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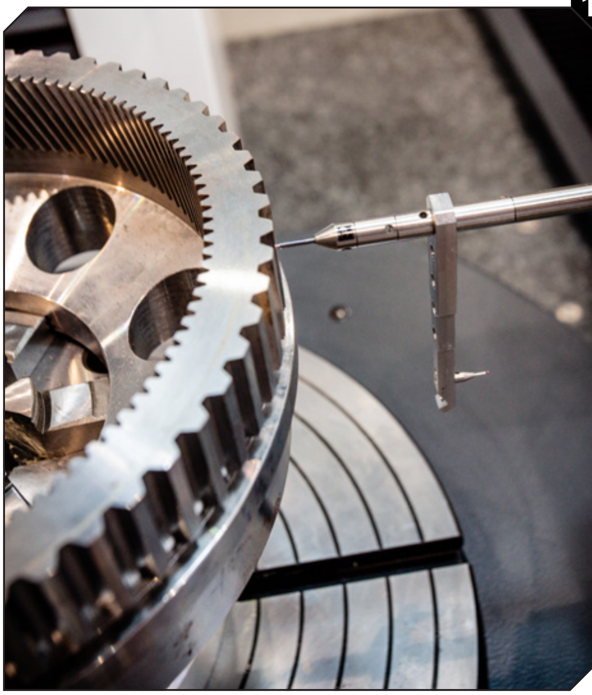

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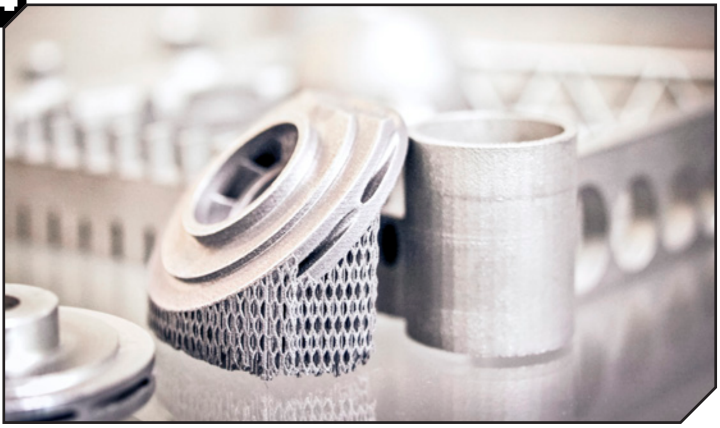

features

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departments

Photo courtesy of Mitutoyo

THE GEAR INDUSTRY'S INFORMATION SOURCE

www.geartechnology.com

Additive Manufacturing

The new packaging system from Höganäs allows for efficient shipping of powder, including possibilities to monitor the position and transport environment, vendor-managed inventory and minimized waste of both bulky packaging material and transport of dead volume and weight. Learn more here:

www.geartechnology.com/videos/Höganäs--Additive-Manufacturing-/

Workholding

Changing heavy workholding fast? It's possible with this centroteX S demonstration from Hainbuch:

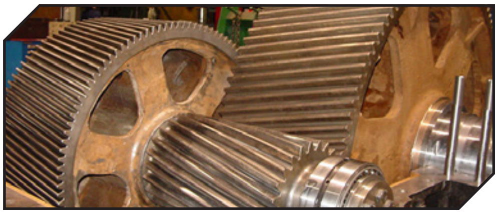
www.geartechnology.com/videos/Hainbuch-centroteX-Demo-/

Gear Talk with Charles Schultz

Take the time during the pandemic to strengthen business relationships, learn more about the gear industry, and develop your own gear-related superpowers. Read more here:

www.geartechnology.com/blog/

Gear Knowledge



Have gear questions? We have the answers in the Michael Goldstein GT Library with electronic issues of *Gear Technology* from 1984 to present:

www.geartechnology.com/issues/

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Michael Goldstein founded Gear Technology in 1984 and served as Publisher and Editor-in-Chief from 1984 through 2019. Thanks to his efforts, the Michael Goldstein Gear Technology Library, the largest collection of gear knowledge available anywhere, will remain a free and open resource for the gear industry. More than 36 years' worth of technical articles can be found online at *www.geartechnology.com*. Michael continues working with the magazine in a consulting role and can be reached via e-mail at *michael@geartechnology.com*.

Navigating without a Road Map

Publisher & Editor-in-Chief
Randy Stott

Often in life we're forced to make decisions with too little information. Phone's dead and you don't have access to GPS? Lost the instructions for assembling that new gas grill? Don't have the recipe for your favorite dessert? "No problem," I often tell my wife or my kids, "I'll just use the Force."

In low-stakes situations like those, you can get away with that. For me, "using the Force" has worked out often enough that my kids might actually believe I have superpowers, or at least some mystical connection to the universe (full disclosure: they're almost all adults now, so there's a small chance they've just been humoring me all these years).

But when the stakes are high, operating with too little information can be risky or even dangerous. Many leaders in business and politics pride themselves on their ability to make the right decisions. Going with their gut has always served them well. They, and those around them, can easily mistake lucky guesses for wisdom (either that, or those around them have just been humoring them all these years).

Throughout the COVID-19 crisis, we've all had to make choices with too little information. At first, whether to cancel our vacations or our business travel. Then, whether to keep our business open or shutter them in the name of safety. Whether to visit grandma. Whether to wear a face mask. Whether to go to the grocery store. Whether to furlough or lay off employees.

The economies of the world have taken a huge hit. The economic impact of this crisis is unprecedented in the history of the world. We're definitely in a recession. It's probably even a depression. No one's really using the "D" word yet, but that's mostly because we don't yet have all the data. And that's the worst part. We have to make decisions now without really understanding just how bad it is.

But to be clear, it's bad.

In May I attended a webinar by Jim Meil of ACT Research. The presentation, titled "Industrial Markets: How bad is it? Where do we go from here?" was presented by the American Gear Manufacturers Association as part of their ongoing webinar series. Meil specializes in industrial markets, including the gear industry, and he has been a regular presenter at the AGMA Annual Meeting and AGMA events for a number of years.

Meil's take was that the road to recovery is going to be quite long. The data he presented was sobering. For example, April's drop in U.S. industrial output was the greatest drop in 100 years of collecting data. Meil's best guess is that economic recovery will begin in the second half of 2020, but that it will probably be 2022 before things are back to normal.

And even Meil, who specializes in this sort of thing, admits there's a lot of hope and guesswork in his prognosis. The problem, he says, is that we just don't know the extent of the damage or what's going to happen next. Will there be a vaccine? Will there be future outbreaks? Is COVID-19 going to come back strongly in the fall and winter?

Regardless, Meil's information is much better than my own. His guesses are better informed than mine.

Even though businesses are opening up and it feels like things are starting to return to normal, don't be fooled. We're still in for some rough times ahead. Having the best information will go a long way toward helping you make the best decisions you can. So I encourage you to visit *www.agma.org* to see what other educational opportunities are available and how else your industry's association can help you. There are more webinars to come, dealing with tough issues like tariffs, trade relations and more. Many of them are open to members and non-members alike, so they're definitely worth checking out.

In a situation as fluid as the one we're in, you're never going to get a detailed road map. But that doesn't mean you should just pick a direction and drive, either. The more information you have, the less your decisions will rely on guesswork. And although you'll still have to fill in some pretty big holes, at least you won't have to rely entirely on using "the Force."

J.Schneeberger Maschinen AG

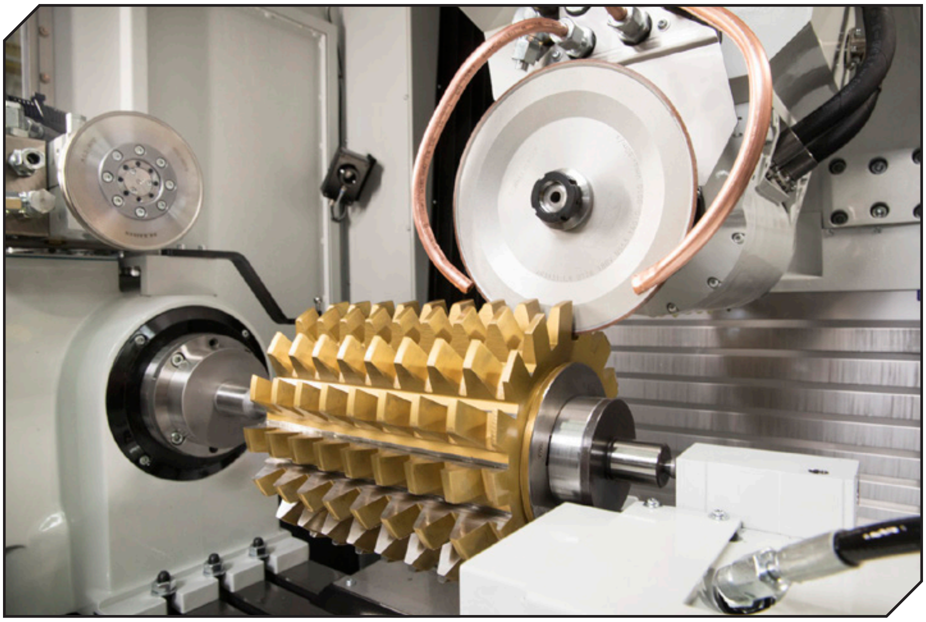
OFFERS MODERN DRIVE TECHNOLOGY FOR SEVERAL GRINDING OPERATIONS WITH CORVUS SERIES

The Corvus series machine is designed to offer, high horsepower 5-axis CNC tool grinder for pelletizers, slab mill cutters, and other applications requiring a long machine bed, high torque headstocks and high horsepower grinding spindles. Today, the machine has evolved with an intelligent modular machine design that allows it to be configured as a 6-axis broach grinder as well as a spline grinder, heavy-duty 5-axis machine, gear hob profiler or sharpener and thread grinder.

High 72 hp grinding motors with wheels up to 450 mm and tools that exceed 450 mm in diameters can be presented to the Corvus NGB. Grinding wheels can be automatically balanced after dressing, auto tails stocks, supports, etc., the options and accessories are endless. For the gear market, a special design of the wheel head called pencil grinding can grind a large gear profile with ease. Options like a wheel changer enhances the roughing, pre grinding and finish grinding of complex gear profiles with probed quality control and dressing options.

The operation of side clearance grinding for small flat broaches has been implemented into the Corvus NGB BBA machine. Side clearance height of a ¼" is not unusual and requires a small wheel. The use of the 30,000 rpm or higher spindle allows for more efficient grinding capability. The standard, double-ended HSK50 spindle remains to grind the face of the broach, straight or on a shear angle. Clamped on a CNC controlled trunnion style table, the tool can be finish ground in a single setup. Qg1 software is a highly graphical interface that welcomes the application knowledge of the operator. This compared to manual dry grinding has been welcomed as leap forward for broach shops, manufacturing or re-sharpening. Such special applications are the backbone of Schneeberger, working towards the easiest and best solution for the customer for affordable pricing.

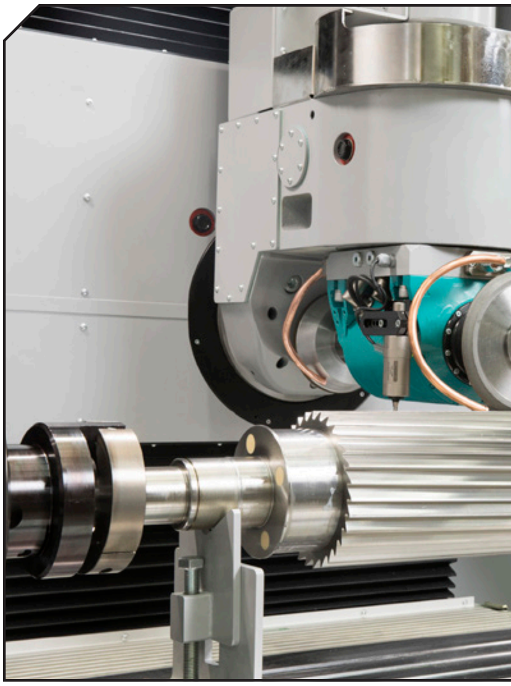
A further version of the Corvus NGB product line is the back off profile grinder, one of the most challenging requirements in manufacturing an aircraft broach. First the broach is profiled with a wide wheel that grinds the complete profile over. Multiple dressing maintains the tight tolerance before the machine switches to the short stroke linear motor vertical axis with a higher rpm spindle using the smaller 2"–3" wheel used to back off the clearance and drop right behind the cutting edge. Anybody manufacturing such broaches is aware of the incredible accuracy requirements, and as a prequalification before removing the broach from the machine appreciates the ability of the probe to scan the ground profile and calculate corrections to the wheel form.



High 72 hp grinding motors with wheels up to 450 mm and tools that exceed 450 mm in diameter can be presented to the Corvus C.

Eliminating multiple setups is the ultimate benefit of this machine as well as the incredible grinding speed the linear motor allows. A 40 percent time improvement is not uncommon. The same machine configuration is used to grind car panel stamping dies. The die form is digitized by the 3D probe and with the reciprocation grinding motion, the form is duplicated on the die to achieve the smallest possible cap for punching out car body panels.

The machine length capacity is offered in various lengths of 850 mm, 1,250 mm, 2,100 mm 3,100 mm. All lengths feature the FANUC linear motor technology to eliminate vibrations, heat and wear as well as offer the highest positioning accuracy. The variety of wheel head configurations offers a wealth of applications, face grinding high helix hobs, coarse pitch hobs profiling as well as face grinding. Rack grinding, thread



roll dies, scrolls compressor screws, any type of broaches can be introduced to the machine. The extreme size of a slab mill cutter with the intricate cutting-edge geometry on the inserts require the rigidity of the Corvus machine. The stationary table accept almost any extreme weight due to the traveling column maintaining grinding forces no matter the size of the tool.

Aside from the flexible modular machine design, Schneeberger offers a variety of automatic loading systems for the tools as well as the wheels packs. A multi pallet system for either 2 or 4 pallets is complimented with a circular magazine tool storage for very heavy tools. Loading carts for easy access or, ultrasonic parts washers and laser marking can be incorporated in the loading cycle.

The Schneeberger technology is complimented with a easy to understand graphical programing interface Quinto *Qg1*. The simple steps using easy to understand pages supported with help text and graphics are essential to make the machine shop conform and user friendly. Also, the latest capability of accepting step file format allows the software and machine to handle just about any type of application, tool or none tools to be ground.

The versatility and flexibility of the Schneeberger Corvus machine welcomes special requests and the challenges that are turned away from the general machining industry.

For more information:
Schneeberger Corp.
Phone: (847) 888-3498
www.schneeberger.swiss

The intelligent modular design allows the Corvus to be utilized for several different grinding applications.

Röders GmbH

OFFERS FLEXIBLE GEARWHEEL PRODUCTION WITH 5-AXIS MACHINING CENTERS

The manufacture of gearwheels for machine building applications usually involves machines especially designed for the purpose. Important techniques include gear hobbing, gear shaping, gear-generating planning, profile milling and profile broaching. Generally, specialized tools whose geometry is precisely adapted to the workpiece are required. Due to the stringent requirements placed on the hardness of the gearwheel surfaces, manufacturing is often carried out in three steps: soft machining, hardening and finishing. New developments in the field of hard machining now enable fast, single-stage manufacture with general-purpose 5-axis machining centers.

"In the production of gearwheels for industrial use, such as in mechanical engineering, speed and flexibility are often crucial factors," said Dipl.-Ing. Jürgen Röders, managing director of Röders GmbH in Soltau.

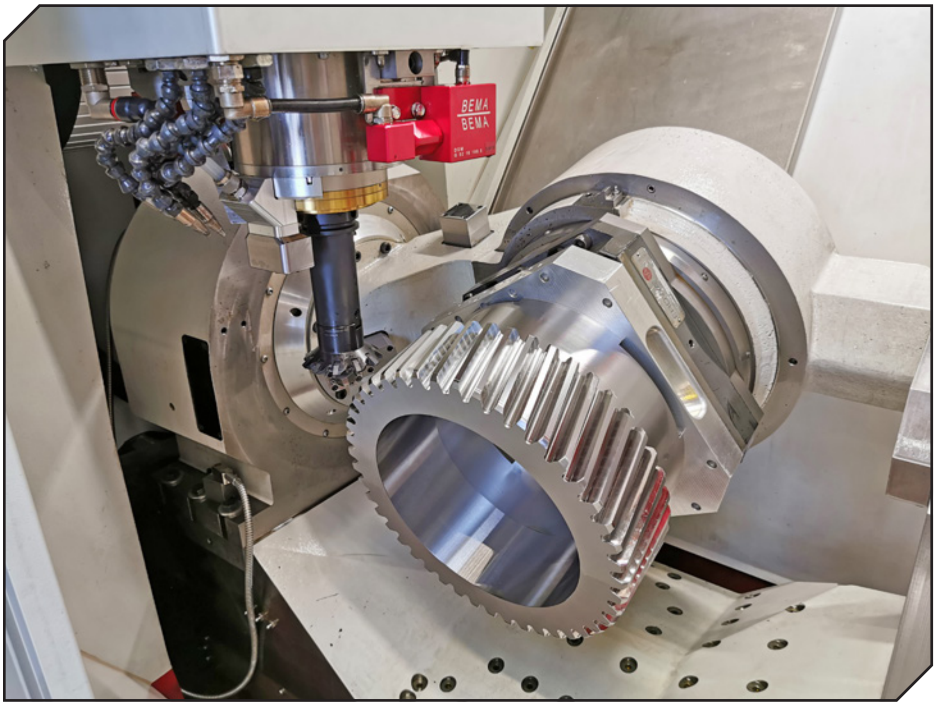
While sectors such as the automotive industry prioritize large quantities, the batch sizes in mechanical engineering are significantly smaller. Sometimes less than ten items are required and occasionally only single pieces. However, the deadline pressure is frequently considerable. This is true when the machining steps and the elaborate advance production of tools with a specially adapted geometry prove to be a handicap. A plant technology which enables a medium-sized gearwheel to be produced in good quality from a hardened blank within roughly one working day is of particular interest for sub-contract job shops, who have specialized in the manufacture of industrial gearwheels in small quantities and short deadlines.

"For the production of gearwheels, one needs purpose-designed CAM software that covers the various types of tooth profile correction," said Carsten Wendt, who supervises the development project. The technology partner here is the CAM software developer Euklid, a company that has developed a program designed precisely for these assignments in the form of *Euklid GearCAM*. This convenient software module supports the user in producing highly accurate gearwheels on standard milling machines. This solution is of particular interest for those companies which need one-off items or small batch sizes as a prototype, a special model or a replacement for failed parts in existing gears — either in parallel to or as a supplement to their normal production.

The program also takes account of the usual tooth profile correction functions such as width and depth crowning as well as tip and root relief. Another benefit of producing on a 5-axis machining center is that no correction is required for what is known as the tooth flank bias, which may cause problems in some of the conventional manufacturing technologies as a consequence of limitations to the machine kinematics. In contrast, this problem does not occur in the first place when a 5-axis milling machine is used.

"The precision of the machining center used plays a crucial role in gearwheel production," said Sales Manager Dr.-Eng. Oliver Gossel. Since Röders developed its system for use in particularly demanding mold and die-making operations, the system inherently meets the most stringent requirements concerning precision and dynamics. Activities within this segment involve machining materials with degrees of hardness in excess of 60 HRC, while maintaining accuracies down to the single micrometer range.

The machines used for this project, such as the RXP 601 DSH, are not only suitable for milling applications, but

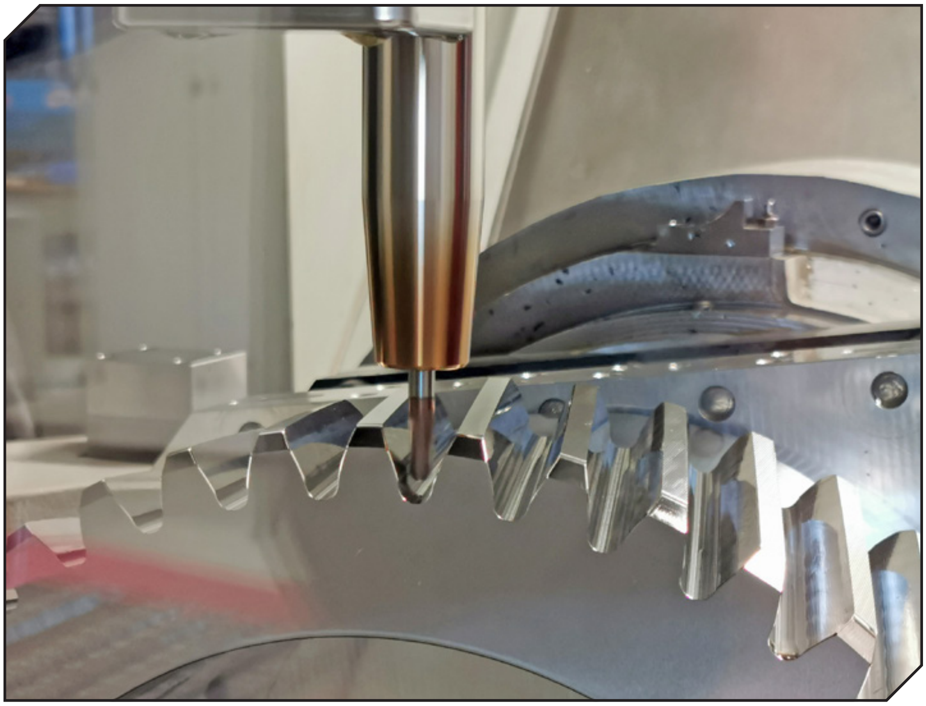


High-quality gearwheels are produced from hardened blanks within a very short time on 5-axis milling centres supplied by Röders.

also for jig grinding. Their accuracy is assured by a whole host of engineering design features, ranging from the use of a solid machine bed made of polymer concrete, via high-precision guide systems and frictionless linear direct drives, through to sophisticated temperature management with internal media flow channels in all essential components. Temperature-conditioned intermediate elements stop the diffusion of heat from the drives into the machine bed.

Particular attention is also paid to the temperature-dependent lengthening of the main spindle, which is monitored and compensated for by the control unit. Another important feature is the exceptionally high clock rate of the controller intervals ("Racecut"), which enables even the smallest path deviations to be detected and corrected. Other positive factors are glass scales with a resolution of 5 nanometers and a patented weight compensation system for the z-axis.

The extensive compensation for all deviations in position and angle of the rotating/swivelling table additionally plays a special role. For this purpose, the unit passes through more than 400 different positions of the two rotational axes and its position is recorded with high accuracy at each step during this process. The position and angle data thus determined are stored in the control system as a reference.


Standard milling cutters from the internal tool magazine are used to produce the tooth root relief. Photo courtesy of Klaus Vollrath.

"Tools with significantly larger dimensions than is usual in milling operations are used in the machining of gears, and therefore, an additional tool magazine is available for them," said Röders.

The magazine arranged beneath the portal can accommodate three tools with diameters of up to 200 mm. As a result, the chain magazine inside the machine remains unchanged and stays stocked with the usual tools of smaller diameters. The position of the magazine and its protective roller shutter prevents even the smallest contaminant particles or chips penetrating, which might otherwise cause angular errors between the machine interface and the tool. A further positive aspect is that the vector control of the main spindle guarantees the transfer of these special tools always takes place in the same angular position so that even after multiple tool changes no misalignment of the grinding tools can occur once they have undergone dressing.

Another special characteristic of these tools is a separate piping circuit for the grinding oil supply which is installed together with the tool as a single package. As a consequence, the nozzle is always exactly aligned and thus guarantees an optimal oil supply for the contact zone between grinding tool and workpiece.

"Since there are hardly any restrictions in the selection of tools, the operator enjoys an exceptional freedom of choice," Gossel said. Instead of expensive and sophisticated special tools such as grinding worms, gear hobbing mills or shaving cutters, the jobs can be carried out with milling cutters, grinding discs and grinding wheels of comparatively simple design. In the case of the grinding tools, the use of a truing wheel makes it possible to choose between a simple planar geometry or the production of a contour with a shape adapted precisely to specifications. The latter solution permits higher productivity.

