporate controller. Pastore brings a positive attitude and many years of finance and accounting experience to the team.

Pastore graduated with an MBA from Chapman University, and received an undergraduate degree from Lemoyne College. She previously served as director of finance for Cascade & Maverik Lacrosse, and vice president of finance of the produce and technology division at Agway. In her spare time, Anna serves on the Board of HumaneCNY Animal Shelter, and loves to travel. She is married, has two grown sons and a beloved dog.

Pastore is looking forward to using her experience and enthusiasm to grow the accounting department and help bring the company to the next level. (*gearmotions.com*)

GMTA's Profilator GmbH

MOVES TO NEW PRODUCTION FACILITY IN GERMANY

GMTA is pleased to announce that Profilator has moved to a modern production facility in Wuppertal-Vohwinkel, Germany. With adjoining office space for the company's administration and technical departments, the new building is 13,000 square meters (139,930 square feet) and triples the size of its past location. Profilator will use the new facility to design, manufacture, and sell the machine tools to the global marketplace.

As of June 18, 2018, Profilator's physical address will be Zum Alten Rangierbahnhof 18, 42329 Wuppertal. The mailing address will be Postfach 11 01 52, 42301 Wuppertal.

June 17 was the last day of operation at the old facility and the Buchenhofenerstrasse 35 location was vacated. From June 18, all deliveries pick-ups, postal deliveries, as well as personal appointments on-site will take place at the new address. However, all clients will be able to reach their contacts at the same phone numbers and email addresses. (*www.gmtamerica.com*)

Siemens Industry, Inc.

OFFERS HANDS-ON AND ONLINE CNC TRAINING OPPORTUNITIES

CNC professionals from around the world are taking advantage of Siemens free training paths: hands-on and online. And the reason is clear. As an operator, you can gain the skills to maximize the output of your machine, increase your value to the business, and further your career. As an owner, you can skill up your staff to generate more shopfloor revenue. The means to control your future is in your hands.

"At the Siemens Technical Application Center, our goal is the education of CNC operators, programmers, and maintenance professionals," says Randy Pearson, technical application center manager for Siemens. "We aim to enhance and expand the knowledge and capacity of our students on SINUMERIK controls. If you want to become a power user, we have the courses for you. We also provide essential training to machine tool builders, importers, and dealers."

Through a team of knowledgeable Siemens instructors, you can gain first-hand experience working on the types of machines you will encounter in your own shop. A comprehensive schedule guides you on the journey from introductory classes through advanced 5-axis programming.

"Every month we provide level one courses on milling and turning," says Pearson. "Level two courses explore advanced G-Code programming, while level three focuses on multi-axis programming."

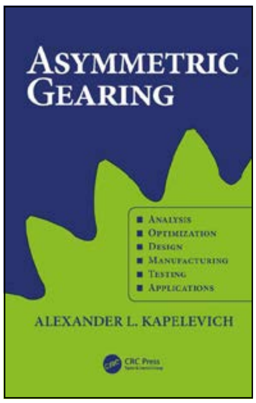
Classes are taught by Siemens machining experts, bringing a wealth of real-world experiences to bear, using several different teaching methods: SINUTRAIN PC-based classroom sessions, simulator-based classroom training and hands-on machining using industry leading brands.

In addition, service and maintenance classes are available to teach personnel how to perform PLC and drive diagnostics, check the topology of the system, commission, and troubleshoot the system.

Getting to a Siemens training center may not always be possible for you. But you still have plenty of options. Live, online courses are presented monthly, which include insightful question and answer sessions. Courses are archived and available on-demand, so you can access them anywhere, anytime. Our ever-growing CNC online learning resources are updated with new and fresh courses often. Plus, for larger groups, custom online training sessions are available. (*usa.siemens.com/cnc4you.com*)

Asymmetric Gearing

NOW AVAILABLE FROM CRC PRESS



Asymmetric Gearing (Hardcover; 271 pp.; CRC Press) by Dr. Alex Kapelevich, is now available for online purchase-at both CRC Press ($149.95) and Amazon ($140.46). Asymmetric Gearing discusses the history of asymmetric gearing systems stretching back to the 19th century. The book covers all aspects of asymmetric gear development from analysis to testing while also detailing real world applications and comparisons with competing symmetric gears. Kapelevich is a consultant at AKGears, LLC and a regular contributor to *Gear Technology*.

(*www.crcpress.com/Asymmetric-Gearing/Kapelevich/p/book/9781138554443*)

Röhm

ACQUIRES MASTER WORKHOLDING

Röhm Products of America Inc., has announced that it has acquired Master WorkHolding Inc. The acquisition enables Röhm to combine its 100 years of workholding experience with Master WorkHolding's 30 years of experience to deliver a truly complete range of standard and custom workholding products and automation solutions for all CNC equipment.