The software offers the choice between various machining strategies and tool preferences for roughing and finishing. Using the tooth geometry and prescribed tolerances, *GearCAM* automatically minimizes the number of tool paths in such a way that the tolerances are maintained exactly. The corresponding cutting and performance data can be obtained from a configurable tool database. Depending on the specifications, the tooth quality may reach level 2 or 3. A further advantage of the new solution is that cylinder surfaces such as the bore or shaft can be machined in-line on one clamping position.

The latest tooling option now available in the form of InvoMilling provides a combination of special milling tools developed in collaboration with Sandvik and a correspondingly optimized milling strategy.

"The system has recorded such a success among our customers that we have since developed special options for automating the processes as well," said Wendt. "First and foremost, these are compact RCS workpiece and tool magazines with integrated handling that enable automated changing of the workpiece so that the milling center can be operated 24/7 almost without interruption. This makes it possible to achieve low manufacturing costs even for one-off items. Thanks to the technology partnership with Euklid, Röders now provides the customer with full application support not only for the milling center, but also for the *Euklid GearCAM* software."

Hence, selecting a system such as this would give customers two highly interesting options at once. Firstly, the user is enabled to produce a ready-to-use gearwheel of high quality from a hardened blank in an exceptionally short time. Additionally, the customer would simultaneously have an extremely precise and powerful 5-axis milling center that could also be used for a wide range of other operations within the firm.

For more information:
Röders GmbH
Phone: +49-5191-603-43
www.roeders.de

Heidenhain

EXPANDS TNC 640 CONTROL CAPABILITY

Heidenhain is bringing to market its new Gen 3 version of its high-end TNC 640 control for machine manufacturers and end users looking for forward-thinking manufacturing capabilities. This control is useful for machines ranging from 3-axis milling to 5-axis simultaneous machining with milling, turning and grinding operations with up to 24 axes. It is scheduled to be displayed at IMTS 2020 trade show in Chicago (Sept. 14–19) in booth #135226.

With its new Gen 3 drives, the TNC 640 boasts powerful inverters and controller technology that are key components in the complete system of its control package. Now providing even higher spindle and axis dynamics during the manufacturing process, these drives also require less space in its electrical cabinet, and result in reduced storage, mounting costs and servicing time.

With Gen 3 drives serving as the new system foundation, new TNC 640 customers will benefit with high availability and surface quality with shortened machining times, as well as with any other upcoming path-breaking functions of Heidenhain controls.

Some of the new feature highlights of this latest generation TNC 640 control include new jig grinding functions, Extended Workspace Compact, Optimized Contour Milling (OCM) within its "Dynamic Efficiency" package, as well as the ongoing option of a "Dynamic Precision" package. Also, Heidenhain's new StateMonitor 1.3 makes it very easy to remotely monitor efficiency improvements and ROI of these new CNC functions.

For more information:
Heidenhain Corporation
Phone: (847) 490-1191
www.heidenhain.us

CMM for Gear Inspection

Why a CMM for Gear Inspection is a Viable Option

John Fox, Dimensional Metrologist, Mitutoyo America

Gear inspection has long been a highly specialized costly investment and an overall challenging part of the gear manufacturing process. Given that complicated gages, testers, and CNC equipment all go into creating high quality gears, companies may want to invest in a CMM to streamline inspection.

A CMM multi-probe checks a precision gear's tooth, taking and recording measurements faster and more accurately than either a micrometer or tooth caliper.

The inspection benefits of CMMs

A CMM can be used for gear measurement, production and setup, including measurement of purchased gears.

One of the reasons CMM equipment has become popular for gear measurement is that it's a more economical and a lower priced option than conventional dedicated gear inspection equipment. Today, the cost of fully-programmable, fully-automated, sophisticated gear checking equipment can range from $300,000 to $350,000 or more. And this doesn't include the cost of master gears and artifacts needed for setting dedicated gear measurement equipment. The cost of all required components can be at least 2.5 times as much as the cost of CMM machine equipped with a rotary table, high-speed scanning probe head and gear measurement software.

CMM's are highly versatile, providing the ability to precisely measure different types of workpieces including small parts like gears and larger parts such as engine blocks. This versatility can be a big money and time saver. All photos courtesy of Mitutoyo America.

Types of CMMs to consider

Of course, it's important to keep in mind that the type of CMM used to measure gears will depend primarily on the gear size and weight. For large gears with diameters of more than a meter, or for those that are overly heavy, a high-precision, horizontal arm CMM with a rotary table solution is best. This kind of CMM is typically used for inspecting large-scale gears like those used in ships and heavy equipment powertrains, as well as turbine gearing and those used in nuclear and thermal power plants. Due to the open-access structure of this style of CMM, inspection of such large gears is easier.

Conversely, bridge CMMs are usually better for measuring small or medium size gears, and come in two available styles. The first style has a fixed table with moving bridge, while the other has a moving table with a fixed bridge. This latter affords greater accuracy because the servo drives are located at the center of gravity, with a moving bridge the X-axis drives along one side, so the accuracy will change as the z-spindle moves in X.

Other inspection uses for CMMs

In addition to replacing dedicated inspection equipment, CMMs can also replace many of the smaller, hand-held and functional gages used in gear inspection. It should be noted that there can be issues around lack of repeatability between operators using manual inspection methods, as well as issues

A small pinion gear is checked by a CMM. Using a CMM to inspect gears allows for faster, more accurate results without having to rely on specialized instruments.

GEARPAK

Gear type	Touch-trigger measurement	Scanning measurement	Required software package/Remarks
Cylindrical spur gear	●	●	**GEARPAK Cylindrical**
Cylindrical helical gear	●	● *1	**GEARPAK Cylindrical** *1: Does not support a cross-stylus
Worm gear (cylindrical)	●	● *2	**GEARPAK Worm** *2: MRT and MPP310 (Q) are required.
Worm wheel (cylindrical)	●	●	**GEARPAK Cylindrical** Cylindrical gears only
Bevel gear	●	—	**GEARPAK Bevel** Supports Gleason gears. Note: Some gears are not supported.
Hypoid gear	●	—	**GEARPAK Hypoid** Supports Gleason gears. Note: Some gears are not supported.

Specialized gear measurement software is key when inspecting many different types of gears with precision. Optimal software modules can analyze measurement results to document, present results and archive the data in practical structures.

concerning slower speed of measurement in general.

It's also good to remember that with manual gages results are written down, making them subject to human error and incorrect values being recorded. An automated CMM can also measure parts while an inspector continues to perform other duties, leading to more accurate, consistent and repeatable results and reporting.

CMMs can even be placed on the shop floor alongside production machines, as long as rapid and dramatic temperature changes, as well as vibrations, are taken into account. If the temperature is somewhat stable, there usually will be no major noticeable errors, even given the tolerances required for gears. And many modern CMMs today come with temperature sensors to help ensure proper compensation is made for any temperature fluctuations that do occur.

Software is important for all forms of gear measurement

Beyond the precision and accuracy of CMMs, one of the keys to accurate gear measurement, whether on a CMM or on dedicated gear checking equipment, is the software. For instance, calculation of whether an involute curve is correct based on data points extracted during measurement requires the use of high-level mathematical formulas and sophisticated algorithms.

That's why it's vital to look for CMMs with software that can handle these calculations, and can even combine intuitive icon-based programming with the ability to import native CAD models. In addition, it's important for users to be able to choose various software modules to analyze measurement results, to document and present results, and to archive the data in practical structures. This means software that integrates with networked systems for inline process control applications, as well as enables true enterprise-wide functionality.

For more information:
Mitutoyo America Corporation
Phone: (888) 648-8869
www.mitutoyo.com

CMM Integration

Mitutoyo CMMs can easily be integrated into automated cells. Mitutoyo has a Solutions Group that is dedicated to designing custom fixtures, automation control boxes, and integration in automated cells. A standard package that includes an IO card and a custom designed control box based on the work cell requirements can be added to any CMM to begin the process of integrating it into a work cell.

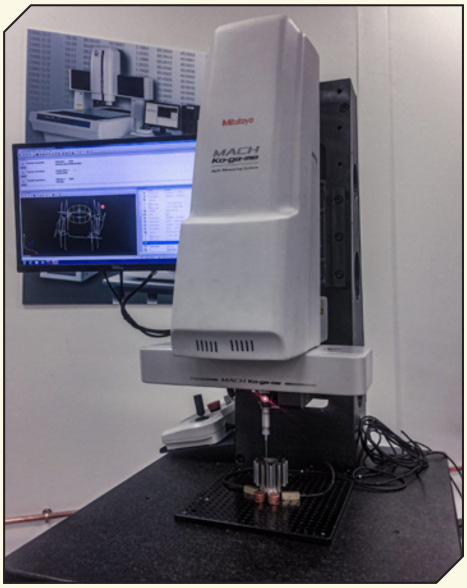
"They have a significant amount of experience setting up automated work cells with all types of robots in a multitude of industries and work with the local application personnel of Mitutoyo to provide a seamless integration process," said Derek Sporleder, application engineer at Mitutoyo, in an interview in 2019.

None of these advances would be possible without a user-friendly software package that can deliver the right inspection tools for machine operators of many different skill levels.

"The developers of the *GEARPAK* software have spent a lot of time developing a workflow that helps guide users through the setup of a gear inspection routine. There are various tool tips that give explanations for each input. The help files for a particular input can be easily accessed and are very informative as well," Sporleder said.

Mitutoyo uses Renishaw probing systems for touch trigger systems and most scanning probe systems so the customer has many options when it comes to probing. Additionally, rotary tables can be integrated into the CMM to improve cycle time as well.

"This gives Mitutoyo the ability to offer a system much more tailored to the customer's needs such that a customer who wants spur gears and is comfortable with discreet touch points could be offered a CMM configuration with a fixed probe head and touch probe system whereas another customer that makes various types of spur, helical, straight bevel and spiral bevels gears may need an indexable probe head with a scanning probe system and a rotary table," Sporleder said. Learn more about CMM inspection here: *www.geartechnology.com/issues/0719x/measurement-management.pdf*



Heat Treating News

Furnace Suppliers and Heat Treaters Remain Busy During Tough Times

Gear Technology Editorial Staff

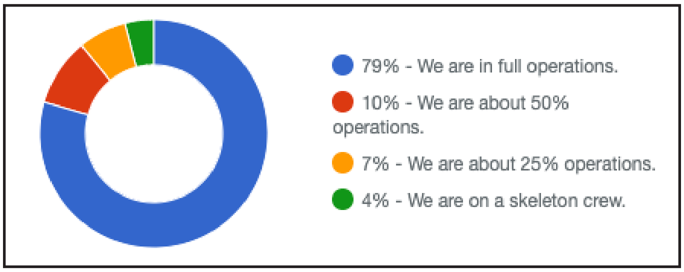
The following section includes the latest news, products and events from the world of heat treating.

MTI

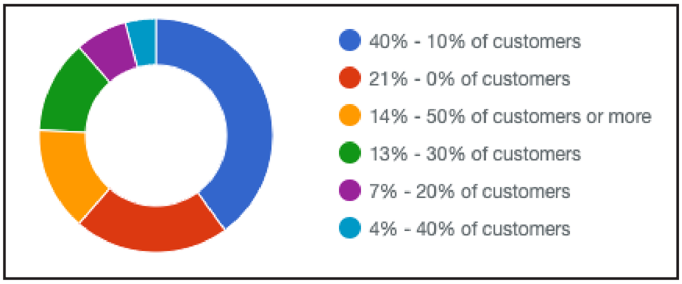
SURVEYS MEMBERS ON COVID-19 ISSUES

The Metal Treating Institute recently conducted a survey of members to determine how the COVID-19 Pandemic has affected the heat treating industry. The survey, which went out the week of May 11, asked members key questions related to their plant operations, customer operations, sales and government support. The results are presented here with MTI's permission:

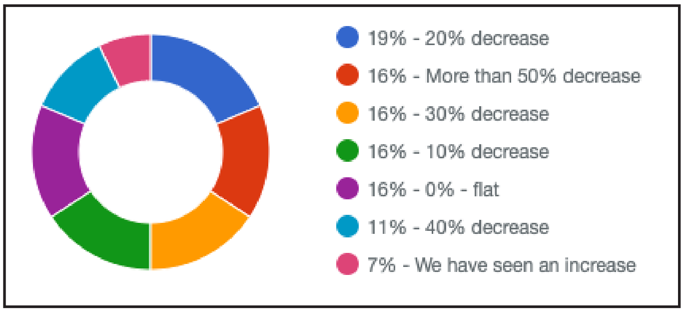
What Level is Your Heat Treat Plant Currently Operating at?



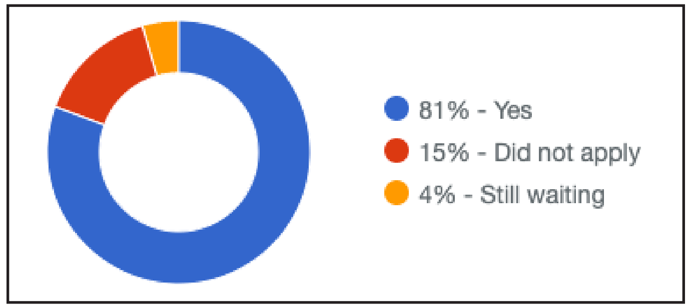
What Percent of Your Customers Are Shut Down?



What Has Been the Impact on Your Monthly Sales Since COVID-19 Started in January?



Have You Actually Received Funding from the PPP Program?



In addition to the survey results, MTI has provided industry with a wide variety of COVID-19-related resources on their web page at *www.heattreat.net/cht/coronavirus.*

IHEA

ANNOUNCES 2020–21 BOARD OF DIRECTORS AND OFFICERS

The Industrial Heating Equipment Association (IHEA) recently announced its 2020–2021 board of directors and executive officers. The new executive officers are Scott Bishop of Alabama Power Company as president, Jeff Valuck of Surface Combustion as vice president and Brian Kelly of Honeywell Thermal Solutions as treasurer. Outgoing president Michael Stowe of Advanced Energy assumes the role of past president.

IHEA President Scott Bishop says, "It is an honor to serve as IHEA's president for the 2020–2021 term. I look forward to continuing the great work IHEA has done for more than 90 years. Also, during this unprecedented time I would like to encourage our members to be proactive in finding ways to better serve our industry and make an impact." Bishop is highly involved in IHEA's Infrared Division. He has served as IRED chairman, presented at numerous workshops and seminars, and provided key support in the recent revision of the *Infrared Process Heating Handbook for Industrial Applications.*

IHEA also welcomes new board member Alberto Cantu of Nutec Bickley. Alberto has been involved with IHEA since 2011 and participates on the Safety Standards and Codes Committee. "I am very excited about this new role; I think it will be a great opportunity to connect with colleagues in the industry and help move it forward," Cantu states.

Continuing their service on the board of directors for 2020–2021 are: Gary Berwick, Dry Coolers, Bob Fincken, Super Systems, Inc., Doug Glenn, *Heat Treat Today*; Francis Liebens, SOLO Swiss Group, Daniel Llaguno, Nutec Bickley; John Podach, Fostoria Process Equipment, a div. of TPI Corp., and John Stanley, Karl Dungs, Inc.

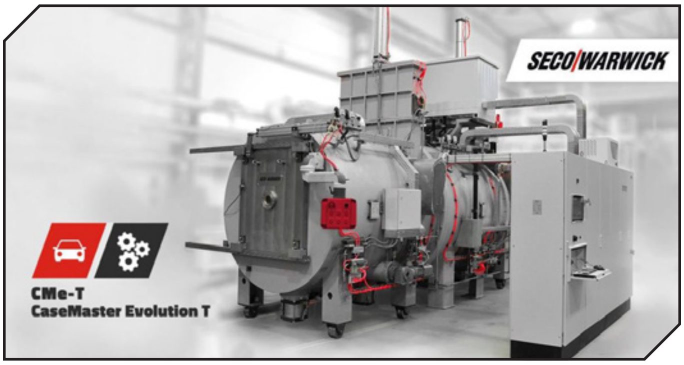
In addition, IHEA also acknowledges its current committee chairpersons: Government Relations Committee led by Jeff Valuck, Surface Combustion, Inc.; Safety Standards and Codes Committee led by Kevin Carlisle, Karl Dungs; Education Committee led by Brian Kelly, Honeywell Thermal Solutions; Marketing Communication & Membership Committee led by Erik Klingerman, *Industrial Heating* Magazine. The Infrared Division is chaired by Scott Bishop, Alabama Power — a Southern Company; and the Induction Division is chaired by Michael Stowe, Advanced Energy. (*www.ihea.org*)

Seco/Warwick

PROVIDES VACUUM FURNACE TO INDIAN MANUFACTURER

One of India's largest air cooler/heat exchanger manufacturers recently selected a vacuum furnace from Seco/Warwick. The customer's choice is a three chamber CaseMaster Evolution (CMe) furnace which will be used for heat exchangers. The client has decided on Seco/Warwick vacuum technology after a long period of trials with single and double chamber furnaces.

The CMe furnace with vacuum loading and cooling chambers is a semiautomatic brazing furnace that is quickly becoming popular especially in automotive, aerospace and defense industries due to its superb performance and high precision. Here, the client's focus was on increasing production volume of its air cooling/heat exchangers.



The client was previously using single-chamber furnaces but Seco/Warwick's three-chamber technology became so attractive that the client conducted a number of trials at various heat solution providers to finally decide on the furnace. The engineering team played a great role in the process with professional support to train the client's crew and acquaint them with the vacuum technology. As both parties stressed, there was a close cooperation on both sides and on all the levels starting with top management and finalizing on operating levels of the production team. Sharing information was transparent and the learning process was smooth.

CaseMaster Evolution–T (CMe-T) is a three-chamber vacuum furnace that delivers economical surface hardening using low-pressure carburizing (LPC) technology and high-pressure nitrogen quenching. The CMe-T furnace can replace existing lines and generators used for mass heat-treatment under protective atmosphere and oil quenching, while ensuring higher precision and process repeatability. This solution stands out not simply because of its three-chamber design, but more significantly because of improved process quality, cost reduction from doubling yields, and increased production flexibility.

These are among the key reasons that aviation and automotive manufacturers are becoming increasingly attracted to CMe-T as their heat treat solution of choice.

"The client has chosen Seco/Warwick technology after long trials with other single and double chamber solutions from our competitors. Although initially the client focused simply on increasing the volume of production there was the whole spectrum of benefits not offered by the competitors. In a word, the advantage through technology prevailed," said Maciej Korecki, vice president, vacuum business segment at Seco/Warwick.

"Our engineering team worked closely with the client since this was the first vacuum technology purchased by the manufacturer; furthermore, Seco/Warwick is prepared to provide full customer assistance in implementing both technology and crew training at the site," added Manoranjan Parta, managing director, Seco/Warwick India.

In addition, the company recently celebrated its 10-year anniversary in China.

"We started in 2010 in the Chinese Year of the Tiger. The Tiger, considered to be brave, cruel, forceful, and terrifying, is the symbol of power. Founded in the tiger year, we were forging ahead, and we were brave enough to challenge and strive for larger market share," says Sławomir Woźniak CEO of Seco/Warwick Group and former managing director of Seco/Warwick China.

"We went through different years representing various animals learning their skills, their ways of thinking and acting. Today Seco/Warwick is in a different place since the start, and we're proud of the whole team and their achievements, and looking to the future with the belief that we are on a good track to our Seco/Revolution," adds Liu Yedong, current managing director of Seco/Warwick China.

Seco/Warwick China gained new momentum in 2015 when Yedong became its general manager and implemented a number of actions to strengthen its presence in the local market. His reputations and industry experience in the Beijing Machine Tool Research Institute and the International Cooperation Department at The Ministry of Machine-building Industry, Voss GmbH, were crucial in achieving Seco/Warwicks objectives.

Heat treating technologies are being developed by the common efforts of all the engineering and technical staff working with clients on various markets across different industries, to understand common and new problems that lead to developing solutions. The Chinese team has provided many great insights and solutions which resulted in 12 unique patents in heat treatment processing.

With todays' total of over 60 employees, Seco/Warwick China boasts over 70% staff with higher education and 25% with professional title certifications. The company has a complete talent training plan and promotion system, it pays attention to the improvement and development of each employee's abilities, it organizes leadership, skill improvement and other trainings, and it is committed to shaping a good corporate culture for employees. (*www.secowarwick.com*)

Salto

ENTERS CANADIAN HEAT TREAT MARKET

Salto Heat Treating offers commercial heat treatment services in Ontario, Canada. The company's equipment allows for higher capabilities, larger projects, quicker set-up time for recurring jobs, and product order charting and traceability. The custom-built I.Q. line allows a 24 to 48-hour turnaround on most applications. Capabilities include:

Annealing: A heat treatment process which alters the microstructure of a material to change its mechanical or electrical properties. Typically, in steels, annealing is used to reduce hardness and help eliminate internal stresses.

Through Hardening: In an atmosphere-controlled furnace, parts are heated to the exact temperature and then quenched in oil, ensuring minimal warping and uniform properties to the parts.

Case Hardening: A cost-effective solution with fast turnaround for surface hardening and improved part or component wear resistance that increases toughness and prolongs component life.

Carburizing: Also referred to as case hardening, carburizing is a process that produces a carbon gradient extending inward from the surface and a surface which is resistant to wear. This treatment is applied to both low carbon steel, and high alloy steel as well.

Air Hardening: This occurs in an I.Q. furnace which results in a better finish and appearance on the part, and controls the minimizing of oxide, scale, distortion and decarburization.

Normalizing: An annealing process applied to ferrous alloys to give the material a uniform fine-grained structure, and to avoid excess softening in steel. It involves heating the steel to 70–120°F above its upper critical point, soaking it at that temperature for a period of time.

Black Oxide: Offers a long-term corrosion resistance and a durable, attractive finish. Unlike paint coatings, black oxide is non-dimensional and will not interfere with the function of the metal parts.

Induction Hardening: While typical scanners can scan up to three feet, this equipment can scan up to 6 ft, with a 9½" diameter and up to 600 lbs. With 24 different diameters of coils in their inventory, Salto offers quick turnaround time on most jobs.

Stress Relieving: Machining and welding induce stresses that can cause long-term distortions, cracking, and tolerance loss, especially in bigger and more complex parts. Stress relieving benefits large complex weldments, castings with heavy machining, and parts with tight dimensional tolerances.

With technology constantly evolving, Salto offers state of the art equipment and custom-designed software. The heat treat team has more than 35 years of experience in the heat treat industry. (*saltoheattreating.ca*)

Bodycote

TO OPEN NEW ILLINOIS HEAT TREATMENT FACILITY

Bodycote will open a new state of the art facility in Elgin, Illinois, USA.

The new purpose-built facility has been designed as a replacement for Bodycote's ageing facility in Melrose Park, Illinois. The Elgin facility is scheduled to be operational in June 2020. It will support manufacturing supply chains in the Midwest region. The Melrose Park facility will be closed once the transfer of customers' work has been completed.

Bodycote continues to invest in acquiring, updating and building new facilities with new capacity and more operationally efficient services. The new Elgin facility is part of this ongoing strategy to provide the best possible capabilities, mix, and geographical network to better serve customers.

Tom Gibbons, president of classical heat treatment, North America, commented "I am delighted to be able to announce the opening of our plant in Elgin, Illinois. Our investment in the new facility enables us to expand our capacity and improve our ability to deliver high-quality heat treatment capabilities to our customers."

Bodycote has more than 70 facilities in North America. (*www.bodycote.com*)

Ipsen USA

ANNOUNCES NEW DIRECTOR OF HUMAN RESOURCES

Ipsen is pleased to announce the hiring of **Janet Nanni, PHR, SHRM-CP,** as its new director of human resources. Nanni stepped into this role after the May 6 retirement of longtime Ipsen HR director Nancy Kolar.

Nanni is responsible for managing all personnel and human resources programs for Ipsen USA, which includes locations in Illinois and Pennsylvania. Before joining Ipsen, Nanni was the director of human resources at Zenith Cutter in Rockford, accountable for global HR initiatives in two countries.

Nanni has more than twenty years of human resources experience in the industrial manufacturing and engineering service industries. She received a bachelor of business administration with an emphasis in human resources from the University of Wisconsin-Whitewater. She is also a Society of Human Resources Management Certified Professional.

Nanni's talent for transforming workplace culture and aptitude for building trust and accountability make her an ideal fit for the role. (*www.ipsenusa.com*)

IHEA

FALL COURSE REGISTRATION OPEN

The Industrial Heating Equipment Association's Fundamentals of Industrial Process Heating Online Learning Course continues to provide a high-level of learning to those in the industrial heat processing industry. IHEA is pleased to announce that registration for the 2020 Fall course is now open; for the past few years, both the Spring and Fall courses have sold out, so the association recommends early registration for those interested. Scheduled to begin October 5, the six-week class will run through November 15. The flexible online format and interactive forums with other students, along with scheduled office hours with the instructor are just a few of the benefits of this program.

The course is designed to allow students to learn in a flexible online format while at home or work. It is an affordable alternative to campus-based classes and allows students to go at their own pace. The course is intended for industrial process heating operators and users of all types of industrial heating equipment. Throughout the in-depth online course, students learn safe, efficient operation of industrial heating equipment, how to reduce energy consumption and ways to improve the company's bottom-line.

The curriculum includes the basics of heat transfer, fuels and combustion, energy use, furnace design, refractories, automatic control, and atmospheres as applied to industrial process heating. Weekly coursework, quizzes and a final exam project are administered to guide students on their progress and evaluate their knowledge of the material. For a complete listing of the topics covered visit *www.ihea.org/event/FundamentalsFall20*.

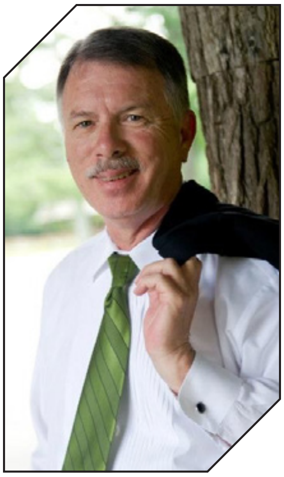
Industry expert Jack Marino will lead students in this 6-week online course. Jack, a registered Professional Engineer with over 40 years' experience in the heat processing business, is a graduate of Rensselaer Polytechnic Institute with a bachelor's degree in Aeronautical Engineering and holds a master's degree in Engineering Science from Penn State.

A former online student remarks, "Because of balancing an extremely busy workload and family life, I am not able to be on a regular schedule or take time in the evening to travel to a class. The advantage for me is that I can check in when time permits and still stay current on all activities. The course information is directly related to my work and I found it to be very beneficial."

Registration for the Fundamentals course is open now through October 1, at *www.ihea.org/event/FundamentalsFall20*. $750 for IHEA members; $925 for non-members. Cost includes an electronic course handbook, course instruction, quizzes and projects, class forums and the opportunity to contact the instructor throughout the course. Printed materials are available for an additional fee.

Thomas M. Crafton

SEPTEMBER 25, 1952–APRIL 28, 2020



Thermcraft President, **Thomas Morris Crafton,** 67, of Winston-Salem, NC passed away Tuesday, April 28th, 2020. He was educated at Trinity High School in Washington, PA, West Virginia University and the Art Institute of Pittsburgh.

Thermcraft was founded in 1971 by Tom's father and mother, Morris L. Crafton and Clara Martin Crafton. In 1978 Tom and his wife, Nancy, moved to Winston-Salem where Tom joined his parents working at Thermcraft, Inc. He was a successful businessman and was greatly admired by his colleagues.

Tom became President & CEO of Thermcraft, Inc. and expanded the company internationally. He has given presentations about small businesses in Washington DC and has relationships with companies throughout the US, Europe and Asia. (*thermcraftinc.com*)

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Additive Manufacturing — an Update

Jack McGuinn, Senior Editor

Writing about additive manufacturing (AM) and the 3-D printing of gears is somewhat akin to publishing an updated dictionary. A new edition dictionary is literally already out of date before it hits Amazon's or your local bookseller's shelves. New words are coined and definitions are updated constantly. So it is with AM — the technology is evolving so quickly that technical papers and other sources of AM information require constant revision.

That said, the benefits, rewards and promise of AM have remained pretty much the same. They include:

- The manufacture of complex geometries such as internal cooling or lubrication channels
- Reduce gear system inertia through the use of advanced designs that are difficult to manufacture conventionally
- Improvement of durability by the use of multiple, optimized materials in a single part
- Changing the cost of manufacturing by only placing material where it is needed
- Reducing product development time and time to market
- Improve safety and repeatability, and assist humans with aids and tools

And by the way, just what *is* additive manufacturing? It is the term used to describe the technologies that build 3D objects by adding layer upon layer of material such as plastic and, ideally for the 3D printing of gears — metal. After collaborating for a year, in January, 2020 the AGMA 3D Printing committee merged with the New Materials committee. The goal of the 3D Printing committee for 2020 was to dive deeper into binder jet for small MIM-type gears, L-PBF for high-end applications and DED for large gear repair. They have also been tracking new technology and materials development in this area closely.

Understand—3D printing for mass productions of gears is still just a goal not an achievement — yet. The committee has been following with great interest the development in the materials development space with the intention of learning more. So they developed a series of specific questions related to new materials and identified seven companies to answer them. The fruits of the committee's labor are reflected by the responses provided by the three responding companies featured in this article.

Therefore the following Q&A provides the latest information available according to experts in the AM materials industry. They include Jeff Grabowski, manager of business development for QuesTek; Dr. Anthony Manerbino, technical sales engineering, Ph.D. materials science, Elementum 3D; Manfred Reiter, business development manager additive manufacturing powder, voestalpine BÖHLER Edelstahl GmbH & Co KG, and Denis Oshchepkov, product manager, additive manufacturing powders for Höganäs AB.

One might consider the following an update to the 2019 white paper report — "Additive Manufacturing Technologies for Gears" — prepared by The Barnes Group Advisors, written primarily by Dr. Kirk Rogers under the auspices of the American Gear Manufacturers Association (AGMA).

Is your company currently producing any powder metallurgy alloys specifically for use in 3D printing applications? Do you know if any of your standard PM alloys are being purchased for use in these types of applications?

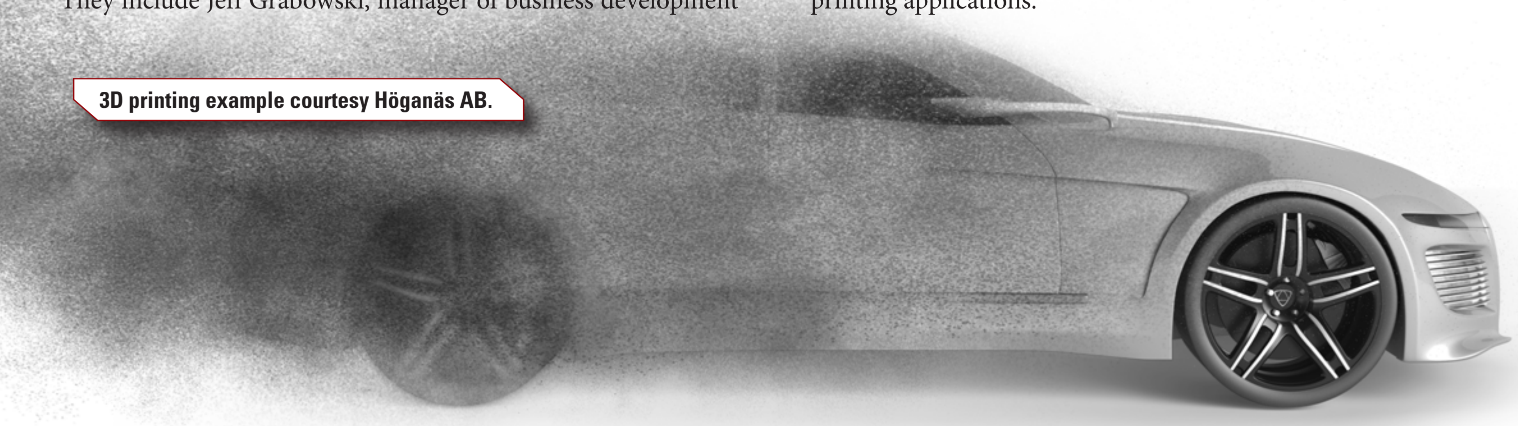
QuesTek. QuesTek does not manufacture powder, but we have worked on more than 50 projects in metallic additive manufacturing to resolve technical and matalallurgical issues that are known in industry. The major issues are cracking of commodity alloys upon rapid cooling, as well as the modeling and fine-tuning of unique microstructures (both beneficial and detrimental phases) that subsequently form.

We have used physics-based models and Integrated Computational Materials Engineering (ICME) technologies to optimize the composition and thermomechanical processing steps to design entirely new alloys across the metallic alloy spectrum including high strength steel, stainless steel, aluminum, titanium, nickel, copper, magnesium, and tungsten. These efforts aim to combine alloy printability with performance.

To date, we have focused on additively manufacturing prototype components of our new Al and steel designs.

Elementum 3D. (We) manufacture a family of Aluminum alloys (1000, 6061, 2024, 7050) refractories, nickel super alloys, and copper powders and Copper powders specifically designed for 3D printing for use in space, aerospace, and automotive applications.

Höganäs AB. We produce a wide range of materials for 3D printing applications.



3D printing example courtesy Höganäs AB.

Are the PM grades that you are manufacturing for 3D printing applications limited to austenitic alloys? Or are you producing martensitic alloys as well? What martensitic grades do you currently offer, and what do you have under development that you can share?

QuesTek. The following are four martensitic steels that QuesTek has designed, patented and demonstrated in AM processes:

- Ferrium C64 steel for gear, tool and die applications.
- QuesTek 17-4 PLUS. QuesTek is near completion of a project focused on designing a best-in-class martensitic stainless steel. QuesTek has demonstrated the ability to achieve higher performance, less variability and less sensitivity to manufacturing (fully heat treated and as-printed conditions) than traditional PH 17-4.
- Ferrium M54, demonstrated in wire AM as a performance upgrade from 4340 and 300M.
- Ferrium PH48S, a high strength, high toughness martensitic stainless steel.

Elementum 3D. We do not manufacture steel powders in house, but have partnered with voestalpine BÖHLER Edelstahl who currently produce powder for 3D printing applications in nickel-based alloys, tool steel, stainless steel, and low alloy steel. Several of these are martensitic grades. Two martensitic grades — BÖHLER M789 AMPO and BÖHLER E185 AMPO — were developed specifically for 3D printing to address the unique challenges of printing martensitic grades.

Höganäs. We produce a range of alloys on Ni, Co and Fe base. Fe alloys include austenitic, ferritic and martensitic grades. Martensitic grades in standard portfolio are following:

- Low alloyed: 4130, 4140,
- Martensitic stainless steel 420
- Maraging steel 1.2709 (18Ni30)
- Martensitic tool steels H13, H11

Additively manufactured piston by laser powder bed fusion (l-pbf) printed at the DMRC Paderborn from BÖHLER E185 AMPO.

What grades of case carburizing steel alloys are currently being produced (if any are) by your company for use in metal 3D printing applications? Are you planning to develop any PM grades of case carburizing alloys such as AISI 8620, 9310, 4320, 3310, etc. that could be used for 3D printing metal gears? Do you offer any other case carburizing alloys that have been used in traditional gear manufacturing that are also available in PM form for 3D printing?

QuesTek. Carpenter Technology is producing QuesTek's Ferrium C64 steel under a license agreement.

One of QuesTek's most advanced alloys in Additive Manufacturing is Ferrium C64 steel. As a wrought / forged product it is one of the highest performance gear steels available due to a unique combination of strength, toughness, fatigue life and temperature resistance. This alloy is beginning to replace common gear steels such as 9310 and Alloy 53, allowing for light-weighting, increased power density and improved thermal stability.

Starting in 2016 under US Army funding, QuesTek began to evaluate and demonstrate Ferrium C64 in Additive processing. It has been atomized several times in >500 lb batches. QuesTek has repeatedly printed on EOS machines test pieces for mechanical testing and microstructural evaluation. The strength and elongation has been found to be nearly the same as C64 forged bar. There is a slight debit in fracture toughness. Initial axial and single tooth bending fatigue results are comparable with that of Ferrium C64 forged bar. The following properties have been achieved on printed C64 that was heat treated: 200 ksi yield strength, 230 ksi ultimate tensile strength, 18% elongation, 85 ksi-in fracture toughness and a surface hardness of 64 HRC. The additive performance of Ferrium C64 so far has outperformed that of wrought AISI 9310.

QuesTek has also printed gear components for testing and has printed gear prototypes for a major aerospace corporation with plans for rig / system testing.

Ferrium C64 powder is commercially available from Carpenter Technology / Carpenter Additive.

Höganäs. Currently in production are case hardenable grade 16MnCr5 and several customer specific grades. We are open for development of other case hardenable grades based on clear business case in the meantime we believe that standardization is very important prerequisite for automotive industry to keep cost down.

Elementum 3D. The BÖHLER E185 AMPO is a low-carbon, low alloy steel designed specifically for case hardening applications, including carburizing, nitriding, and carbonitriding. voestalpine BÖHLER Edelstahl's development partner of this grade specifically targeted gearing applications. However, it does not require these heat treatments to achieve high strength, toughness, and good ductility; a development goal of BÖHLER E185 AMPO was also to achieve these important properties in the as-printed state, without any heat treatment, so it could also be used for rapid prototyping. But when heat treated you can even further improve the mechanical strength properties.

The issue of porosity in the 3D printing of metals is an important factor in determining their suitability for heavy or critical loading applications. A number of different issues can impact this. The lack of consistency of the powder particle geometry (spherical particles are preferred), size range in particle diameters for a given load of material, and oxidation on the surfaces of the powder particles can all potentially aggravate porosity issues. What tolerances on these parameters is your manufacturing process capable of holding today? Do you have the ability in your production process to alter the manufacturing steps and procedures that are available for narrowing the range(s)

Additively manufactured C64 single tooth bending fatigue gear samples. (Courtesy QuesTek.)

on any of these specific parameters?

Elementum 3D. The BÖHLER AMPO powders that voestalpine BÖHLER Edelstahl produces are all done with state-of-the-art VIGA units. Vacuum induction melting insures low gas contents. Argon atomization produces excellent sphericity. Oxidation is controlled with the use of Argon throughout atomization, sieving, and handling. These steps are used with all powder production; therefore, it is not intended to tweak manufacturing steps in order to alter the printing characteristics. With powders produced with state-of-the-art technology, Elementum 3D also refines 3D printer machine parameters to optimize part specific manufacturing.

Höganäs. We possess different atomization processes for production of powders for 3D printing actual tolerances depend on specific process, particle size distribution and alloy. The actual tolerances are also dependent on the produced volume and variations of the alloys therefore Höganäs seeks standardization of the steel alloys.

QuesTek. We are not a producer of Ferrium C64 steel, and the parameters in question are controlled by the alloy producer. Ferrium C64 has been atomized several times and printed with porosity levels ~0.1%.

What interest in hardenable steels is there in the AM community?

QuesTek. For applications in gears, hand tools, tool and dies and fast replacement of old gears where the supply chain no longer exists.

There is currently a void in industry where materials such as stainless, maraging and tool steels which are widely available in powder for AM are not ideal for gears because they are lacking one or more of the following: strength, toughness, ductility, ability to surface harden / low surface hardness.

Höganäs. The automotive and general industry show high interest in such material.

Elementum 3D. We, along with partner voestalpine BÖHLER Edelstahl, have established this relationship because we do believe there is strong interest in hardenable steels for Additive Manufacturing. This is why nearly all of BÖHLER AMPO powders for these applications can be heat treated, whether through quenching and tempering, maraging, or precipitation hardening.

Which gear steels have you produced in powder form for AM or other use?

Elementum 3D. BÖHLER E185 AMPO is designed specifically for gear applications, using 3D printing.

Höganäs. 16MnCr5.

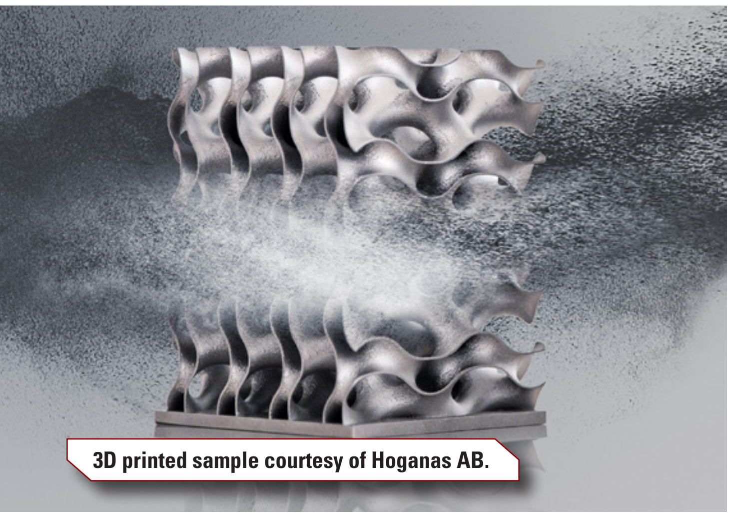
QuesTek. We do not produce powder.

Are you aware of any developments in AM-specific hardenable steels for uses such as gears?

QuesTek. I am not aware of any steels that were "designed" specifically for Additive Manufacturing (in that the material did not exist prior to AM being so popular).

Based on QuesTek's knowledge of the metal AM marketplace, we feel Ferrium C64 steel appears to be one of the most technically advanced high-performance gear steels being demonstrated in AM, though I am aware of others such as a product from GKN. Ferrium C64 was highlighted as such in the 2019 AGMA white paper on AM opportunities for the gear industry.

Elementum 3D. BÖHLER E185 AMPO was specifically developed as an AM-specific, hardenable steel for use in gears.



3D printed sample courtesy of Hoganas AB.

Have you done any comparative studies on your AM alloys compared to their traditionally manufactured counterparts? What did the studies reveal?

Elementum 3D. The development of **BÖHLER** E185 AMPO included comparative tests against the European standard grade for carburizing, DIN 1.71731 (16MnCr5). Tests included plasma nitriding, which showed BÖHLER E185 AMPO produced slightly harder, deeper case hardening when treated alongside 16MnCr5. Tests in the heat-treated condition showed also slightly better mechanical properties with a 3 times higher toughness than 16MnCr5.

Höganäs. We are constantly working on property verification and process development for 3Dprinted steels, including benchmark with traditional steels.

QuesTek. So far it is fairly similar, with no clear debit on mechanical tests. Fracture toughness was slightly lower and fatigue is still under evaluation. Component level testing will be conducted in later 2020.

What size parts have been produced out of your ferrous alloys? What quality expectations have there been for these parts?

QuesTek. Up to about 5" in length and 3" in diameter. Components printed well without cracking, and are nearing component level testing.

Elementum 3D. Size ranges are only limited by the build volume of the 3D printer. For laser bed powder fusion

(LBPF), Elementum 3D utilized EOS M290 and M400 3D printers with build volumes of 10" × 10" × 12" and 15" × 15" × 15" respectively. In most of the cases the expectation for the 3D printed parts is to provide equal life to the conventional parts, while enabling improvements in design and weight reduction that 3D printing is known for.

Höganäs. As we are aware, there are components up to 200 × 200 × 200 mm (being) produced, but in many cases customers are not sharing their application.

Have any of your AM alloys been used in a gearing application? If so, do you have any field performance feedback?

Höganäs. We have run internal investigation for 3D printing of gears.

Elementum 3D. BÖHLER E185 AMPO was developed with a partner for these specific applications and is currently being evaluated for long-term field performance of gears.

QuesTek. There has been no application of Ferrium C64 steel to date into real world applications. However, QuesTek has found significant interest from major aerospace OEMs, gear manufacturers and other companies that have to maintain large inventories of part numbers of gears and see AM as a solution. As the initial round of DoD funding is winding down, QuesTek is expecting 1-2 new contracts focused specifically on further advancement to raise the Technology Readiness Level of Ferrium C64 in AM.

The potential exists to achieve similar to improved gear performance by using an AM process versus traditional manufacturing and there are many potential benefits such as shorter lead times on small quantity orders and ability to use AM to further light weight a component. However, at the moment it is likely a more costly manufacturing method and thus the business case must be made.

Acknowledgement. Our thanks to the AGMA 3D Printing committee for the information gathered that was included in this article. Care to become an AGMA Printing committee member? Simply contact Mary Ellen Doran at *doran@agma.org.*

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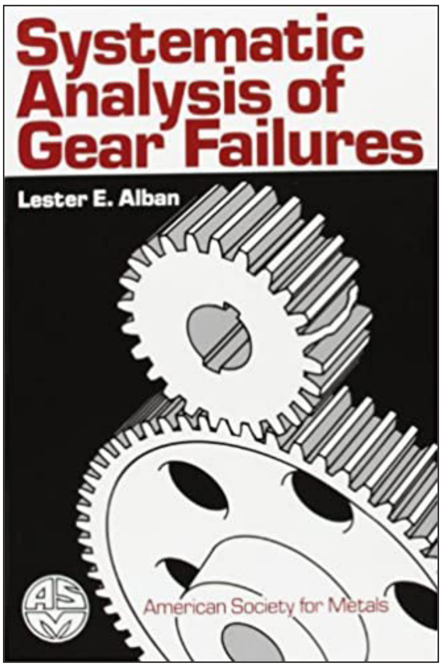
Ten Top Books for Gear Failure Analysis

Robert Errichello

Introduction

The purpose of this article is to provide an overview of proven books or standards dealing with failure analysis. Following you will find a short description of ten books or standards. At the end of the document you will find an overview and a detailed reference list.



1. Systematic Analysis of Gear Failures

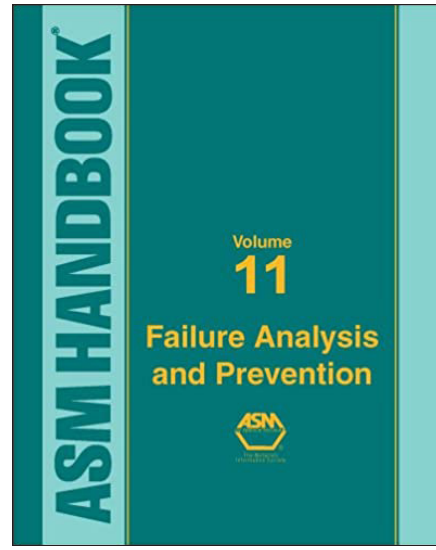
This book, by the metallurgist Lester E. Alban, who retired from Fairfield Gear in 1983, was published in 1985, so it contains some outdated nomenclature, such as "case crushing," which is now called "subcase fatigue." Nevertheless, it contains good practical knowledge from an experienced metallurgist that is helpful in understanding the metallurgical aspects of failures. It emphasizes a systematic approach to investigating failures, which includes careful review of all available background information and documentation, field examination of failed components by visual and physical means, and laboratory examination of all relevant components. It provides reliable guidance on the proper metallurgical properties of carburized gears. The chapter on modes of failure is relatively brief, and it uses outdated nomenclature, but it does contain many good images of failure modes. The chapter on causes of gear failure is a good discussion of microsegregation in forgings and its detrimental effects on diffusion of carbon during carburizing, which causes patchy, retained austenite at the surface of a carburized component. The discussion of case/core separation, which the author calls "internal rupture," is especially valuable because it points out the four factors that aggravate case/core separation:

- Deep case depth
- High core hardness
- Sub-zero treatment
- Shot peening

The author states: "Each factor by itself may be beneficial, but, when these factors exist together, they can be detrimental." The discussion of induction hardening illustrates the important fact that the terminus of a hardened case and unhardened area is an area with a high peak of tensile residual stress, which is a self-induced "metallurgical notch" that often results in fatigue failure.