"With Master WorkHolding joining the Röhm team, we will be able to deliver even more comprehensive workholding and automation solutions," said Matthew Mayer, chief executive officer for Röhm Products of America. "Both companies have prioritized helping manufacturers obtain quality solutions that maximize productivity and throughput, and this acquisition will make it even easier for our customers to obtain the highest levels of efficiency in turning, milling, grinding and robotic applications."

Established in North Carolina in 1988, Master WorkHolding has specialized in the design and manufacture of custom prismatic workholding for manufacturers across the continent and around the world. Following the acquisition, the company will serve as Röhm's North American manufacturing entity and provide the company with prismatic clamping fixtures.

"This year marks Master WorkHolding's 30th anniversary, and we are thrilled to celebrate it with our merger with

Röhm," said Mike Powell, the company's founder and president. "Together, we will be able to provide custom and standard lines of stationary and rotating workholding and automation, offering our customers a complete range of solutions."

An active member of the Society of Manufacturing Technology (SME) and the Association of Manufacturing Technology (AMT), the latter of which he served as director, Powell has more than 40 years of experience as a strong supporter of the manufacturing industry. His company, which began as a two-man operation, is widely regarded as one of the premier workholding suppliers in the industry. Prior to the acquisition, the ISO 9001-2015-certified Master WorkHolding sold and delivered thousands of projects over the last 30 years. (*www.rohm-products.com*)

Bourn & Koch

ANNOUNCES PERSONNEL CHANGES

Bourn & Koch, Inc. is pleased to announce that **Joe Goral Sr.** has accepted a new position within the company as business unit manager — grinding machine tools. Goral has worn many hats at Bourn & Koch. His first position with the company in 2013 was inside sales for the Bullard & King machine tool lines. He then served as technical support engineer, where he was responsible for successfully executing a new marketing strategy for Bourn & Koch machine tools. Most recently, he was the product manager for grinding machines at Bourn & Koch.

Bourn & Koch, Inc. of Rockford, IL, is pleased to report that **Rob Swiss** has recently joined the company as the national sales manager for gear manufacturing machinery. Swiss will be responsible for the sales and support of all gear manufacturing equipment for Bourn & Koch. This includes the new gear machinery lines of Bourn & Koch brand horizontal gear hobbers; Bourn & Koch and Fellows gear shaper brands; as well as all in-stock and custom remanufactured gear manufacturing machinery. Swiss will also assist with the design and development of new gear manufacturing machinery for Bourn & Koch. (*www.bourn-koch.com*)

Gear Expo

BECOMES MOTION + POWER TECHNOLOGY EXPO

The new Motion + Power Technology Expo (MPT Expo), formerly Gear Expo, has announced its inaugural event in October 2019. This unique trade show and conference, will bring 4,000 professionals looking for technical solutions from across the Mechanical Power Transmission, Fluid Power and Electrical Drive industries for three days of educational sessions, networking, and a full exhibit hall featuring industry leading companies. Motion + Power Technology Expo will take place at the Cobo Center in Detroit, MI, October 15–17, 2019 and is owned and operated by TheAmerican Gear Manufacturers Association (AGMA).

MOTION + POWER
TECHNOLOGY EXPO

The new Motion + Power Technology Expo will feature 80,000 net square feet of space, and include 300+ exhibitors from across the supply chain including gear companies, machine tools suppliers and electric drive solutions. The National Fluid Power Association (NFPA) will be a co-sponsor of the show, and will host a 5,000 set square foot Pavilion within the show, featuring 50 exhibitors.

"We are excited to transform Gear Expo into the MPT Expo with our partners including the National Fluid Power Association (NFPA). This is much more than a name change; through MPT Expo, AGMA is transforming the legacy of Gear Expo to include solutions from the mechanical, fluid and electric industries," said Matthew Croson, president, AGMA. "By creating a wider focus, exhibitors will have the opportunity to connect with more buyers from a wide variety of industries, and attendees will be presented with all three power transmission solution sets in one place. MPT Expo will be a great place to see and test out all of the latest advances in the industry."

With such important industry partnerships like the one created with NFPA, both associations are dedicated to keeping a technically-focused education program. Those in attendance will be offered a wide-ranging series of informative seminars taught by industry leaders and insiders. MPT Expo will be a convenient and affordable destination to advance one's knowledge of the industry, hone technical skills, and dive into the latest research and technical developments. Additional information about MPT Expo and new association partnerships will be released over the next few months.