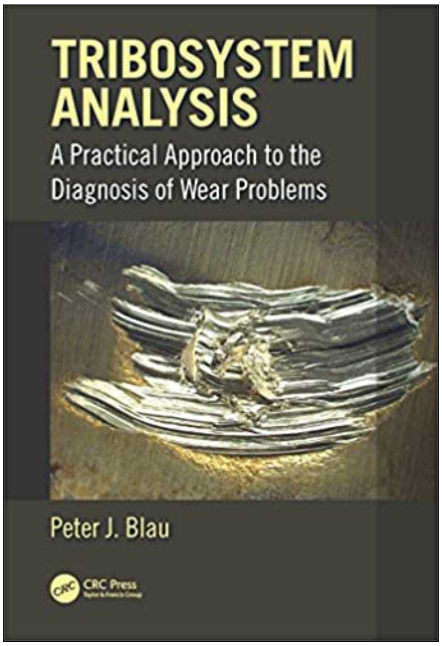
2. ANSI/AGMA 1010-F14, Appearance of Gear Teeth-Terminology of Wear and Failure

This is AGMA's official nomenclature for failure modes, mechanisms, and root causes of gear failure. Written by the AGMA Nomenclature Committee, it includes recommended remedies for each failure mode. Table 1 is an updated table of the original ANSI/AGMA 1010-F14 Table 1. It shows the latest classification system nomenclature that is currently being considered for the next version of ANSI/AGMA 1010. Although Table 1 is only a draft version of the classification system, and therefore not yet officially adopted by AGMA, it is likely to be approved by AGMA and published in the next version of ANSI/AGMA 1010.



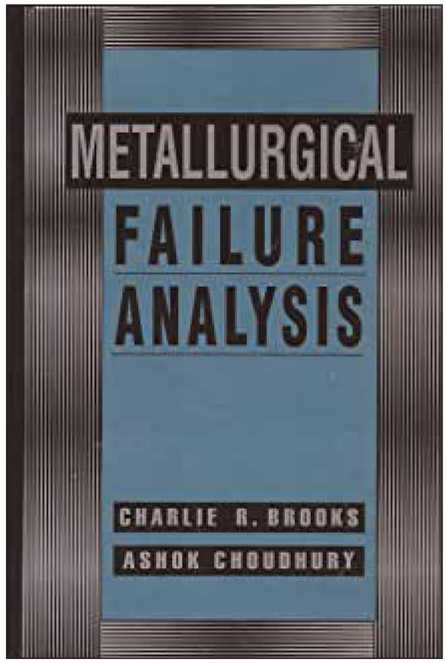
3. ASM Handbook, Vol. 11, Failure Analysis and Prevention

The ASM Handbooks are known for their authoritative quality and content, which is largely due to the devoted efforts of their editors, authors, and reviewers. Unfortunately, Vol. 11 (2002) does not have a separate chapter devoted to gears; rather, it provides the information on gears in separate chapters devoted to failure modes such as macropitting, micropitting, bending fatigue, and so on. The earlier version of Vol. 11 (1986), written by Lester Alban, was better organized and it had a separate chapter on failures of gears. However, the material is essentially the same as Alban's textbook, so one is better off by simply referring to his textbook. A yet-earlier version of the ASM Handbook, Vol. 10 (1975) and written by the ASM Committee on Failures of Gears, also had a separate chapter on failures of gears. However, it is dated and the nomenclature is essentially obsolete. Currently, ASM is planning a new version of Vol. 11, which apparently will have a separate chapter on gear failures.



4. Tribosystems Analysis

Peter J. Blau is a renowned tribologist who recently retired from Oak Ridge National Laboratory. He is currently the co-editor-in-chief of the *Wear Journal*, and a consultant in tribology. He contributed to ASTM G40-15 "*Terminology Relating to Wear and Erosion*," ASTM Annual Book of Standards, and has developed a classification system for wear problems in tribosystems. His book, "*Tribosystem Analysis*," features a good overview of the tools a tribologist uses to investigate wear problems, types of surface damage, options for solving wear problems, and tribotesting. The chapter on tools for imaging and characterizing worn surfaces is especially good, and includes discussion of light optical microscopy (LOM), specimen mounting, specimen cleaning, and cross-sectioning, taper-sectioning, and transmitted-versus-reflected light illumination. Surface roughness imaging and measurement methodology are also presented in detail, and the capabilities of SEM and TEM microscopy are compared. The book introduces the tribosystem analysis (TSA) form that provides a systematic method to define the characteristics of specific wear problems, which facilitates diagnosis and remedy for wear problems. Overall, this book provides a good overview of failure analysis of wear problems from a tribologist's perspective.



5. Metallurgical Failure Analysis

This book by Professor Charlie R. Brooks and Dr. Ashok Choudhury is an excellent introduction to failure analysis. It emphasizes fractography, i.e. — the study of fracture surfaces. It includes numerous fractographs to illustrate the morphology of fracture surfaces for many modes of crack propagation. The text accompanying each fractograph is the best I've seen.

Chapter 1 describes the many tools that failure analysts use for investigating failures — including light optical microscopy (LOM), transmission electron microscopy (TEM), and scanning electron microscopy (SEM). It includes seven appendices that cover all aspects of the handling and cleaning of fracture surfaces.

Chapter 2 explains the macroscopic orientation and features of fracture surface topography, starting with tensile testing and continuing with the effects of 3D principal stresses; material response to stresses; stress concentration; triaxial stress and constraint; plane stress versus plane strain; strain rate and temperature; crack propagation; ductile versus brittle fracture; fracture mechanics; fatigue failure; and ending with creep deformation. The description of ductile versus brittle fracture is the best I've seen on this often complex subject.

Chapter 3 is a very thorough (93 pages) treatment of fracture mechanisms, which includes numerous fractographs that illustrate the many ways that cracks can propagate. Plastic deformation by crystal slip due to shear stress, and by cleavage due to tensile stress, is explained, and examples of ductile void coalescence and quasi-cleavage fracture are given. Fatigue fracture topography including Stage I crack initiation, Stage 2 crack propagation, and Stage 3 fracture, is illustrated with fractographs. Features including microscopic striations and macroscopic beach marks are illustrated and their mechanisms explained. A series of six SEM fractographs at steadily increasing magnification presents excellent views of the morphology of beach marks. The chapter concludes with a treatment of high-temperature fracture topography, environmentally assisted fracture, and stereo examination of fracture surfaces, comparing SEM and TEM fractographs.

Chapter 4 illustrates the fractography of tensile overload, torsion overload, bending overload, and fatigue fracture. The unique morphology of fatigue fractures of rotating shafts in bending is illustrated by charts that show the influence of high and low nominal stress in combination with high and low stress concentrations. Fractographs are used to demonstrate the correlation of micro- and macrofractographic features of fracture surfaces.

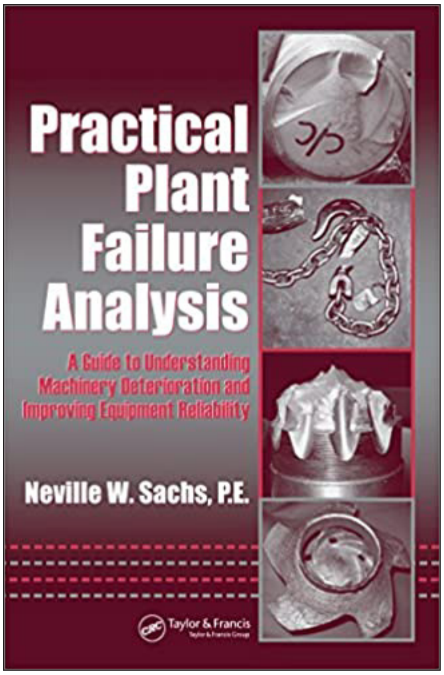
Chapter 5 presents eight case histories that illustrate the application of the principles of metallurgical failure analysis.

Overall, this book is an excellent introduction to failure analysis that emphasizes the principles without getting bogged down in needless detail. It is one of the best resources for understanding fractography.

6. ISO DTS-10825-1

7. and ISO TR- 10825-2

These two ISO documents remain in draft form as of this writing; they were created in cooperation with the AGMA Nomenclature Committee and are very similar — but not exactly the same — as ANSI/AGMA 1010-F12. ISO DTS 10825-1 provides the terminology and definitions including a lot of illustrations of the appearance of the individual failure modes. ISO DTR 10825-2 provides additional information for finding the cause of a failure mode and mitigation possibilities. Both documents shall replace the ISO TS 10825:1995.



8. Practical Plant Failure Analysis

■ Neville W. Sachs has written a guide to understanding machinery deterioration and improving equipment reliability. It is a book for engineers and maintenance people, which explains why failures occur and how to prevent them from recurring. It describes how to perform a thorough failure investigation and emphasizes the importance of on-site visual inspection of failed components. It is a primer on failure analysis that is written in a practical, down-to-earth style that would appeal to most mechanical engineers. The text covers many different components, including belt drives, rolling-element bearings, gears, fasteners, chains, lip seals, and flexible couplings.

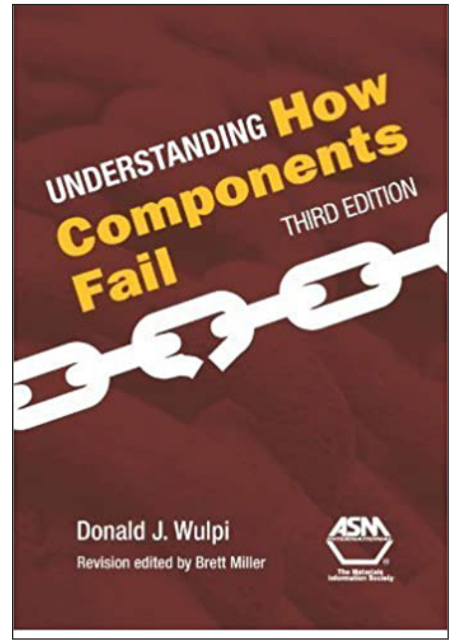
9. Failure Atlas for Hertz Contact Machine Elements

■ Tibor E. Tallian created the comprehensive "*Failure Atlas for Hertz Contact Machine Elements*;" the *Atlas* consists of parts I and II:

Part I has 1-Introduction, 2-Failure Classification, and 3-Appearance Classification. Readers should read Part I to understand how to navigate and interpret the *Atlas* before proceeding to actually using it.

Part II consists of plates (images) that illustrate the morphology of the failure mode. Each chapter of Part II is introduced by a description of the definition, failure process, morphology, causes and effects of the failure mode(s) covered. Sixteen failure modes are discussed (chapters 4 through 19). The Annex gives titles of the failure modes (plates). Examples include: rolling element bearings, gears, and cams. Each image is fully described by type, scale, component, speed, load, lubrication, and failure code. Following the image data, the failure description, image description, and suspected causes are listed.

Overall, Tallian's *Atlas* is a very comprehensive treatise on Hertzian contact failure modes. Unfortunately, some of the images have relatively poor resolution (due to publishing problems). The publisher provided a supplement of enhanced printing of a few of the problematic images. However, the enhanced images were not much improved over the original images. Nevertheless, Tallian's *Atlas* remains a classic work.



10. Understanding How Components Fail

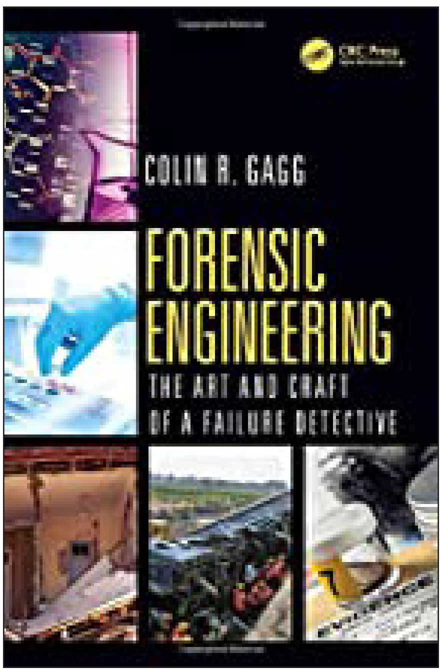
■ Donald J. Wulpi is a great teacher, which makes *Understanding How Components Fail* an easy read. It is ASM's classic best-seller and is a must-read for any person interested in becoming a failure analyst. Wulpi has a knack for relating component failure to everyday examples that make complex metallurgical subjects easy to understand. There are 14 chapters:

1. Techniques of Failure Analysis
2. Distortion Failures
3. Basic Single-Load Fracture Modes
4. Stress Systems Related to Single-Load Fracture of Ductile and Brittle Metals
5. Mechanical Properties
6. Stress versus Strength
7. Residual Stresses
8. Brittle Fracture
9. Ductile Fracture
10. Fatigue Fracture
11. Wear I
12. Wear II
13. Corrosion
14. Elevated-Temperature Failures

Each chapter illustrates the subject matter with large drawings and large images of the failed components and their fractographs. The many sketches, analogies, photographs, and examples make for a very thorough, yet easy to understand presentation of the basics of failure analysis.

Summary and Conclusion

Ref. No.	Strength	Weakness
1	Good, practical, metallurgical guidance on failure analysis. Especially good for carburized gears. Best description of case/core separation.	Outdated nomenclature. Only for gear failures.
2	Most comprehensive classification system for gears. Best resource for morphology, mechanism, and root cause of failure.	Only for gear failures.
3	Most authoritative and best writing style. Best resource for all aspects of failure analysis including how to manage a failure investigation.	Poorly organized, which makes it difficult to find information on gears.
4	Highly systematic nomenclature for wear failure modes. Good description of tools used by tribologists.	Some nomenclature conflicts with reference 2. Only for wear failures.
5	Best resource for microscopy and fractography. Excellent text accompanies each fractograph. Best description of ductile versus brittle behavior.	Limited information on gears.
6	Similar to reference 2. A work in progress.	Some outdated nomenclature.
7	Similar to reference 2. A work in progress.	Some outdated nomenclature.
8	Best description for how to conduct a failure investigation. Good practical information for industry. Good description of morphology of shaft failures.	Some outdated nomenclature. Information on gears limited.
9	Classic Atlas for Hertzian contact failures. Good writing style by a renowned bearing expert. Good description of morphology and mechanism.	Images have poor resolution due to reproduction problems. Only for Hertzian failures.
10	Good writing style and best introduction to the basics of failure analysis. Many everyday examples of failures enhance learning.	None.



Room for One More—Addendum to "Ten Top Books for Gear Failure Analysis". Shortly after I submitted the manuscript: "Ten Top Books for Gear Failure Analysis" to *Gear Technology*, I discovered a new book on failure analysis (Ref. 11), i.e.—***Forensic Engineering—the Art and Craft of a Failure***. The book, by Colin R. Gagg, is for anyone interested in learning what it is that a failure investigator does, what the responsibilities are, and what tools and methodology are used to discover failure modes and root causes. Although the book is not specifically for gear failure analysis, it will appeal to all professionals that are interested in failure analysis.

Dr. Gagg, now retired from academia, has taught the postgraduate forensic engineering course at the UK Open University for 30 years. He is now an independent failure analyst with over 800 forensic investigations to his credit. His book contains a multitude of case histories that demonstrate the principles of failure analysis. His teaching experience has shown him that case studies are effective teaching tools. As Confucius said:

I Hear, and I Forget
I See, and I Remember
I Do, and I Understand

The moral: tell me and I will forget. Show me and I will remember. Involve me and I will understand. In other words, we learn best by doing. After teaching the AGMA Gear Failure Analysis Seminar for over 25 years, I wholeheartedly agree that case studies are effective teaching tools.

Dr. Gagg's book contains over 400 high-resolution, color images of failed components that illustrate a wide variety of product failures and serve as a working manual for practitioners of forensic engineering. His well-written case histories are a joy to read, and I guarantee you will obtain a good background in the art and craft of a failure detective.

For more information.

Questions or comments regarding this paper? Contact Robert Errichello—*rlgears@mt.net.*

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Robert Errichello, PE, heads his own gear consulting firm—GEARTECH (*rlegears@mt.net*)—and is a founder of GEARTECH Software, Inc. A graduate of the University of California at Berkeley, he holds B.S. and M.S. degrees in mechanical engineering and a master of engineering degree in structural dynamics. In his more than 30 years of industrial experience, Errichello worked for several gear companies; he has also been a consultant to the gear industry for more than 20 years 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. He is also a longtime technical editor for Gear Technology magazine and STLE Tribology Transactions, and has presented numerous seminars on design, analysis, lubrication and failure analysis of gears.


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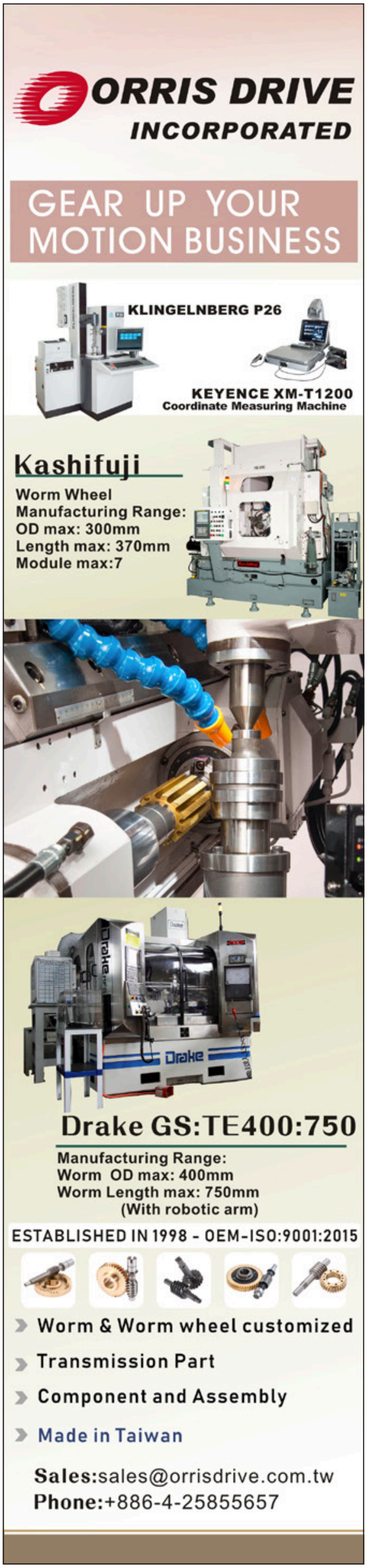
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Quantitative Residual Stress Measurements for Improved Quality Control and Process Optimization in Gears and Additively Manufactured Components

Wade Gubbels and James Thomas

Introduction

The required endurance and performance of gears (and many other components) are increasingly more demanding. Designers are tasked with improving capacity, fatigue strength and lifetime while still managing weight and cost. Enhancements are being found in changes to geometry, heat treatment and surface modifications, just to name a few. The research and development of gear modifications is aided in large part by sophisticated modeling and analysis software. Efficient development requires validation techniques and testing, which yield data-rich results and quantitative feedback. Manufacturing these ever-more complex geometries with increasingly tighter tolerances dictate that inspection and control methodologies and technologies advance accordingly as well. In this article, the focus is put on one technology, X-ray diffraction (XRD), and more specifically, residual stress measurement by way of XRD for both process development and quality control.

Almost all manufacturing processes introduce residual stresses, of which some are beneficial, and others are detrimental to component performance and longevity. Historically, residual stresses have been an afterthought in component design. However, current trends in light-weighting, miniaturization and focus on manufacturing costs have placed a greater importance on the topic. The proliferation of additive manufacturing techniques, some of which are notorious for creating parts having near (or above) yield residual stresses, has made the ability to characterize, optimize, and control residual stress a necessity.

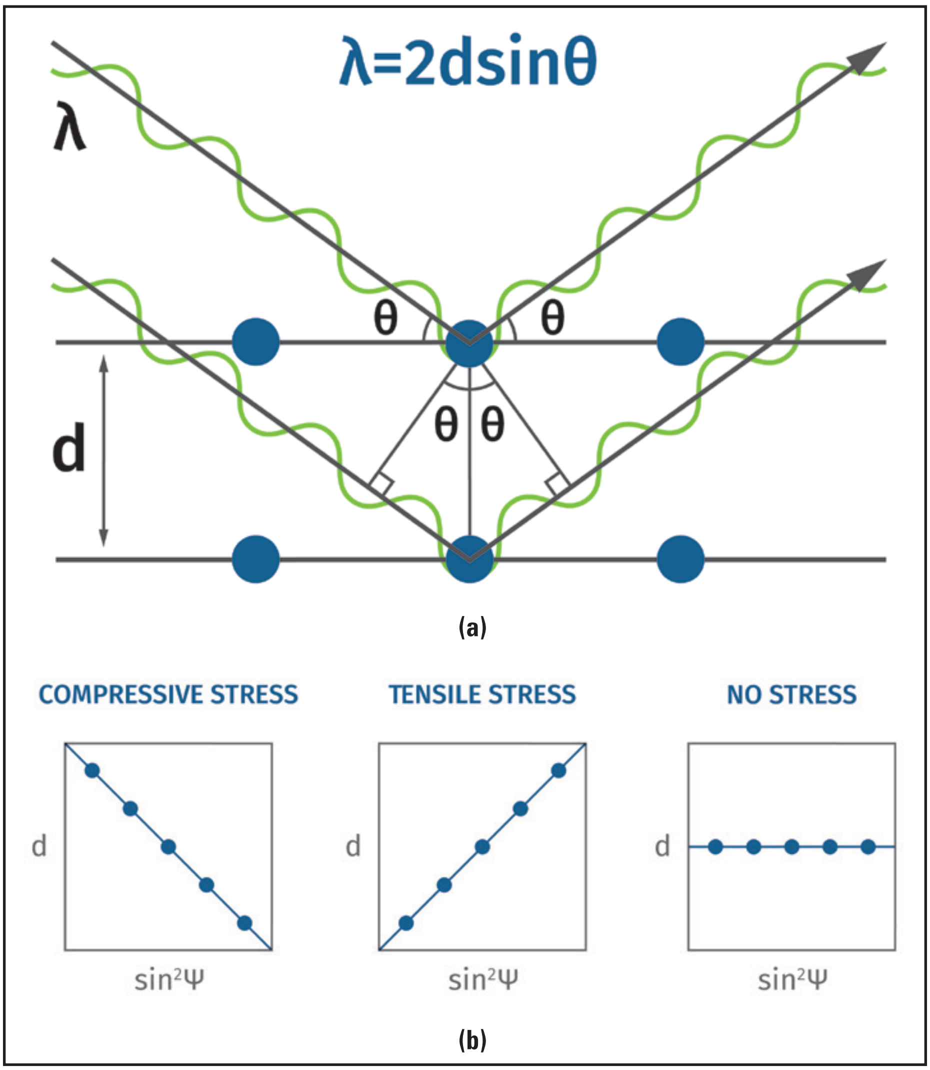

Figure 1 a) Illustration of X-ray diffraction as described by Bragg's Law; b) *d* vs $\sin^2\Psi$ plots from compressive, tensile and neutral stress states.

Residual Stresses and Their Importance

While the term *residual stress* is well known and generally understood, it is helpful to revisit the definition and reiterate the important role residual stresses play in modern gear design and manufacturing. Residual stresses are the stresses which remain in a material volume after all external loads are removed. They develop as an elastic response to incompatible local strains (Ref. 1). For example, during shot peening the surface layer is plastically deformed and thus looks to expand. The underlying material restricts this expansion (local strain) and thereby holds the surface and near surface material in a state of compression. These relatively shallow, sometimes high magnitude, compressive stresses are balanced out by tensile stresses acting on the interior volume of material.

Common mechanisms for creating residual stresses and some typical manufacturing processes and in-service events associated with these mechanisms include (Ref. 1):

- Non-uniform plastic deformation — forging, bending, rolling, and in-service surface deformation
- Surface modification — machining, grinding, peening and corrosion or oxidation
- Material phase and/or density changes — typically a result of large thermal gradients from welding, heat treatment/quenching, and frictional heating during machining or in-service

Residual stresses are no less important than applied stresses. In practice "total stress," which is the summation of residual and applied stress, should be considered. In the total stress equation, both residual and applied stress are weighted equally. For example, in shot peened gear teeth, the near surface compressive residual stress counteracts the large tensile loads encountered on the flank surface during tooth bending, thereby effectively reducing the net effect or "total stress." In practice the influence of residual stresses on performance are more nuanced, and thorough characterization and control of residual stress is required.

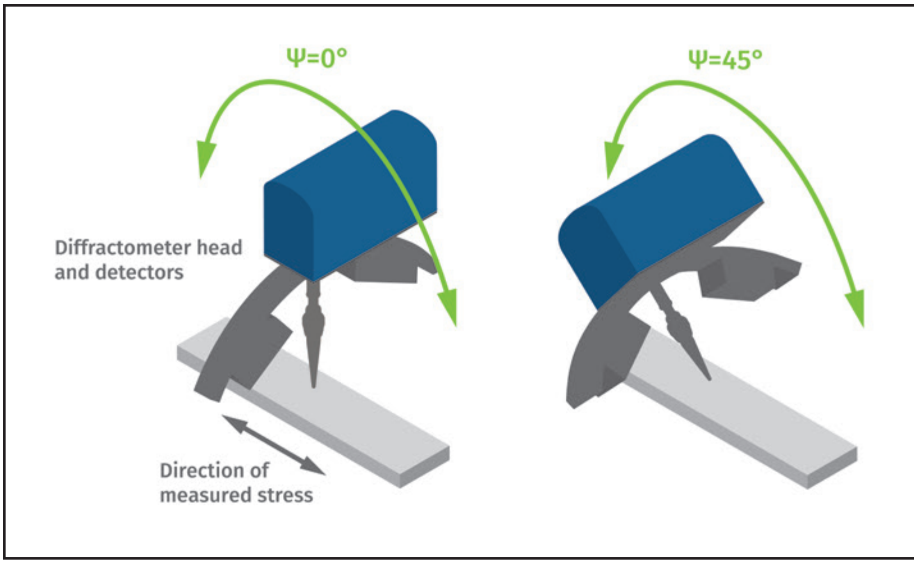

Figure 2 Illustration of a diffractometer head measuring at two different psi angles and the associated direction of measurement.

X-ray Diffraction Residual Stress Measurement

There are several methods capable of providing near surface residual stress information. XRD is an accurate and practical method for quantifying near surface residual stresses such as those developed during shot peening and other similar surface treatments. XRD also has several advantages as related to other mechanical, ultrasonic, or magnetic methods available (Ref. 2). In addition, industrial standards for the technique have been published by EN, ASTM, and SAE, further establishing the method for surface and near surface stress characterization (Refs. 3–5).

X-ray diffraction, as the name implies, requires the utilization of electromagnetic radiation known as X-rays. X-rays are higher in energy but shorter in wavelength than visible light. As such, they can be used to probe the inter-atomic distance of most crystalline materials, typically penetrating between 1 to 10 μm into the surface of a given material. The X-rays utilized in residual stress measurements are commonly referred to as "soft," as they are lower in energy than the "hard" X-rays commonly used in medical imaging. For most commercially available XRD equipment, the X-ray power is low and safe working distances are short (6–10 feet). Nevertheless, safety precautions and interlocked systems are typically utilized.

X-rays diffract from the crystallographic lattice of a material at an angle equal to 2θ as governed by Bragg's law. As shown in Figure 1a, λ is the wavelength of the incident X-rays, θ is the diffraction angle and *d* is the lattice spacing of the crystal planes. Therefore, if the wavelength is known and the diffraction angle is accurately measured, then the lattice spacing can be easily calculated.

By assuming a planar stress state in the measured volume, the lattice spacing in the direction normal to the surface (Ψ = 0°) can be used as an un-strained reference. This removes the need for a stress-free reference sample. The diffraction angle is then recorded for different, non-normal angles commonly referred to as Ψ angles or tilts as illustrated in Figure 2. Comparing the measured diffraction angles (θ) and change in lattice spacing (*d*) recorded at each angle gives a linear distribution of *d* vs. $\sin^2\Psi$, as shown in Figure 1b. This information, combined with the appropriate material parameters (Modulus and Poisson's ratio), yields the stress in the direction parallel to the plane of Ψ tilting. Any in-plane direction of stress can be measured by simply rotating the sample, or the diffractometer head. It is important to note than by measuring in three independent directions (at a single location) the planar principal stresses can be determined.

In many cases, surface residual stress alone is not enough. For instance, as shown in Figure 3, an abusively ground component can have compressive residual stress on the surface. It is the presence of sub-surface tensile stresses which leads to early failure. This stress vs. depth information can be acquired by incremental layer removal and subsequent XRD measurement of each new free surface. This process is commonly referred to as an XRD residual stress depth profile. Layer removal is commonly achieved by localized electrolytic so as not to introduce new stresses or cause noticeable redistribution of stresses elsewhere in the sample. There are, however, corrections available when necessary (Ref. 6).

Typically, XRD depth profiles are limited to a final depth of approximately 1 mm, but under proper circumstances measurement can be made to greater depths. For many manufacturing processes, such as those shown in Figure 2, 1 mm is well beyond the depth needed to thoroughly characterize the induced residual stresses.

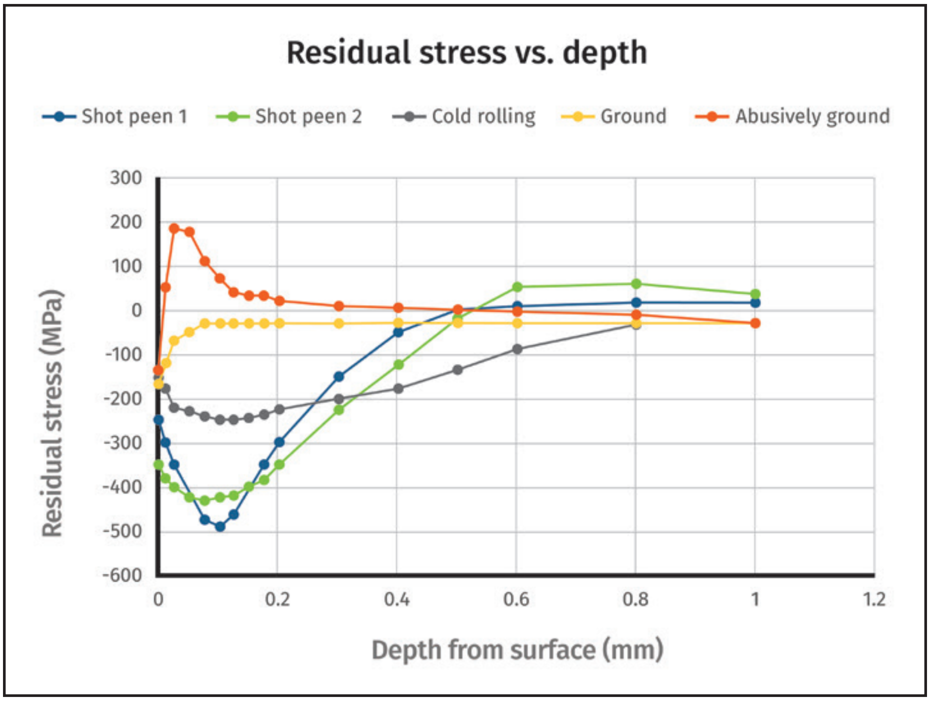

Figure 3 Example residual stress depth profiles for common processes in steel components.

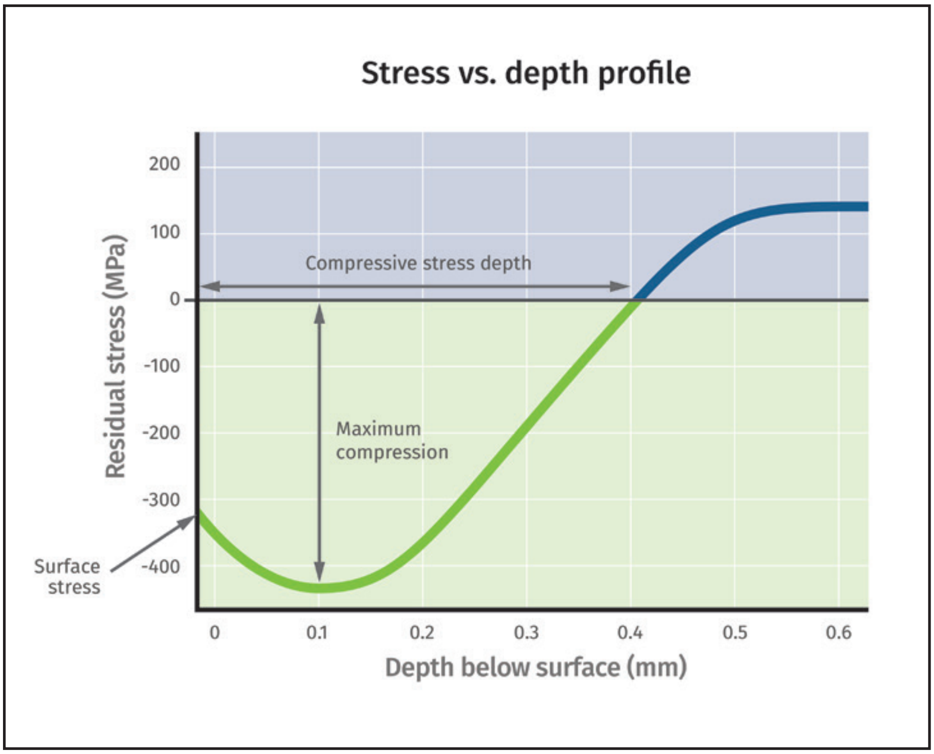

Figure 4 Characterisitcs of a shot peen induced residual stress depth profile.

XRD for Quality Control in Shot Peened Gears

Shot peening typically results in an easily recognizable U-shaped curve. Shot peen induced residual stress depth profiles have several common characteristics. The surface stress is always less compressive than the stress acting on the material immediately below the surface, due to the excessive cold working and plastic deformation. The profile reaches a maximum compression, at some specific depth, and then increases until crossing the neutral axis. This point designates the compressive stress depth. Slight changes in any of these characteristics (magnitude, depth, gradient, etc.) can result in significant effects on a component's longevity.

Shot peening processes have traditionally been established and controlled using Almen intensity. Almen strips are specified pieces of metal which are deformed during peening of one side. The height of deformation or arching is carefully measured and then related to peening intensity and coverage. This method is widely used, and specific standards are available (Ref. 7). The method does, however, have several limitations. Almen intensity is essentially a measure of the area under (or above) the stress profile curve. Therefore, equivalent Almen intensities can be obtained from two peening processes which produce significantly different stress vs. depth profiles: the two shot peen profiles shown in Figure 3, for example. For manufacturers which have identified stress profile characteristics as critical measures of part performance, such as surface stress, maximum compression or maximum compressive depth, a more capable inspection is required. XRD residual stress depth profiles provide the necessary information.

For example, a gear manufacturer determined that previously undetected variation in their shot peening process led to early fatigue failure in several products. Through subsequent review and development, they established specific requirements on the compressive residual stress-depth profiles required to meet the expected part life cycles for several gear types. These limits and tolerances were determined through modeling, XRD validation and fatigue testing. Next, they implemented XRD residual stress inspections to verify that these newly established standards were being met in manufacturing. The following steps and Figure 5 explain the inspection process which was integrated.

1. Section sample for accessibility
2. Align sample and reference depth gauge
3. Measure radial (root-to-tip) stress, σ_0, at exposed flank surface
4. Electrochemically remove material to a depth, D_1
5. Measure radial stress σ_1
6. Electrochemically remove material to a depth, D_2
7. Measure radial stress σ_2
8. Print report showing pass/fail determination, proceed accordingly

In the above, $D_{1,2}$ refer to specific depths that are determined separately for each gear type measured and $\sigma_{0,1,2,}$ are the residual stresses measured in the radial direction at each respective depth. In this case, a tolerance of ±0.005 mm was placed on each measured depth. This precision is met with relative ease using preprogrammed electropolishing parameters (time, flow, voltage, etc.) which are customized for each gear type and required depth. The depth tolerance provides insight into the level of control necessary to insure part quality/performance.

Inspections are completed using a customized solution, like that shown in Figure 6, with combined safety enclosure, sample trolley, and integrated electropolish station. One part per peening lot is tested and the duration of the process (steps 1–8 above) take approximately 40 minutes with sectioning accounting for 10+ minutes depending on the size of gear being tested. The geometry and size of gears being tested requires that portions of the gear are sectioned for appropriate accessibility of the incoming and diffracting X-rays. Part specific measurement routines (tilt angles, exposure times, etc.) and electropolishing parameters were preprogrammed, making steps 3–8 nearly push-button. This, in combination with straightforward pass/fail acceptance limits, allows measurements to be performed by non-technical operators without the need to analyze diffraction patterns or assess characteristics of the measured residual stress-depth profiles.

This specific application is shared to highlight the capability of XRD for both establishing and controlling residual stress requirements. Furthermore, it illustrates the evolution of the technology from a formerly time- and skill-intensive technique to one which can now be utilized in a manufacturing environment for high precision quality control with reasonably low investments in time, cost and effort.

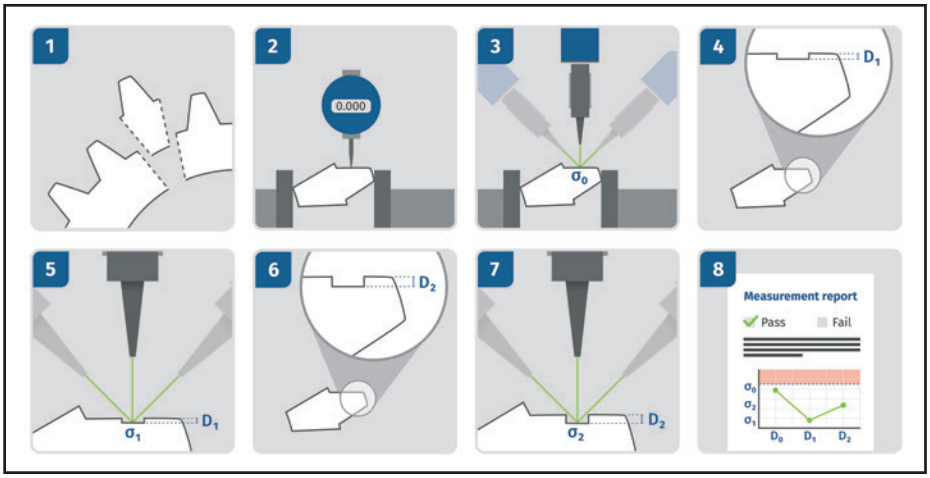

Figure 5 Illustrated inspection process steps 1–8.

1. Section sample for accessibility, 2. Align sample and reference depth gauge, 3. Measure radial (root-to-tip) stress, σ_0, at exposed flank surface, 4. Electrochemically remove material to a depth, D_1, 5. Measure radial stress, σ_1, 6. Electrochemically remove material to a depth, D_2, 7. Measure radial stress, σ_2, 8. Print report showing pass/fail determination, proceed accordingly

Figure 6 Commerical off-line XRD inspection station.

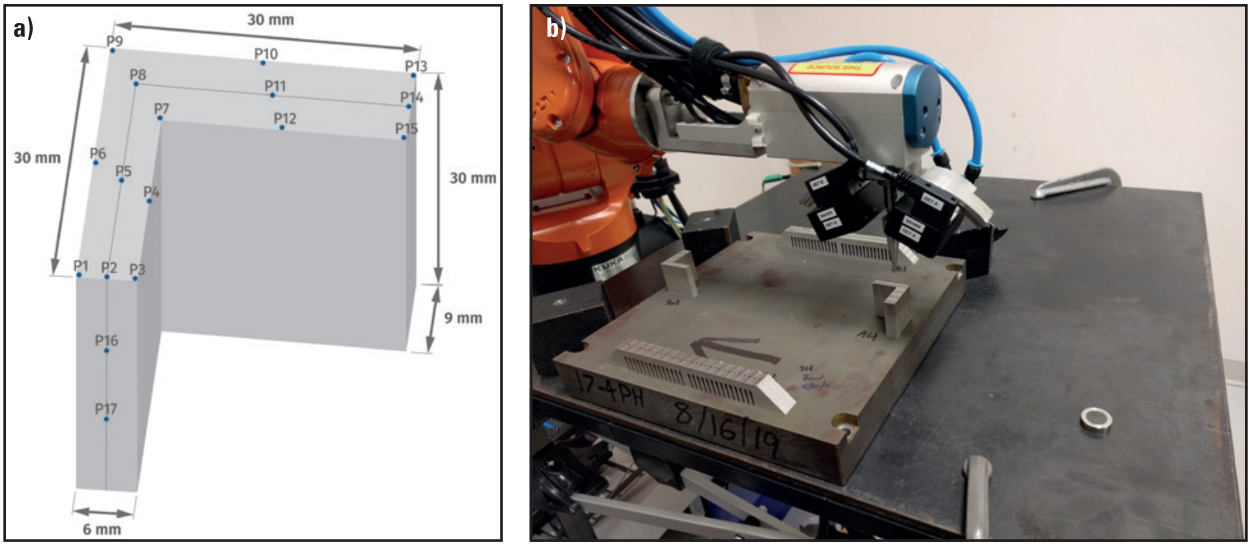

Figure 7 **a) Diagram of residual stress measurement locations on sample under test; b) additive samples on build plate during XRD measurement.**

Additional Applications

While XRD is well suited for characterizing stress in common steels, it can be used to accurately measure near surface stress in nearly any crystalline material. The applications are vast and constantly increasing in complexity and breadth. Amid the increasingly more popular industry that is additive manufacturing (AM), it is important to explain that XRD is capable of measuring residual stress in most metal additive components just as with most traditionally manufactured metal parts. This includes processes such as directed energy deposition and powder bed fusion.

In these cases, as with most AM processes, each component is built through successive layer-by-layer melting. The resulting cyclic thermal loading and temperature gradients can result is relatively high magnitude residual stresses. It is common for these stresses to result in warping, cracking or layer delamination (Ref. 8). As a result, an increased importance has been placed on the comprehensive understanding of residual stress formation in AM, especially as an increasing number of structural AM components are being utilized in the aerospace, automotive and medical device industries.

The factors affecting residual stress in AM parts are many, and the topic is a very active area of research. In some applications unfavorable stresses are remediated by post-process heat treatments and/or surface treatments such as peening. Some are investigating in-situ controls while others look to find optimal build parameters via modeling. Regardless, validation is necessary and the most widely utilized techniques for measuring residual stress in AM parts are X-ray and Neutron diffraction (Ref. 9). The latter can be used for 3D, volumetric analysis of residual stresses; however, the method is severely limited by the instrumentation required, i.e. a nuclear reactor. While slightly less capable, XRD instruments and measurement services are readily available through commercial equipment suppliers or accredited service measurement providers.

The following provides a straightforward example of XRD residual stress measurements for AM model validation. Researchers at the University of Pittsburgh aimed to develop an alternative method for determining the J-factor of as-built Inconel 718 samples as the standard test method isn't practically applicable for parts manufactured via laser powder bed fusion for various reasons (Ref. 10).

Their modified approach required the creation of a residual stress simulation and subsequent experimental validation of said model. Samples were printed using specific parameters and a total of seventeen (17) locations were selected for XRD residual stress measurements. These measurements consisted of both surface stress and stress-depth profiles. Figure 5a shows the specified locations and 5b the sample during measurement. Table 1 presents the predicted and measured principal stresses. In this case, the agreement was satisfactory and provided the validation necessary to confidently

Table 1 **Comparison of numerically predicted residual stress values to experimentally measured (XRD) values**

Measurement position	Principal stress Simulation predicted (MPa)	Principal stress Measured XRD (MPa)	Prediction error (%)
P1	147	146	0.7
P2	167	182	8.2
P3	148	139	6.5
P4	505	455	10.9
P5	636	644	1.2
P6	501	490	2.4
P7	592	548	8.0
P8	635	653	2.8
P9	312	342	8.8
P10	518	721	28.2
P11	635	699	9.2
P12	511	358	42.6
P13	318	681	53.2
P14	560	612	8.5
P15	320	447	28.4
P16 (1.0 mm)	87	193	55.2
P17 (1.0 mm)	673	751	10.4

proceed with their simulated approach to determining fracture characteristics in additive parts.

Summary

Residual stresses play a crucial role in modern manufacturing. Carefully engineered surface stress profiles can yield significant performance advantages in various components. Alternatively, undiagnosed detrimental residual stresses can lead to diminished load capacity, reduced part life and catastrophic failure. XRD is an accurate and reliable method of measuring residual stress. XRD residual stress measurements are indispensable, whether validating numerical simulations or verifying in-line production processes. Technological advances and commercially available hardware as well as accredited measurement service providers have made XRD accessible and affordable regardless of application.

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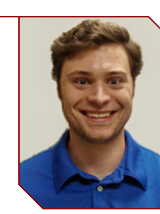


James Thomas received a B.S. in Physics from the University of Pittsburgh and is the General Manager of American Stress Technologies. He has been with the company for 11 years specializing in using magnetic Barkhausen noise for materials characterization and defect detection. James' work and research with Barkhausen noise technology have been published in several industry publications including Advanced Materials and Processes, American Institute of Physics, and SAE International Journal of Materials and Manufacturing.

Converting Revacycle to Coniflex

Dr. Hermann J. Stadtfeld

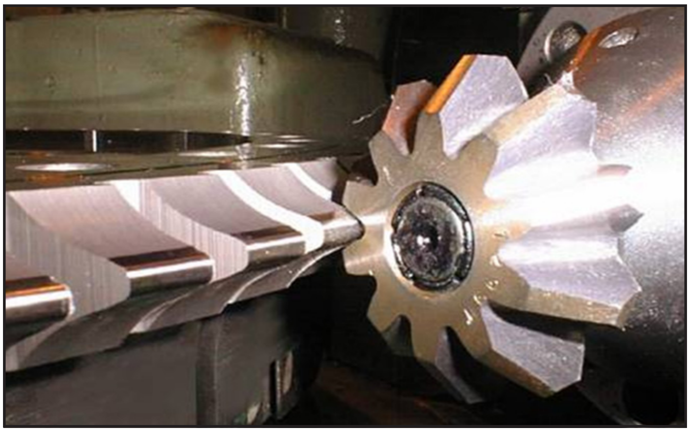


Figure 1 Broaching of a differential gear with Revacycle.

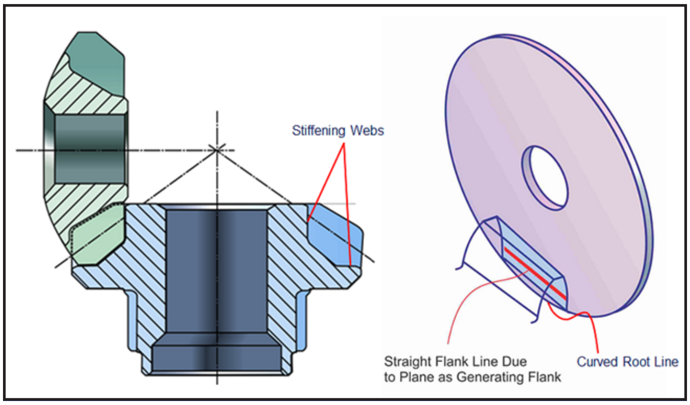


Figure 2 Root form of forged (left) and Coniflex (right) differential gear teeth.

Figure 3 Forged differential gear with pittings.

(The following is another chapter from Dr. Hermann J. Stadtfeld's new book, Practical Gear Technology, part of an ongoing series of installments excerpted from the book. Designed for easy understanding and supported with helpful illustrations and graphic material, the e-book can be accessed for free at Gleason.com.)

Traditional Cutting of Differential Gears with Revacycle

Automotive differential gears are generally Gleason Revacycle designs. Revacycle gears are cut by a large circular broach which is extremely productive (Fig. 1). Differential gears require the highest power density of all bevel gear types. Typical features of differential gears related to the high power density are the high pressure angle of 25° and even more and course pitch teeth with near miter ratios. The wide root fillets of the Revacycle gears have a fully rounded radius for maximal root bending strength. The Revacycle process performs a non-generated form cutting of the tooth profiles. The broach cutter moves from toe to heel during the roughing portion of the cycle and then back to the toe in a climb cutting mode in order to finish the flank surfaces and generate a straight root line. However, the flank profiles of Revacycle cut gears have no involute profile. Revacycle blades have a radius which approximates an involute while simultaneously creating some profile crowning.

A Revacycle cutter requires a large number of relief ground blades and the part geometry depends on an experimental trial-and-error optimization loop. Both — the blades and the development process — are expensive, which is only justified for large quantities of produced differential gears.

Forging of Differential Gears

The large quantities in connection with the high power density led the forging companies to promote forging of differential gears. They promoted the advantages of the grain flow of forged teeth in connection with the possibility of improving the profile from the Revacycle radius to a spherical involute. Additionally, it is possible with forging to create a web as shown (Fig. 2, left) at toe and heel in order to increase the tooth stiffness.