Hundreds of companies have already signed up for exhibit space on the show floor, including industry leaders Timken Power Systems, Meritor, EMAG LLC, Gleason Corporation, Klingelnberg, Kapp Group, Mitsubishi Heavy Industry America, and others. (*www.agma.org*)

AMB 2018

MEETS AND EXCEEDS EXPECTATIONS

The AMB 2018 trade fair closed its doors recently. "Exhibitors, visitors and, of course, Messe Stuttgart are very happy – the AMB trade fair was a complete success," Ulrich Kromer von Baerle, spokesperson for the management team, recently announced. "There was a lot to offer, especially with regard to digitalization in production," Kromer added. This was true from the Digital Way and the Showcases to the exhibitors' stands.

"We had 1,553 exhibitors over an exhibition space of what is now more than 120,000 gross square meters, plus 91,016 visitors. These are all record figures for the Stuttgart trade fair center," Kromer announced. "We have started drawing visitors from further afield: Eighteen percent of the visitors came from 83 countries to attend AMB in Stuttgart." According to Kromer, this success has confirmed Messe Stuttgart's intention to push ahead with expansion plans it has announced as part of its 2025 master plan, such as the construction of additional parking spaces, a new Hall 11 and a second convention center towards the west of the trade fair site.

"We are extremely happy with AMB 2018. We were in Hall 10 for the first time, and we were very impressed with our stand location," said Irene Bader, director of global marketing at DMG Mori. Bader was equally complimentary of the new AMB concept with a new distribution of stands in the halls. "The whole trade fair site was buzzing, and people were flooding in from Entrance West, which was near to us, from 9 a.m. on the first day."

The quality of the visitors was also exceptional, according to Bader. After only three days, the number of quotations requested was far ahead of the previous AMB. Visitors to the trade fair mostly directed their questions towards topics that were focal points at the DMG Mori trade fair stand.

From September 15 -19, 2020, AMB will be celebrating its 20th trade fair. (*www.messe-stuttgart.de*)

AGMA

PRESENTS DISTINGUISHED SERVICE AWARD AT FALL TECHNICAL MEETING

The American Gear Manufacturers Association (AGMA) presented Terry Klaves, retiree from Milwaukee Gear/Regal, with the AGMA Distinguished Service Award during the 2018 Fall Technical Meeting last week in Oak Brook, Illinois. This award is presented to someone who has demonstrated dedication and leadership for the advancement of the gear industry and AGMA, exemplified superior vision and exceptional knowledge that has been shared with colleagues and achieved admiration and respect of peers. "Terry is a true example of a gear industry steward that has generously dedicated himself to the advancement of AGMA and its members," said Amir Aboutaleb, vice president of AGMA's Technical Division. "His leadership remains an intricate part of growing our technical department and fostering the future of young gear engineers."

Klaves began his career at Falk Corporation as a co-op student and completed his BS and MS degrees at the University of Wisconsin-Milwaukee. His long career took him to Milwaukee Gear in 2000 and was eventually promoted to Vice President of Engineering before retiring in 2017. His 45-year career continues through consulting and developing education and training courses and aiding in the AGMA mission. Most notably with AGMA, Terry was instrumental in the Epicyclic Committee, where he worked on AGMA 6123 including an annex on load distribution for floating planetary drives. Since joining the AGMA Technical Division Executive Committee in 2011, Klaves remains active on the Accuracy, Worm Gearing and Epicyclic committees. He also presented at the 2015 Fall Technical Meeting (FTM) on Advanced Mesh Analysis of Parallel Shaft Gearing and continues to contribute as a moderator. (*www.agma.org*)

November 1–6—JIMTOF 2018 Tokyo, Japan. The 29th International Machine Tool Fair showcases state of the art technologies and new inventions in the machine tool manufacturing industry where large numbers of national as well as international players from various parts of the globe will come to share their thoughts and opinions through this platform etc. in the plant, machinery and equipment industry. The event includes a keynote lecture by Hideyuki Sakamoto, director, executive vice president, Nissan Motor Co., Ltd., and a wide range of lectures, seminars and talk sessions to introduce and discuss the prospects of machine tools in various sectors. For more information, visit *www.jimtof.org*.

November 13–16—Formnext Frankfurt, Germany. Formnext is more than an exhibition and conference. It's an entire platform for companies from the world of additive manufacturing. Here, a veritable who's-who from the realms of design and product development, industrial tooling, production solutions, quality management, and measurement technology comes together with leading providers in basic materials and component construction. It will also explore clever ways in which AM can be integrated into process chains in industrial production. In addition, top international speakers and other experts will be on hand to engage conference attendees in in-depth discussions at the highest technical level. For more information, visit *www.mesago.de/en/formnext/For_visitors/Profile/index.htm*.