Preparation and setup cost for forging are extremely high and only justified for large size mass production. After the design of the gear geometry, a copper electrode is manufactured, either by a gear cutting process or with a machining center using ball nose end-mills. In case of the machining center, surface point clouds are processed rather than basic machine settings. This makes it possible to modify the root geometry of the electrode as shown (Fig. 2, left). The electrode is used to create the forging die as the negative form of the final differential gear with a spark erosion process (EDM). Certain corrections have to be made because of the forging billet temperature of about 1,000°C.

The corrections consider the proportional shrinking and the systematic tooth form distortion after cooling down to ambient temperature. An additional die is manufactured which has the gear tooth shape at the tempering temperature. This is the calibration die used to eliminate the random tooth distortions of each forged bevel gear and to improve the surface finish of the tooth flanks.

The webs of the forged differential gears (Fig. 2, left) are overrated because they prevent the free bending which can cause cracks in the web transition to the teeth; it also promotes early pitting due to the elimination of a "free contact breathing" under varying loads. Figure 3 shows a forged differential gear with pittings on the left flank. Although there are geometry freedoms like the webs which can be applied in forging, but not in cutting, the forged differential gears with the highest strength are the ones that just duplicate the Revacycle geometry (Ref. 1).

The Coniflex Process

Many truck and off-road vehicle applications do not require very large quantities of differential gears. Low-quantity differential gears are often manufactured using the Coniflex cutting method instead of Revacycle or forging.

Coniflex is a bevel gear cutting process developed for industrial straight bevel gears. In the past, mechanical cradle-style machines with many setup axes were used to cut Coniflex gears with an interlocking HSS dual cutter arrangement (Fig. 4). Although Coniflex is slow compared to Revacycle, it is the fastest-generating straight bevel gear manufacturing process available. Coniflex replicates in the root (in face width direction) the radii of the Coniflex cutter disks, as indicated (Fig. 2, right). The curved root line has no negative effect on the strength of a Coniflex straight bevel gear (within the recommended limits of face width/cutter radius < 0.4).

With Coniflex it is possible to approximate the Revacycle geometry. Common differences of Revacycle versus Coniflex gears are the blank geometry, the slot root geometry, the curved non-generated profiles and the larger pressure angles.

The Coniflex-Plus Process

The latest development in the manufacturing of straight bevel gears is the Coniflex-Plus technology. A single carbide stick blade cutter is used in a high-speed dry cutting process on free-form Phoenix machines (Fig. 5). The same machines are used for spiral bevel and hypoid gear cutting. At first view it appears that a single cutter, compared to the dual interlocking cutter arrangement in Figure 4, produces the straight bevel gears much slower. In reality, the facts that the cutting speed is 4 times higher with the Coniflex-Plus cutter head and the indexing motion of the gearless direct drive work spindle of the Phoenix II is significantly faster than the indexing of a mechanical machine (Fig. 4) make this new process more than twice as fast compared to the traditional Coniflex process using HSS blades. The new Coniflex process also has a higher flexibility because of the stick blades, which can be re-ground with optimized blade geometry rather quickly. The Phoenix machine kinematic allows applying a first-order modified roll which increases or reduces the profile crowning without the requirement of blade re-grinding. Three section universal motions (UMC) can be used in order to create a tip relief which eliminates rolling noise in cases of high-load-affected deflections.

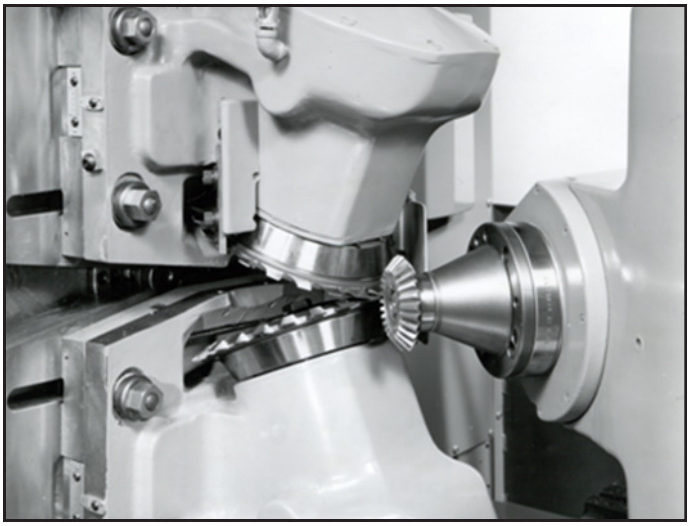


Figure 4 Coniflex cutting with an interlocking HSS dual cutter arrangement.

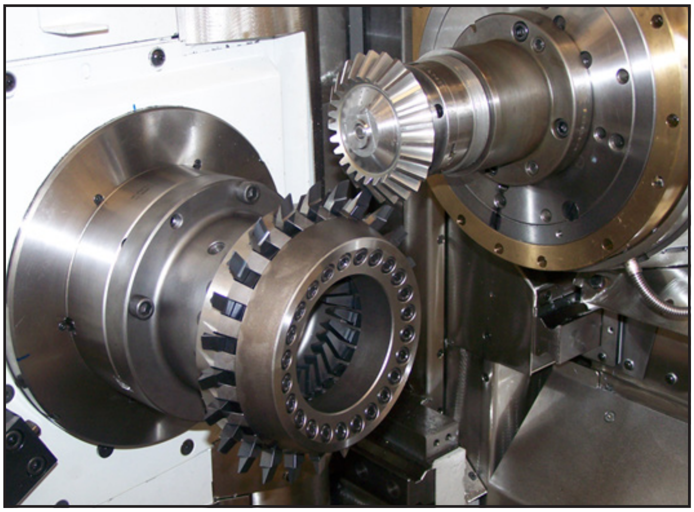
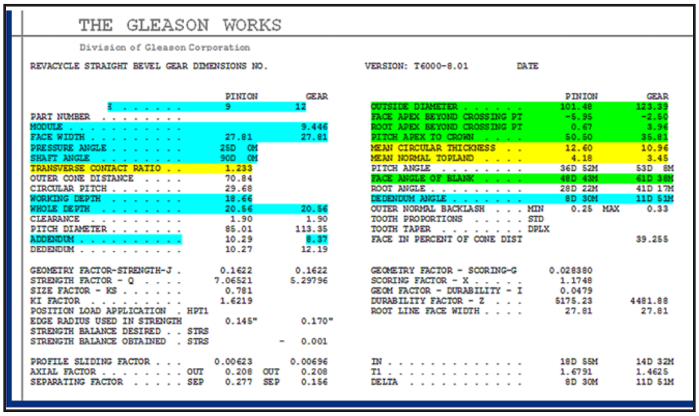


Figure 5: Coniflex-Plus high-speed dry cutting on a PhoenixII 275HC machine.

Coniflex-Plus optimizations and summary calculations are supported in the *UNICAL* software. TCAs and CMM download files can be generated, and closed loop corrections via *GAGE* are a standard today.



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THE GLEASON WORKS
Division of Gleason Corporation
REVACYCLE STRAIGHT BEVEL GEAR DIMENSIONS NO.                VERSION: T6000-8.01        DATE

                                PINION      GEAR                                                PINION      GEAR
# . . . . . . .                   9          12        OUTSIDE DIAMETER . . . . . . .          101.48      123.39
PART NUMBER . . . . . . . . .                          FACE APEX BEYOND CROSSING PT             -5.95       -2.50
MODULE . . . . . . . . . . . .              9.446      ROOT APEX BEYOND CROSSING PT              0.67        3.96
FACE WIDTH . . . . . . . . . .  27.81       27.81      PITCH APEX TO CROWN . . . . .            50.50       35.81
PRESSURE ANGLE . . . . . . . .  25D  0M                MEAN CIRCULAR THICKNESS . .              12.60       10.96
SHAFT ANGLE . . . . . . . . .   90D  0M                MEAN NORMAL TOPLAND . . . . .             4.18        3.45
TRANSVERSE CONTACT RATIO . .    1.233                  PITCH ANGLE . . . . . . . . . .         36D 52M     53D  8M
OUTER CONE DISTANCE . . . .     70.84                  FACE ANGLE OF BLANK . . . . .           48D 43M     61D 38M
CIRCULAR PITCH . . . . . . . .  29.68                  ROOT ANGLE . . . . . . . . . . .        28D 22M     41D 17M
WORKING DEPTH . . . . . . . .   18.66                  DEDENDUM ANGLE . . . . . . . .           8D 30M     11D 51M
WHOLE DEPTH . . . . . . . . .   20.56       20.56      OUTER NORMAL BACKLASH . . . MIN  0.25  MAX   0.33
CLEARANCE . . . . . . . . . . .  1.90        1.90      TOOTH PROPORTIONS . . . . . . STD
PITCH DIAMETER . . . . . . . .  85.01      113.35      TOOTH TAPER . . . . . . . . . DPLX
ADDENDUM . . . . . . . . . . .  10.29        8.37      FACE IN PERCENT OF CONE DIST                         39.255
DEDENDUM . . . . . . . . . . .  10.27       12.19

GEOMETRY FACTOR-STRENGTH-J .    0.1622      0.1622     GEOMETRY FACTOR - SCORING-G        0.028380
STRENGTH FACTOR - Q . . . .     7.06521     5.29796    SCORING FACTOR - X . . . . . .     1.1748
SIZE FACTOR - KS . . . . . . .  0.781                  GEOM FACTOR - DURABILITY - I       0.0479
KI FACTOR . . . . . . . . . .   1.6219                 DURABILITY FACTOR - Z . . . .      5175.23      4481.88
POSITION LOAD APPLICATION . HPT1                       ROOT LINE FACE WIDTH . . . . .      27.81        27.81
EDGE RADIUS USED IN STRENGTH    0.145"      0.170"
STRENGTH BALANCE DESIRED . . STRS
STRENGTH BALANCE OBTAINED . STRS          - 0.001

PROFILE SLIDING FACTOR . . .    0.00623     0.00696    IN . . . . . . . . . . . . . . .        18D 55M     14D 32M
AXIAL FACTOR . . . . . . . . . OUT  0.208  OUT  0.208  T1 . . . . . . . . . . . . . . .        1.6791      1.4625
SEPARATING FACTOR . . . . . . SEP  0.277  SEP  0.156   DELTA . . . . . . . . . . . . . .        8D 30M     11D 51M
```

Figure 6 **Revacycle dimension sheet.**

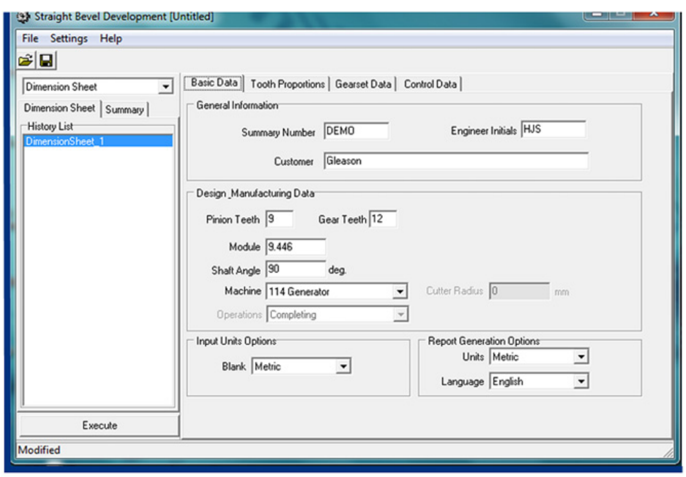


Figure 7 **Basic data input screen.**

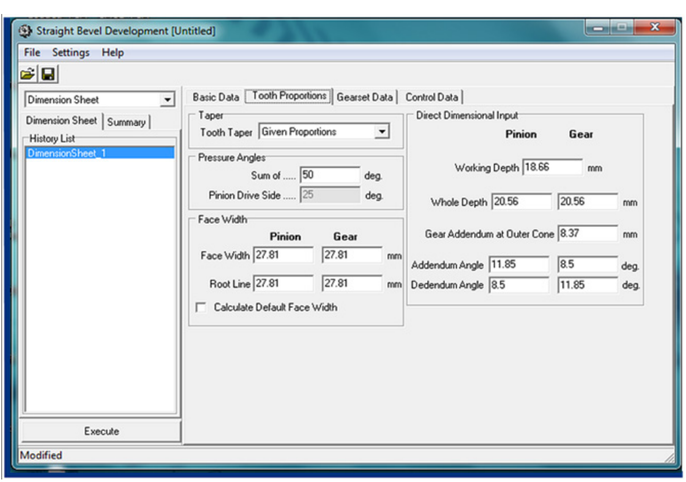


Figure 8 **Tooth proportions screen.**

Conversion of Revacycle to Coniflex-Plus

Revacycle design calculations are performed with the Gleason T6000 program; a dimension sheet of a typical Revacycle differential gearset is printed here (Fig. 6).

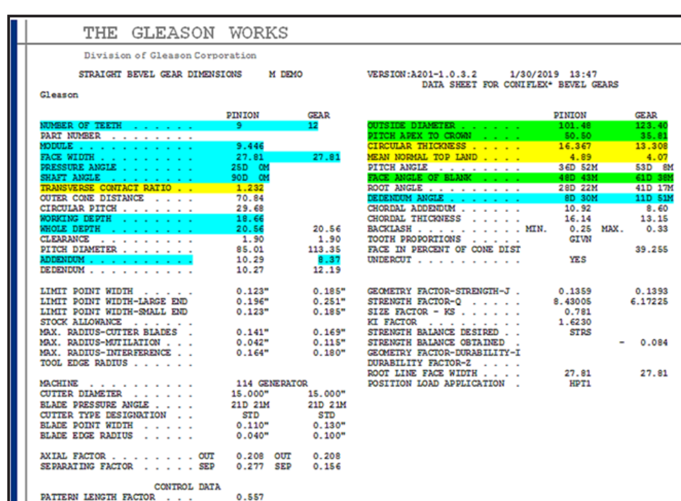
The blue-highlighted items (Fig. 6) mark the items used as input for the straight bevel mechanical program; the yellow-highlighted items are strength-relevant parameters; the green-highlighted items are the specifications of the blank dimensions.

The initial goal of a complete duplication of the Revacycle dimension sheet with a Coniflex design will not be entirely possible due to the different gear theory-related assumptions and rules between Revacycle and Coniflex. However, the approximation of the original Revacycle dimensions is generally very close.

Coniflex design calculations are conducted in the Gleason *Straight Bevel Mechanical* program. The blue-highlighted items are used to fill out the basic data screen and the tooth proportions screen as shown (Figs. 7 and 8). In order to achieve the closest possible duplication in the second screen (Fig. 8) as "tooth taper" the option "given proportions" is chosen in the drop-down tab. After complete input of the data the dimension sheet calculation is started by clicking "execute."

The resulting dimension sheet is shown (Fig. 9). All the blank design relevant data (highlighted in green) duplicate the original Revacycle blank precisely. Missing is the dimension "face apex beyond crossing point;" this dimension is not shown in the Coniflex dimension sheet because it is zero in all standard Coniflex cases. However, in cases that the Coniflex program is forced to accommodate given proportions, there is the possibility of a face apex beyond crossing point of not equal to zero. This dimension will only become visible after the *SBF* output file from the *Straight Bevel Mechanical* program is imported into the Coniflex conversion module of *UNICAL*.

If the dimension sheet data indicates a good duplication of an existing differential gear job, the basic data file (*SBF*-file) is imported to the *UNICAL*-Coniflex software program which features analysis tools like tooth contact calculation, undercut check, calculation of backlash, clearance and more. All optimizations required to duplicate in addition to the dimension sheet data also the tooth contact and fine tune the tooth thicknesses of pinion and gear of the given Revacycle design can be done in *UNICAL*.



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THE GLEASON WORKS
Division of Gleason Corporation
     STRAIGHT BEVEL GEAR DIMENSIONS     M DEMO            VERSION:A201-1.0.3.2      1/30/2019  13:47
                                                                   DATA SHEET FOR CONIFLEX* BEVEL GEARS
Gleason

                                PINION      GEAR                                               PINION      GEAR
NUMBER OF TEETH . . . . . . .     9          12        OUTSIDE DIAMETER . . . . . . .         101.48      123.40
PART NUMBER . . . . . . . . .                          PITCH APEX TO CROWN . . . . .           50.50       35.81
MODULE . . . . . . . . . . . .  9.446                  CIRCULAR THICKNESS . . . . . .          16.367      13.308
FACE WIDTH . . . . . . . . . .  27.81       27.81      MEAN NORMAL TOP LAND . . . . .           4.89        4.07
PRESSURE ANGLE . . . . . . . .  25D  0M                PITCH ANGLE . . . . . . . . . .        36D 52M     53D  8M
SHAFT ANGLE . . . . . . . . .   90D  0M                FACE ANGLE OF BLANK . . . . .          48D 43M     61D 38M
TRANSVERSE CONTACT RATIO . .    1.232                  ROOT ANGLE . . . . . . . . . . .       28D 22M     41D 17M
OUTER CONE DISTANCE . . . .     70.84                  DEDENDUM ANGLE . . . . . . . .          8D 30M     11D 51M
CIRCULAR PITCH . . . . . . . .  29.68                  CHORDAL ADDENDUM . . . . . . .          10.92        8.60
WORKING DEPTH . . . . . . . .   18.66                  CHORDAL THICKNESS . . . . . .           16.14       13.15
WHOLE DEPTH . . . . . . . . .   20.56       20.56      BACKLASH . . . . . . . . . . . . MIN.   0.25  MAX.   0.33
CLEARANCE . . . . . . . . . . .  1.90        1.90      TOOTH PROPORTIONS . . . . . .            GIVN
PITCH DIAMETER . . . . . . . .  85.01      113.35      FACE IN PERCENT OF CONE DIST                        39.255
ADDENDUM . . . . . . . . . . .  10.29        8.37      UNDERCUT . . . . . . . . . . . .          YES
DEDENDUM . . . . . . . . . . .  10.27       12.19

LIMIT POINT WIDTH . . . . . .   0.123"      0.185"     GEOMETRY FACTOR-STRENGTH-J .           0.1359      0.1393
LIMIT POINT WIDTH-LARGE END     0.196"      0.251"     STRENGTH FACTOR-Q . . . . . .          8.43005     6.17225
LIMIT POINT WIDTH-SMALL END     0.123"      0.185"     SIZE FACTOR - KS . . . . . . .         0.781
STOCK ALLOWANCE . . . . . . .                          KI FACTOR . . . . . . . . . .          1.6230
MAX. RADIUS-CUTTER BLADES .     0.141"      0.169"     STRENGTH BALANCE DESIRED . .            STRS
MAX. RADIUS-MUTILATION . . .    0.042"      0.115"     STRENGTH BALANCE OBTAINED .                     -  0.084
MAX. RADIUS-INTERFERENCE . .    0.164"      0.180"     GEOMETRY FACTOR-DURABILITY-I
TOOL EDGE RADIUS . . . . . . .                         DURABILITY FACTOR-Z . . . .
                                                       ROOT LINE FACE WIDTH . . . . .          27.81       27.81
MACHINE . . . . . . . . . . . .  114 GENERATOR         POSITION LOAD APPLICATION .             HPT1
CUTTER DIAMETER . . . . . . .   15.000"     15.000"
BLADE PRESSURE ANGLE . . . . .  21D 21M     21D 21M
CUTTER TYPE DESIGNATION . .       STD         STD
BLADE POINT WIDTH . . . . . .   0.110"      0.130"
BLADE EDGE RADIUS . . . . . .   0.040"      0.100"

AXIAL FACTOR . . . . . . . . . OUT  0.208  OUT  0.208
SEPARATING FACTOR . . . . . . SEP  0.277  SEP  0.156

                         CONTROL DATA
PATTERN LENGTH FACTOR . . .     0.557
```

Figure 9 **Straight bevel dimensiond sheet.**

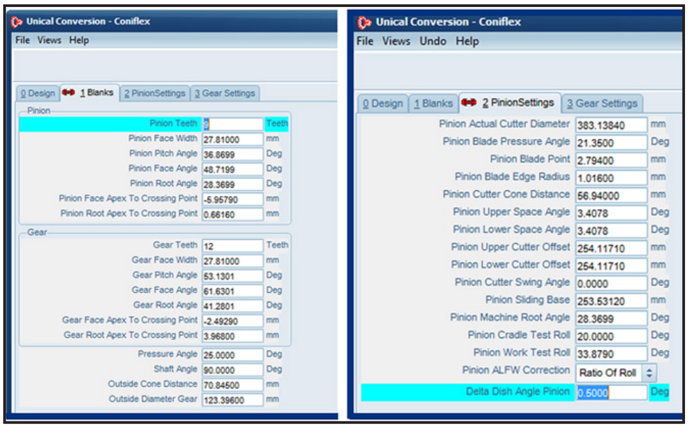


Figure 10 ***UNICAL*** **conversion input for Coniflex.**

The *SBF* file created by the *Straight Bevel Mechanical Program* is now loaded into the *UNICAL Conversion Module* "CONIFLEX." The screen "1 Blanks" (Fig. 10, left) shows in addition to the data of the dimension sheet also the pinion and gear face and root apex distances.

The screen "2 Pinion settings" (Fig. 10, right) and "3 Gear Settings" allow in the last input tab to enter a delta dish angle. For the present Revacycle conversion, a 0.5° delta dish angle was entered to the pinion and the gear settings in order to achieve sufficient length crowning. Before a delta dish angle is entered, the Coniflex data have to be converted to *UNICAL* followed by a TCA run. If the length crowning is found too small, then a change back to the Coniflex conversion module has to happen. Now an approximated amount of delta dish angle is entered (same amount for pinion and gear to keep pinion and gear cutter blades equal). After this, the conversion is repeated and the next TCA run will reveal if an additional fine tuning of the delta dish angle is necessary.

The first TCA after the conversion is shown (Fig. 11). The Ease-Off shows too much profile crowning, very small length crowning and a large spiral angle error. In case of a Revacycle conversion, the flank geometry is rather exotic compared to regular straight bevel gears, which explains the bad initial Coniflex TCAs. The length crowning correction is done in the conversion module under pinion and gear setting with a 0.5° delta dish angle for pinion and gear cutter. Profile crowning and spiral angle can be corrected in the *UNICAL* optimization module. Because of the large amounts of spiral angle and profile crowning errors, 50% of the required corrections were applied to the pinion and 50% to the gear. The resulting TCA for the present conversion is shown (Fig. 12).

The Ease-Offs (Fig. 12) reflect the original Revacycle crowning very well. The contact pattern on coast- and drive-side are identical and look good from location and size. The fuzzy contact boundaries are a phenomenon which is often seen in Revacycle conversions. The explanation is a numeric instability of the TCA applet, which is a result of the large amounts of modified roll required to reduce the large profile crowning from the original Revacycle-Coniflex conversion. Revacycle geometries have very tall teeth, which appear to create a large profile crowning when converted to a generated involute geometry. The fuzzy boundaries will not exist in the real manufactured parts.

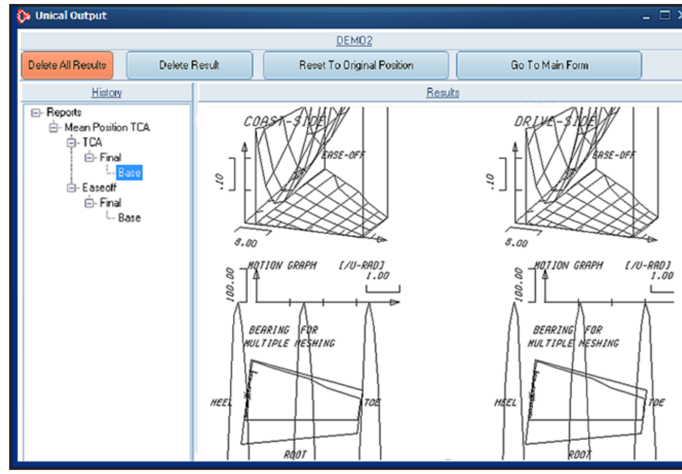


Figure 11 Coniflex TCA after conversion.

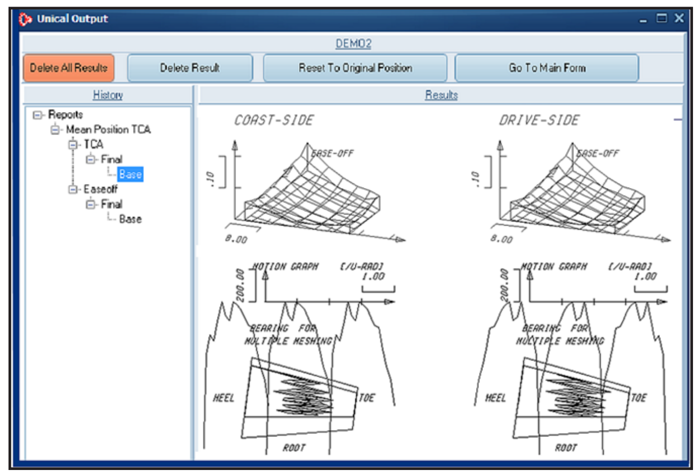


Figure 12 Revacycle-Coniflex TCA after optimization.

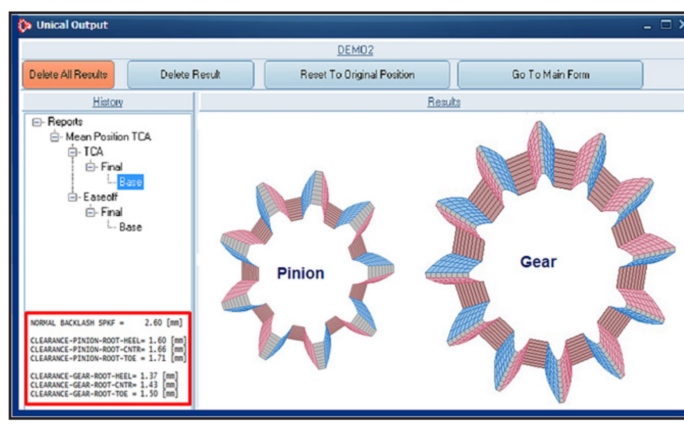
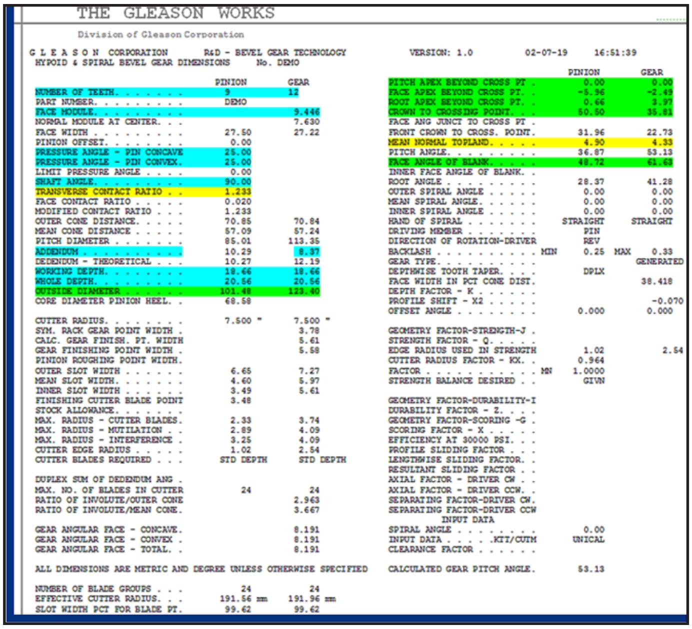


Figure 13 Converted pinion and gear geometry (initial).

In addition to the analysis and optimizations discussed above, the top-root clearance, the backlash as well as the tooth thicknesses have to be checked and corrected in *UNICAL* if necessary. Figure 13 shows in the graphic a healthy looking pinion and a gear with thin teeth and thin toplands. At the bottom-left the normal backlash shows 2.60mm. A gear tooth thickness correction of 2.30 mm is required to achieve the correct tooth thicknesses and a backlash of 0.25 mm.



THE GLEASON WORKS

Division of Gleason Corporation

G L E A S O N CORPORATION   R&D - BEVEL GEAR TECHNOLOGY   VERSION: 1.0   02-07-19   16:51:39
HYPOID & SPIRAL BEVEL GEAR DIMENSIONS   No. DEMO

	PINION	GEAR
NUMBER OF TEETH.	9	12
PART NUMBER.	DEMO	
FACE MODULE.		9.446
NORMAL MODULE AT CENTER. . .		7.630
FACE WIDTH	27.50	27.22
PINION OFFSET.	0.00	
PRESSURE ANGLE - PIN CONCAVE	25.00	
PRESSURE ANGLE - PIN CONVEX.	25.00	
LIMIT PRESSURE ANGLE	0.00	
SHAFT ANGLE.	90.00	
TRANSVERSE CONTACT RATIO . .	1.233	
FACE CONTACT RATIO	0.020	
MODIFIED CONTACT RATIO . . .	1.233	
OUTER CONE DISTANCE.	70.85	70.84
MEAN CONE DISTANCE	57.09	57.24
PITCH DIAMETER	85.01	113.35
ADDENDUM	10.29	8.37
DEDENDUM - THEORETICAL . . .	10.27	12.19
WORKING DEPTH.	18.66	18.66
WHOLE DEPTH.	20.56	20.56
OUTSIDE DIAMETER	101.48	123.40
CORE DIAMETER PINION HEEL. .	68.58	
CUTTER RADIUS.	7.500 "	7.500 "
SYM. RACK GEAR POINT WIDTH .		3.78
CALC. GEAR FINISH. PT. WIDTH		5.61
GEAR FINISHING POINT WIDTH .		5.58
PINION ROUGHING POINT WIDTH.		
OUTER SLOT WIDTH	6.65	7.27
MEAN SLOT WIDTH.	4.60	5.97
INNER SLOT WIDTH	3.49	5.61
FINISHING CUTTER BLADE POINT	3.48	
STOCK ALLOWANCE.		
MAX. RADIUS - CUTTER BLADES.	2.33	3.74
MAX. RADIUS - MUTILATION . .	2.89	4.09
MAX. RADIUS - INTERFERENCE .	3.25	4.09
CUTTER EDGE RADIUS	1.02	2.54
CUTTER BLADES REQUIRED . . .	STD DEPTH	STD DEPTH
DUPLEX SUM OF DEDENDUM ANG .		
MAX. NO. OF BLADES IN CUTTER	24	24
RATIO OF INVOLUTE/OUTER CONE		2.963
RATIO OF INVOLUTE/MEAN CONE.		3.667
GEAR ANGULAR FACE - CONCAVE.		8.191
GEAR ANGULAR FACE - CONVEX .		8.191
GEAR ANGULAR FACE - TOTAL. .		8.191

ALL DIMENSIONS ARE METRIC AND DEGREE UNLESS OTHERWISE SPECIFIED

	PINION	GEAR
NUMBER OF BLADE GROUPS . . .	24	24
EFFECTIVE CUTTER RADIUS. . .	191.56 mm	191.96 mm
SLOT WIDTH PCT FOR BLADE PT.	99.62	99.62

	PINION	GEAR
PITCH APEX BEYOND CROSS PT .	0.00	0.00
FACE APEX BEYOND CROSS PT. .	-5.96	-2.49
ROOT APEX BEYOND CROSS PT. .	0.66	3.97
CROWN TO CROSSING POINT. . .	50.50	35.81
FACE ANG JUNCT TO CROSS PT .		
FRONT CROWN TO CROSS. POINT.	31.96	22.73
MEAN NORMAL TOPLAND.	4.90	4.33
PITCH ANGLE.	36.87	53.13
FACE ANGLE OF BLANK.	48.72	61.63
INNER FACE ANGLE OF BLANK. .		
ROOT ANGLE	28.37	41.28
OUTER SPIRAL ANGLE	0.00	0.00
MEAN SPIRAL ANGLE.	0.00	0.00
INNER SPIRAL ANGLE	0.00	0.00
HAND OF SPIRAL	STRAIGHT	STRAIGHT
DRIVING MEMBER	PIN	
DIRECTION OF ROTATION-DRIVER	REV	
BACKLASH . . . . MIN	0.25	MAX 0.33
GEAR TYPE.		GENERATED
DEPTHWISE TOOTH TAPER. . . .	DPLX	
FACE WIDTH IN PCT CONE DIST.		38.418
DEPTH FACTOR - K		
PROFILE SHIFT - X2		-0.070
OFFSET ANGLE	0.000	0.000
GEOMETRY FACTOR-STRENGTH-J .		
STRENGTH FACTOR - Q.		
EDGE RADIUS USED IN STRENGTH	1.02	2.54
CUTTER RADIUS FACTOR - KX. .	0.964	
FACTOR . . . . MN	1.0000	
STRENGTH BALANCE DESIRED . .	GIVN	
GEOMETRY FACTOR-DURABILITY-I		
DURABILITY FACTOR - Z. . . .		
GEOMETRY FACTOR-SCORING -G .		
SCORING FACTOR - X		
EFFICIENCY AT 30000 PSI. . .		
PROFILE SLIDING FACTOR . . .		
LENGTHWISE SLIDING FACTOR. .		
RESULTANT SLIDING FACTOR . .		
AXIAL FACTOR - DRIVER CW . .		
AXIAL FACTOR - DRIVER CCW. .		
SEPARATING FACTOR-DRIVER CW.		
SEPARATING FACTOR-DRIVER CCW		
INPUT DATA		
SPIRAL ANGLE	0.00	
INPUT DATA . . . . . .KIT/CUTM	UNICAL	
CLEARANCE FACTOR		
CALCULATED GEAR PITCH ANGLE.	53.13	

Figure 14 Final dimension Sheet from *UNICAL*.

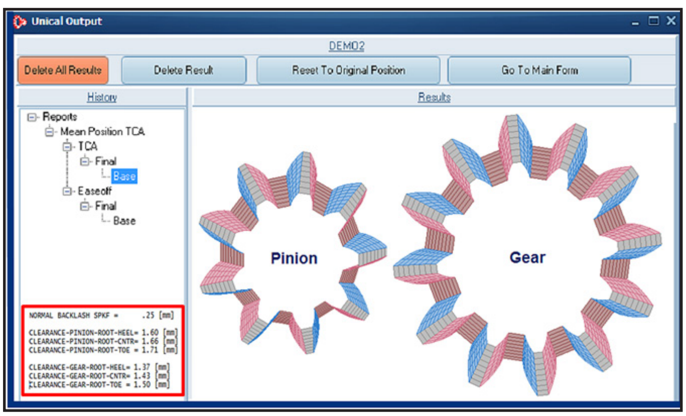


Figure 15 Converted pinion and gear geometry (final).

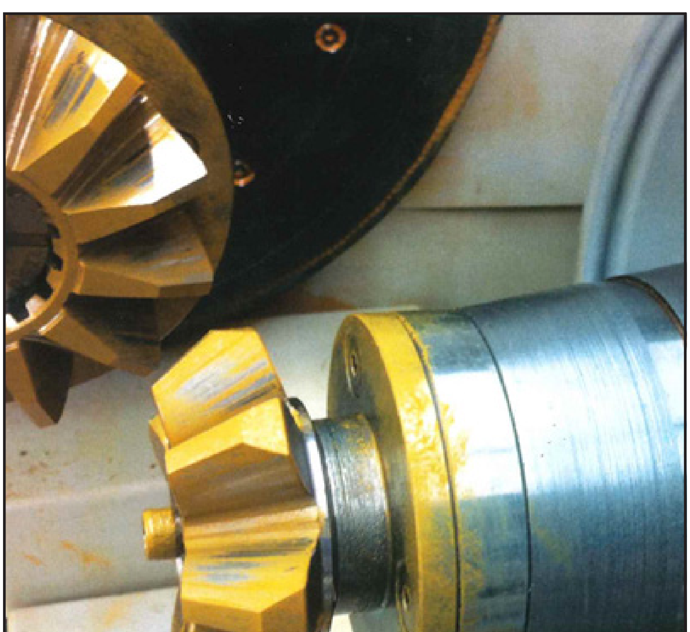


Figure 16 Rolled tooth contact on bevel gear tester.

The final dimension sheet calculation in *UNICAL* (Fig. 14) shows that all values — except the mean normal toplands — are very close to the straight bevel mechanical dimension sheet (Fig. 9).

The gear mean normal topland in the *UNICAL* and *Straight Bevel Mechanical* are different to the original Revacycle. This is a result of the involute profile function of Coniflex, in case of duplicating the Revacycle tooth thicknesses (the latter is an objective).

The pinion and gear graphics, reflecting the final dimension sheet are shown (Fig. 15). Tooth thicknesses and toplands are now balanced, and the teeth as well as the root width look well proportioned. At the bottom-left the box with backlash and clearances shows that all values are in the desirable range.

Tooth thickness, depth and root fillet are next to surface structure and finish the criteria for assuring comparable strength and performance. Except for the tooth thickness, all properties of the new Coniflex dimension sheet are duplicating the Revacycle calculation.

In order to check if the tooth thickness was matched correctly, the CMM inspection (coordinate) file of the newly developed Coniflex differential set should be used for the inspection of the original Revacycle pair. The measured tooth thickness differences (at the 5x9 grid center point) of the new Coniflex pair should be corrected in order to match the pinion and gear tooth thicknesses of the original Revacycle pair. If the correct Revacycle reference gear tooth thicknesses have been established, then the strength of the new Coniflex differential gearset will be comparable to the original Revacycle pair.

Nominal tooth surface grids for a CMM are also a standard of the new software. If the measured flank form deviates from the theoretical target, then corrections can be calculated with the *G-AGE* software, residing on the CMM computer. Thus the latest closed correction loop methods can be applied for Coniflex straight bevel gears and are of course also available for all developments of differential gear designs (Ref. 2).

Manufacturing and Roll Testing of Coniflex Differential Gears

For the example conversion of this chapter, a 15” Coniflex-Plus cutter head with carbide blades was used. *UNICAL* generates all the summaries for the Pentac stick blade grinding and for the cutting of pinions and gears. CMM download files and closed loop *G-AGE* corrections are also available for a straightforward production of Coniflex differential gears.

Roll testing results after soft cutting are displayed (Fig. 16). Tooth contact position and size are close to the theoretical TCA results. The differential pinion in the front has a large chamfer surface at the top-heel. The differential gear (or side gear) in the background has a toe border which is equal to the front face of the gear. Those and similar modifications of the tooth boundaries are very common for differential gears. Those tooth boundary modifications have to be considered at the time of tooth contact development.

It is possible in *UNICAL* to define an arbitrary three-sided heel-top-toe boundary which, however, is rather time-consuming because it would require to enter the L and R coordinates of the corner points directly into the *UNICAL* file.

In the photo in Figure 16 the cutting flats from the generating process can be easily recognized. This was a compromise which the manufacturer of this differential set was willing to make in order to reduce the cutting time to the required minimum. The low number of teeth, as well as the fast generating roll during cutting, resulted in a cutting time of 64 seconds for the pinion. Considered the large whole depth of more than 20mm, this is a good cutting time for a low quantity and flexible differential gear production. Another advantage of Coniflex is the possibility of cutter consolidation. Pinion and gear of the sample design in this chapter had been manufactured with the same 15" diameter Coniflex cutter and with the same blades. Because in Coniflex, the pressure angle is independent from the blade angle and the profile curvature does not require curved blades, it is possible to use one blade geometry for one or several part families.

Summary

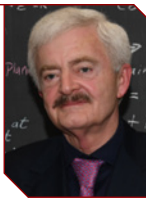
Mathematically precise tooth surface definition and contact analysis help to develop state-of- the-art straight bevel gears for many industrial applications. The new Coniflex-Plus manufacturing process utilizes high-speed dry cutting with production times per slot which are about twice compared to the fast Revacycle process.

The Coniflex-Plus innovation inspired many manufacturers of trucks and off-road vehicles to utilize the Coniflex-Plus technology to produce high-quality differential gears in medium and low batch sizes in a modern and flexible manufacturing environment.

For more information.
Questions or comments regarding this paper? Contact Hermann Stadtfeld— *hstadtfeld@gleason.com.*

References

1. Stadtfeld, H.J. "Differential Gears, Broached with Gleason REVACYCLE Compared to forged Parts," Gleason Company Publication, Rochester, New York, April 2001.
2. Stadtfeld, H.J. "Ask the Expert — "Computerized Differential Gear Development," ***Gear Technology Magazine***, October 2012, Pages 40 to 42.



Dr. Hermann J. Stadtfeld is the Vice President of Bevel Gear Technology and R&D at the Gleason Corporation and Professor of the Technical University of Ilmenau, Germany. As one of the world's most respected experts in bevel gear technology, he has published more than 300 technical papers and 10 books in this field. Likewise, he has filed international patent applications for more than 60 inventions based upon new gearing systems and gear manufacturing methods, as well as cutting tools and gear manufacturing machines. Under his leadership the world of bevel gear cutting has converted to environmentally friendly, dry machining of gears with significantly increased power density due to non-linear machine motions and new processes. Those developments also lower noise emission level and reduce energy consumption.

For 35 years, Dr. Stadtfeld has had a remarkable career within the field of bevel gear technology. Having received his Ph.D. with summa cum laude in 1987 at the Technical University in Aachen, Germany, he became the Head of Development & Engineering at Oerlikon-Bührle in Switzerland. He held a professor position at the Rochester Institute of Technology in Rochester, New York From 1992 to 1994. In 2000 as Vice President R&D he received in the name of The Gleason Works two Automotive Pace Awards — one for his high-speed dry cutting development and one for the successful development and implementation of the Universal Motion Concept (UMC). The UMC brought the conventional bevel gear geometry and its physical properties to a new level. In 2015, the Rochester Intellectual property Law Association elected Dr. Stadtfeld the "Distinguished Inventor of the Year." Between 2015–2016 CNN featured him as "Tech Hero" on a Website dedicated to technical innovators for his accomplishments regarding environmentally friendly gear manufacturing and technical advancements in gear efficiency.

Stadtfeld continues, along with his senior management position at Gleason Corporation, to mentor and advise graduate level Gleason employees, and he supervises Gleason-sponsored Master Thesis programs as professor of the Technical University of Ilmenau — thus helping to shape and ensure the future of gear technology.

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Influence of the Contact Conditions in Cold Rolling on the Density Profile of Powder Metallurgical (PM) Gears

Tim Frech M.Sc., Dr.-Ing Dipl.-Wirt.-Ing Christoph Löpenhaus and Prof. Dr.-Ing. Dr.-Ing. E.h. Dr. h.c. Fritz Klocke

Introduction and Motivation

Powder metal (PM) gears can be an energy and resource efficient replacement for conventional wrought gears (Ref. 1). To illustrate the possible savings in resources and process energy, Figure 1 shows a comparison of the 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 (Ref. 3). Because of the near-net-shape process, PM gears require less raw-material-per-part. Thus, less energy is used per produced part. PM gears are, hence, an economic alternative for conventional gear manufacturing.

Due to production by pressing and sintering, PM gears are porous. Since pores reduce the loaded area and are also probable crack initiators, the porosity determines the strength of the PM component. PM gears can be densified to increase their local density and, therefore, the load-carrying capacity (Ref. 2). PM gears are compacted locally since they are mainly loaded directly at the surface. A common process to densify PM gears locally is the cold rolling process. The contact conditions in the cold rolling process determine the density profile and, therefore, the material properties of the PM component. The influence of the contact conditions in cold rolling of PM gears on the resulting density profile is yet to be investigated.

Analogy Test of Cold Rolling of PM Gears

The meshing of two gears is characterized by continuously changing contact conditions due to changing contact radii as well as different sliding velocities (Fig. 2-left). Each contact point between the meshing gears can be described by

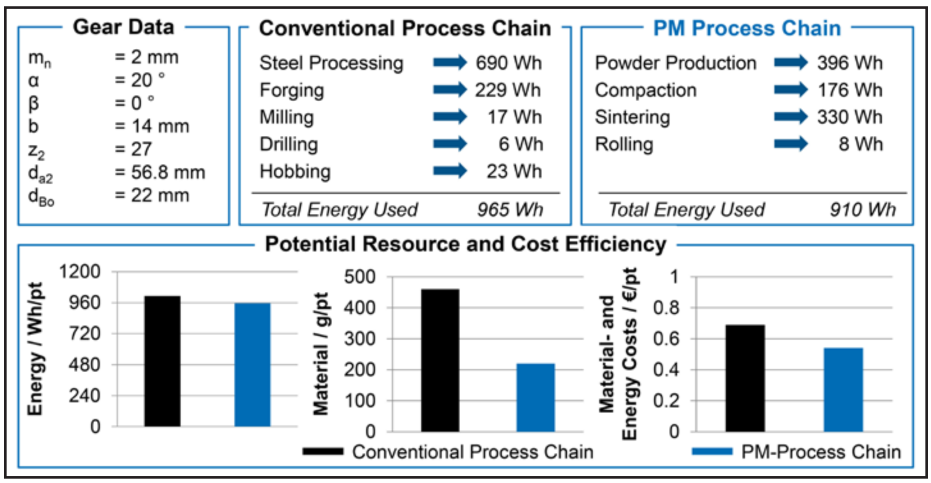

Figure 1 Cost and resource efficiency of PM gears.

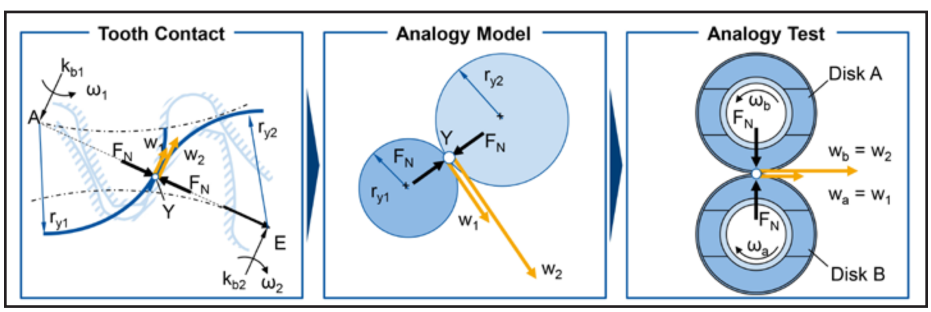

Figure 2 Analogy test for cold rolling of gears.

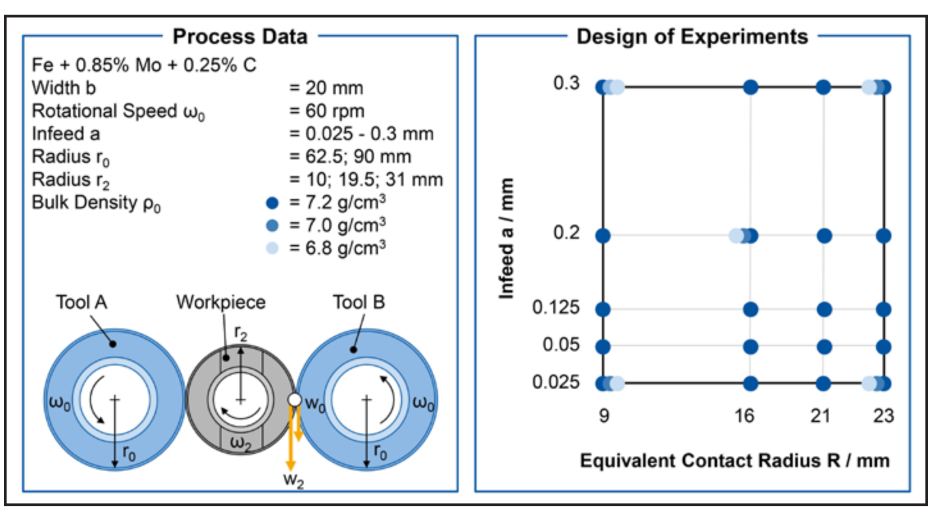

Figure 3 Design of experiments.

(This paper was first presented at International VDI Conference on Gears 2017, International Conference on High Performance Plastic Gears 2017, International Conference on Gear Production 2017, Garching/Munich VDI-Berichte 2294, 2017, VDI Verlag GmbH, Page 1265–1276.)

the equivalent contact radius and the relative speed between both contact partners. The equivalent contact radius R can be calculated with the individual contact radii r_1 and r_2 by Eq. 1.

$$R = \frac{r_1 \cdot r_2}{r_1 + r_2} \quad (1)$$

An analogy test was derived to investigate the influence of the contact conditions individually. According to Gräser, the relative speed between the contact partners does not influence the normal material flow and, hence, the densification of PM gears (Ref. 3). Therefore, the contact conditions will be investigated at constant slip of $s = 0$.