December 3–6—CTI Symposium Germany 2018 Berlin, Germany. CTI Symposium Germany provides the latest automotive transmission and drive engineering for passenger cars and commercial vehicles. The international industry event delivers the appropriate platform to find new partners for purchase and sales of whole systems and components. Automobile manufacturers, transmission and component companies give an overview and outlook on technical and market trends including digital manufacturing, IoT, zero-emissions, electric vehicles, hybrid transmissions and more. Speakers include representatives from Audi, ZF, VDA, Valeo, Jaguar, LG Chem, Magna Powertrain and more. For more information, visit *drivetrain-symposium.world*.

December 4–6—Power-Gen International 2018 Orlando, Florida. Power-Gen International provides comprehensive coverage of the trends, technologies and issues facing the generation sector. Displaying a wide variety of products and services, Power-Gen International represents a horizontal look at the industry with key emphasis on new solutions and innovations for the future. Topics include plant performance, cyber security, energy storage, flexible generation and more. To celebrate the 30th anniversary, the show is awarding 30 scholarships to new attendees. Learn more at *www.power-gen.com*.

December 5–7—AGMA Steels for Gear Applications Clearwater Beach, Florida. This new AGMA class allows attendees to make use of steel properties in a system solution and understand the potential that different steel options can offer for their various applications. Those in attendance will explore performance of the material and how the steel produced effects the component and system. Objectives include material properties, selecting materials, verifying and specifying steel properties, and applying methods. Gear engineers, gear designers, material specialists or metallurgists at OEMs, Tier 1s, Tier 2s etc, production engineers, technicians and managers should consider attendance. Instructors include Lily Kamjou, Patrik Olund and Fredrik Lindberg. For more information, visit *www.agma.org*.

January 7–11—SciTech 2019 From its creation in 1963, the American Institute of Aeronautics and Astronautics (AIAA) has organized conferences to serve the aerospace profession as part of its core mission. Spanning over 70 technical discipline areas, AIAA's conferences provide scientists, engineers, and technologists the opportunity to present and disseminate their work in structured technical paper and poster sessions, learn about new technologies and advances from other presenters, further their professional development, and expand their professional networks that furthers their work. Five focus areas include science and technology, aviation, space, propulsion and energy/defense. For more information, visit *scitech.aiaa.org*.

January 14–16—A3 Business Forum 2019 Orlando, Florida. The Association for Advancing Automation (A3) Business Forum is the world's leading annual networking event for robotics, vision & imaging, motion control, and motor professionals. Over 600 global automation leaders attended the 2018 show. A broad range of companies participate including Amazon, Ametek, GM, Fanuc, ATI, Gudel and more. The event includes keynote and breakout sessions on the human exploration of Mars, a global economic outlook, automation market update, trends in robotics, responsible artificial intelligence and others to be announced. Networking opportunities include a golf scramble, a wellness walk, and a first timer's reception. For more information, visit *www.a3automate.org/a3-business-forum/*.

January 22–25—World of Concrete 2019 Las Vegas, Nevada. Original equipment manufacturers from around the world and exclusive U.S. distributors of equipment, tools, products and services for the commercial construction, concrete and masonry industries attend World of Concrete. The show attracts approximately 1,500 exhibitors and occupies more than 700,000 net square feet of indoor and outdoor exhibit space. World of Concrete is the premier event for the commercial construction trades. Education tracks include engineering, safety and risk management, general business, business and project management and concrete 101. Interactive workshops include trainer training, construction boot camp, sales and more. For more information, visit *www.worldofconcrete.com*.

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

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

gear TECHNOLOGY

Gear Technology's Statement of Ownership, Management and Circulation

Additional information about *Gear Technology* and its audience can be found in our 2018 media kit. Download it at *www.geartechnology.com/adinfo.htm*

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f. Total Distribution *(Sum of 15c and e)* ▶			10,124	10,759
g. Copies not Distributed *(See Instructions to Publishers #4, (page #3))* ▶			300	300
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c. Total Requested Copy Distribution (Line 15f) + Requested/Paid Electronic Copies (Line 16a) ▶	13,360	13,981
d. Percent Paid and/or Requested Circulation (Both Print & Electronic Copies) (16b divided by 16c × 100) ▶	70%	76%

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17. Publication of Statement of Ownership for a Requester Publication is required and will be printed in the September/October 2018 issue of this publication.

18. Signature and Title of Editor, Publisher, Business Manager, or Owner: Michael Goldstein, Publisher & Editor-in-Chief — Date: 10-1-18

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☐ My company BUYS GEARS (22)
☐ I DESIGN gears (23)
☐ I am a SUPPLIER to the GEAR INDUSTRY (24)
☐ OTHER (Please describe) ______________________

What is your company's principal product or service? ______________________

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