Design of Experiments

The design of experiments of the analogy tests for rolling of $Fe + 0.85\%\ Mo + 0.25\%\ C$ is shown in Figure 3. The infeed will be varied in a range of $0.025 < a < 0.3$ mm and represents typical infeeds of the cold rolling of gears. The used cold rolling machine Profiroll PR15HP allows to construct contact radii $R > 9$ mm. In the cold rolling of PM gears, contact radii of up to $R = 20$ mm can be found. Hence, the contact radii are varied in a range of $9 < R < 23$ mm.

The bulk density is varied in the range $6.8 < \rho_0 < 7.2\ g/cm^3$. Since the highest bulk density is most relevant for highly loaded applications such as gears, the influence of the process parameters is investigated full factorial. The lower bulk densities are investigated at the corners and the central point of the experimental plan.

The influence of the different process parameters is investigated numerically. The analogy process is modelled as a dynamic-explicit model in the FE program *Abaqus*. The model is validated experimentally for the reference test parameters with existing material models that have been validated in previous investigations (Ref. 6). The FE model uses the flow curve determined by Kauffmann to calculate the yield strength of the material as well as the Gurson-Tveergard-Needleman model to describe the influence of hydrostatic and deviatoric stress states on the material deformation (Refs. 4–6). Since friction does not influence the normal material flow, friction is not considered in the FE model (Ref. 3).

The numerically and experimentally obtained density profiles are shown

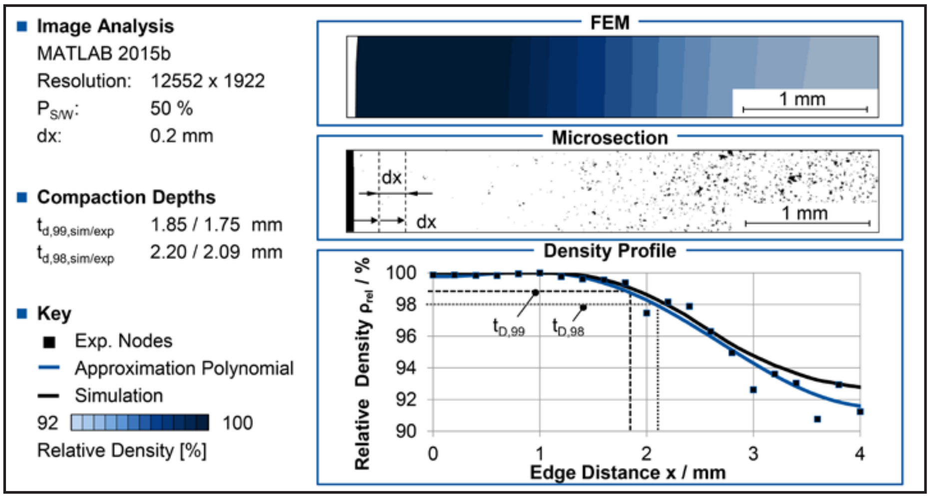

Figure 4 Validation of the FE model.

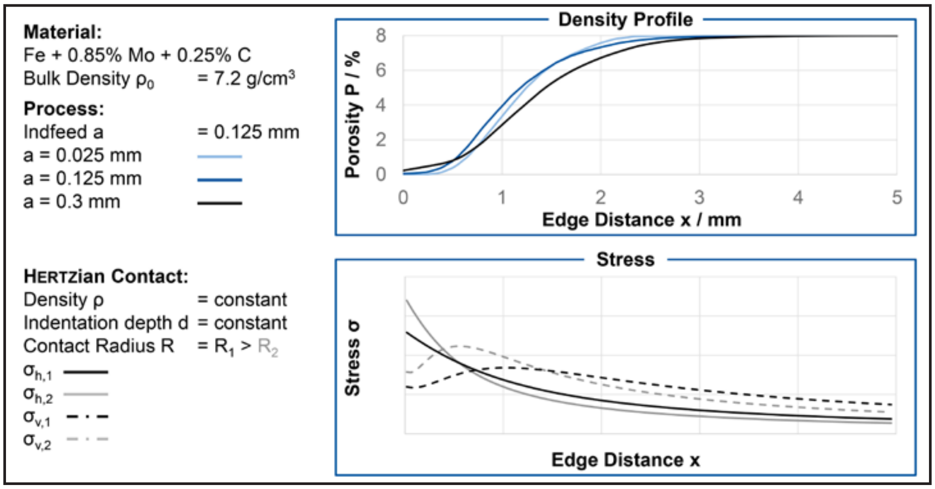

Figure 5 Influence of the equivalent contact radius on the density profile.

(Fig. 4). The simulated cross section of the analogy test component is shown on top while the experimentally obtained micro section is shown (Fig. 4-middle). To get a more quantitative comparison between both cross sections, the density profile of both sections is shown (Fig. 4-bottom).

Since the simulated density profile shows a qualitatively and quantitatively good fit to the experimentally obtained density profiles, it is expected that the simulation provides an appropriate image of the reality.

Influence of the Process Parameters on the Density Profile

To analyze the effect of different process parameters on the density profile, the different process parameters are varied individually while other process parameters are kept constant.

The influence of the equivalent contact radius *R* is shown on the left side of Figure 5. The equivalent contact radius is varied between $9 < R < 23$ mm while the infeed is $a = 0.125$ mm at a bulk density of $\rho_0 = 7.2\ g/cm^3$.

The equivalent contact radius influences the fully densified edge area as well as the gradient of the density profile. A low contact radius *R* leads to deeper densification at the surface but also to a steep decrease onto the bulk density when compared to higher contact radii *R*. The different depths of full densification as well as the different gradients can be explained with the Hertzian theory (Ref. 7). On the bottom of Figure 5, the stresses in the workpiece for two different contact radii are shown qualitatively while $R_1 > R_2$. The indentation *d* as well as the density ρ_0 are constant. The von Mises stresses calculated from the deviatoric stresses are shown in dashed lines. While it is assumed that conventional parts with full density are only deformed plastically by the Von Mises stresses, PM parts are also influenced by the hydrostatic stresses. It can be seen that both the hydrostatic stresses $\sigma_{h,2}$ and the von Mises stresses $\sigma_{v,2}$ of the lower contact radius R_2 are high directly beneath the surface with a steep gradient into the core of the workpiece. Because of their gradient, the stresses $\sigma_{h,1}$ and $\sigma_{v,1}$ of contact radius R_1 rise above $\sigma_{h,2}$ and $\sigma_{v,2}$ deeper under the workpiece surface. Therefore, low equivalent contact radii R result in a deeper full densified area beneath the surface but also in a steep decline of the density. The reason for the different density profiles at different equivalent contact radii R can be found in the resulting stress profile of the different contact conditions.

Additional to the investigation of the contact radius, the influence of the infeed a is also investigated. Different density profiles for different infeed a are shown (Fig. 5). The contact radius as well as the bulk density are constant at $R = 16$ mm and $\rho = 7.2$ g/cm^3 respectively. Furthermore, the stresses in the material resulting from the Hertzian contact are shown at the bottom Figure 6.

As it can be seen at the top of Figure 6, the densification depth rises when increasing the infeed. The reason for the higher densification can be seen (Fig. 6, bottom) as the stresses out of the Hertzian contact increase at higher infeed. Therefore, the higher densification depths at higher infeed can also be traced back to the stresses out of the contact conditions.

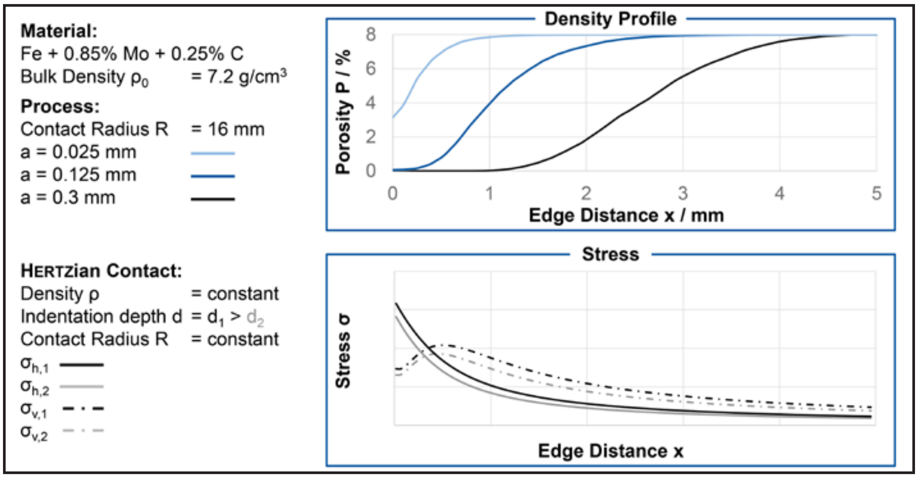

Figure 6 **Influence of the infeed and the bulk density on the density profile.**

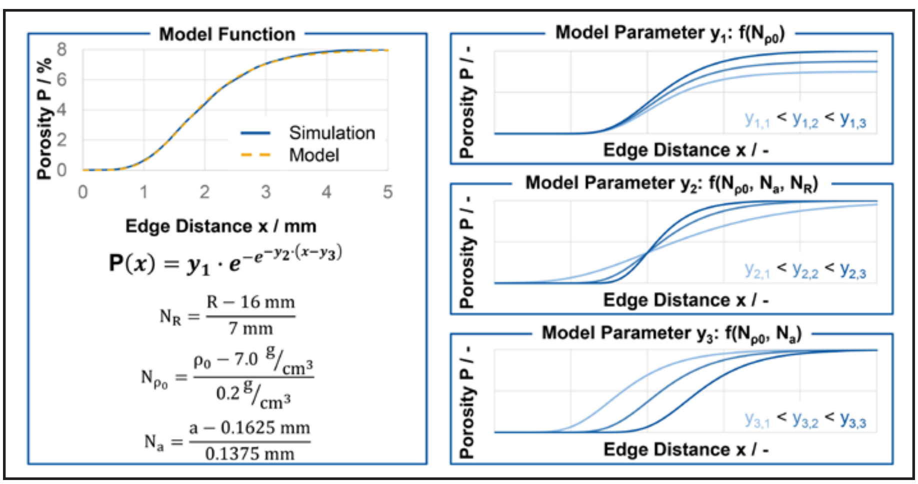

Figure 7 **Modelling approach.**

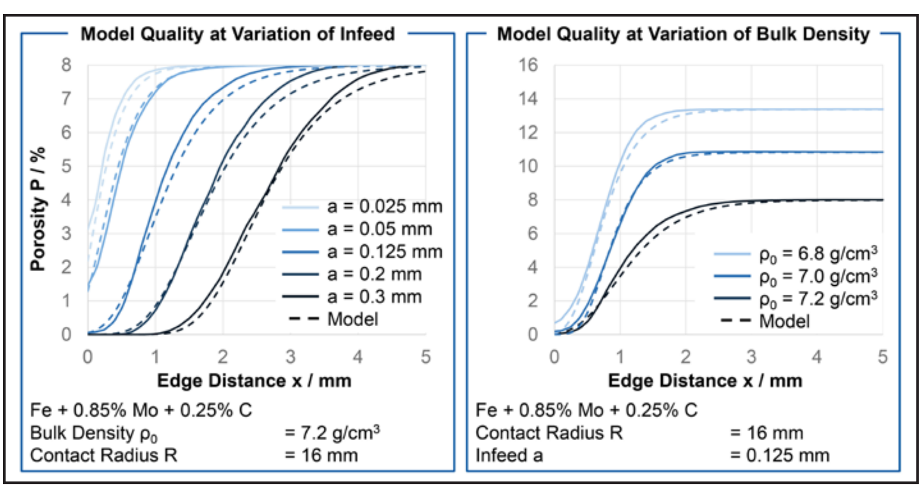

Figure 8 **Modelling the density profile in cold rolling.**

Modelling the Density Profile

To describe the density profile not only qualitatively but also predict it quantitatively, a model function needs to be found. As it can be seen on the left side of Figure 7, the density profile can be described with Eq. 1. The numerical obtained density profile is shown in solid lines while the fitted profile of Eq. 2 is shown in dashed lines.

$$P_x = y_1 \cdot e^{-e^{-y_2 \cdot (x-y_3)}} \quad (2)$$

To ensure the comparability of the influence among each other, the different process parameters are scaled on values ± 1 and can be calculated with Eqs. 3–5.

$$N_{\rho 0} = \frac{\rho_0 - 7.0\,g/cm^3}{0.2\,g/cm^3} \quad (3)$$

$$N_R = \frac{R - 16\,mm}{7\,mm} \quad (4)$$

$$N_a = \frac{a - 0.1625\,mm}{0.1375\,mm} \quad (5)$$

The influence of the different model parameters y_i can be seen (Fig. 7-right). Model parameter y_1 defines the threshold value of the model function. Model parameter y_2 influences the rise while parameter y_3 shifts the abscissa section of the model function.

Based on the density profiles in the previous section, the influence of the process parameters on the model parameters y_i can be analyzed statistically. Model parameter y_1 influences the threshold value of the model function. Hence, it is only influenced by the bulk density and can be calculated by Equation 6 with a coefficient of determination of $R^2 = 0.99$.

$$y_1 = 0.1 - 0.03 \cdot N_{\rho 0} \quad (6)$$

Model parameter y_2 determines the gradient of the model function. As discussed in the previous chapter, the gradient is influenced by contact radius and the infeed as well as by the bulk density. Since the process parameters are scaled (Eqs. 2–4), the weight of each process parameter can be determined out of Eq. 7.

$$y_2 = 2.6 - N_a \cdot (1{,}4 - 0.8 \cdot N_a - 0.3 \cdot N_{\rho 0} - 0.3 \cdot N_R) - 0.4 \cdot N_{\rho 0} - 0.3 \cdot N_R - 0.4 \cdot N_{\rho 0}^2 \quad (7)$$

The main influencing factor is the infeed a. The weight of the parameters contact radius R, bulk density ρ_0 as well as interdependencies between the different process parameters are nearly similar in Equation 7, therefore showing the same influence. By Equation 7, model parameter y_2 can be calculated with a coefficient of determination of $R^2 = 0.97$.

The abscissa section of the model function is shifted by model parameter y_3. The statistical significant process parameters are the infeed a and the bulk density ρ_0. The contact radius R does not show a significant influence on model parameter y_3 (Eq. 8). Due to the scaled process parameters, it can be seen that the infeed a has the greatest weight in Equation 8, while the bulk density ρ_0 and the interdependencies between both process parameters display a lower weight. Equation 8 allows to calculate model parameter y_3 with a coefficient of determination of $R^2 = 0.98$.

$$y_3 = 1.0 + 0.2 \cdot N_{\rho 0} + 1.0 \cdot N_a + 0.2 \cdot N_a \cdot N_{\rho 0} \quad (8)$$

With Equations 6–8, the model parameters for the model function in Equation 2 can be determined. This allows for a calculation of the density profile of cold rolled cylindrical PM components and, therefore, the determination of the density-dependent material parameters such as Young's modulus.

Quality of the Modeled Density Profile

To determine the quality of the mathematical model, the simulated density profiles are compared to the calculated density profiles. Figure 8 (left) shows the model quality at a variation of the infeed, and the variation of the bulk density on the right side. The density profiles obtained by simulation are shown in solid lines, the calculated density profiles are shown in dashed lines.

Both sides of Figure 8 show a very good match between the model and the simulation. Therefore, the model approach is an appropriate approach to calculate the density profile of PM components in the cold rolling process based on the contact conditions.

Summary and Outlook

The powder metallurgic process chain offers advantages in resource and energy consumption in mass production when compared to conventional 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 mainly stressed locally at and directly beneath the flank, gears are suitable for local densifying processes such as cold rolling.

The knowledge of the local density is of high importance when determining the mechanical properties and, therefore, the load-carrying capacity of powder metal components. The density profile is determined by the densification process and its process parameters or contact conditions respectively. Based on the Hertzian theory as well as on previous research, the process parameters infeed, equivalent contact radius and the bulk density were identified as relevant process parameters. The contact conditions of the cold rolling process of gears were transferred to an analogy test. This analogy test allows separation of the different and constantly changing contact conditions of the gear rolling process from each other so that the influence of each parameter can be determined individually. The infeed was varied in the range of $0 < a < 0.3$ mm, the equivalent contact radius in the range of $9 < R < 23$ mm while the bulk density was varied in the range $6.8 < \rho_0 < 7.2$ g/cm^3. The influence of the different process parameters was determined by FE simulations. The simulative results are qualitatively as well as quantitatively an adequate match to experimentally obtained density profiles.

The densification of PM steels is influenced by the Von Mises as well as the hydrostatic stresses in the material. An increase of the bulk density increases, due to the density-dependent Young's modulus, the stresses at constant infeed and equivalent contact radius. Additionally, a lower pore volume needs to be densified. Therefore, materials with higher density can be densified deeper. Due to the higher material deformation, a higher infeed also increases the stresses in the material and, hence, the densification. The equivalent contact radius of the workpiece-tool contact affects the slope of the density profile but not its depth.

To predict the mechanical properties of densified PM components, the density profile was modelled based on the contact conditions of the cold rolling process. The density profile of cold rolled PM components can be predicted with an appropriate model function. Therefore, the influence of the process parameters on the different model parameters was analyzed qualitatively. Then, this analysis was used to calculate the model parameters quantitatively.

The review of the model quality showed that the calculated density profiles show a good match to the simulated density profiles. Therefore, the determined model is capable to predict the density profile of cold rolled PM components based on the contact conditions.

The obtained results allow determination of the local density and, therefore, the mechanical properties based on the contact conditions of the cold rolling process. On the one hand, the information about the material properties of the PM workpiece allows a calculation of the local process forces. On the other hand, the results obtained from the analogy tests need to be transferred to the actual cold rolling process of gears. The constantly changing contact conditions of this process need to be considered to determine the local density profile at the tooth flank as well as in the tooth root.

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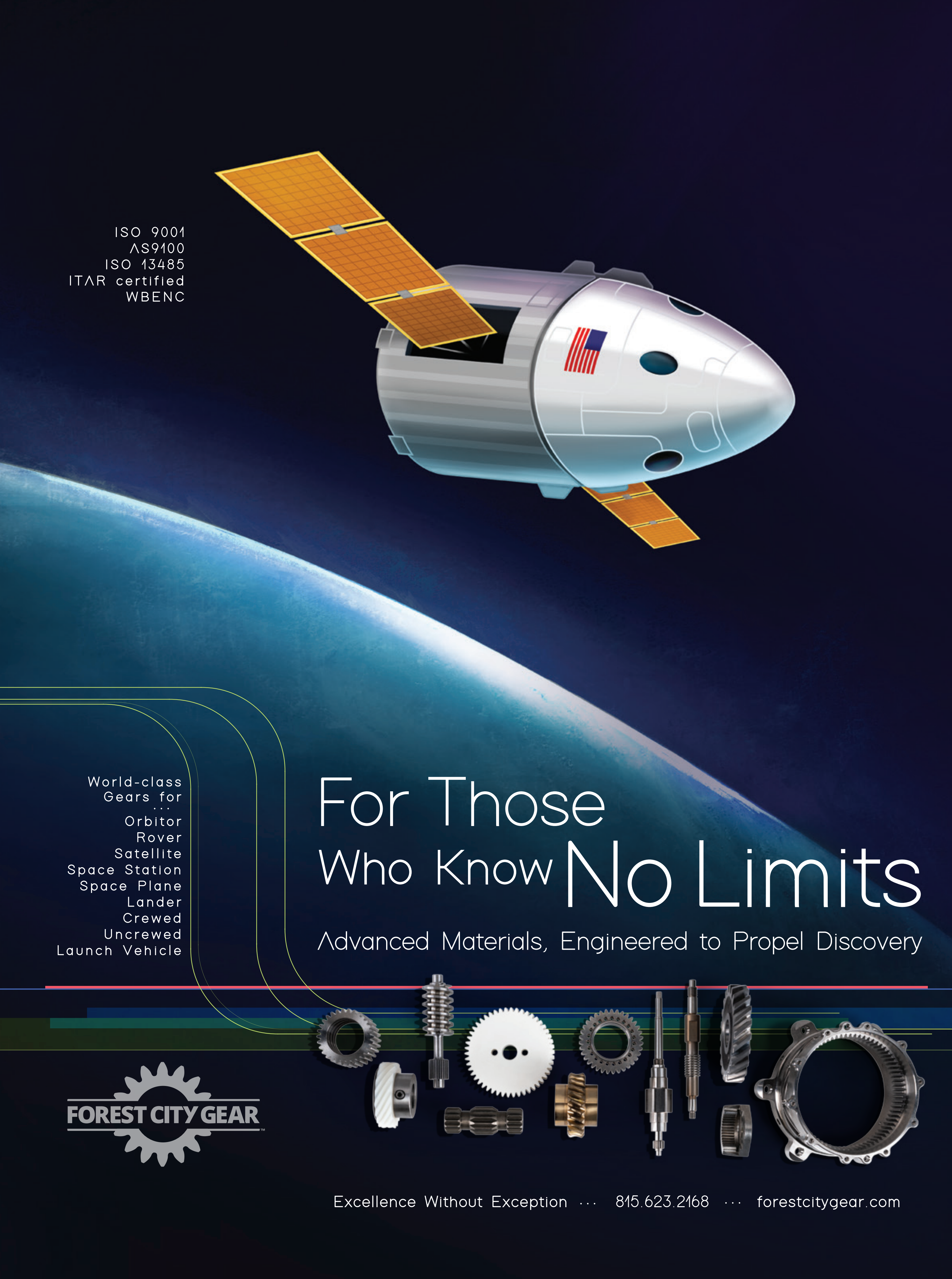
Dr.-Ing. Tim Frech has been working since 2019 as the Head of Gear Technology at Humbel Gear Technology, a gear manufacturer specializing in applications for racing, aviation, e-motive and railway industry, in Switzerland. He worked as a research assistant at WZL gear department from 2014 to 2019, focusing on the manufacturing process of powder metal gears. Previously, he worked as a student assistant in gear soft manufacturing in the WZL gear department. In 2019, he got his Ph.D. from RWTH Aachen University. He got his Master of Science degree in Mechanical Engineering in 2014 and his Bachelor of Science degree in Mechanical Engineering in 2013, specializing in development and design engineering.

Dr.-Ing. Dipl.-Wirt.-Ing. Christoph Löpenhaus is since 2019 working as the Business Development Manager Geared Bearings with Cerobear GmbH, a leading manufacturer of tailored high performance ceramic, hybrid and all steel bearing solutions. Cerobear was acquired by NHBB in 2013 and serves various industries such as aerospace, space, or race. From 2014–2019 he was Chief Engineer of the Department of Gear Technology of WZL, RWTH Aachen / Laboratory of Machine Tools and Production Engineering (WZL), RWTH Aachen with research focus on gear manufacturing, design, and testing. He previously held positions at the institute as Team Leader, Group Gear Testing, and Research Assistant. His educational background is in the field of Industrial Engineering with a diploma in 2009 and a Ph.D. in mechanical engineering in the field of gear technology in 2015. For his scientific achievements he was awarded the Springorum Commemorative Coin in 2010 and the Borchers Badge in 2016.

Prof. Dr.-Ing. Dr.-Ing. E.h. Dr. h.c. Dr. h.c. Fritz Klocke began his distinguished career (1970–1973) as an apprenticed toolmaker while at the same time pursuing his production engineering studies at Lemgo/Lippe Polytechnic, and later (1973–1976) at Technical University Berlin. He then (1977–1981) went on to serve as Assistant at the Institute for Machine Tools and Production Engineering, Technical University Berlin. Starting in 1981, Klocke achieved or received the following academic credentials and awards: Chief Engineer; (1982) Doctorate in engineering; (1984–1994)employed at Ernst Winter & Sohn GmbH & Co., Norderstedt; (1984) Head of Process Monitoring; (1985) Technical Director, Mechanical Engineering Department; (1985) Awarded Otto Kienzle Medal by the Universities Production Engineering Group; (1995) Director of the Chair of Manufacturing Technology at the Institute for Machine Tools and Production Engineering (WZL) of the RWTH Aachen, and director of the Fraunhofer Institute for Production Technology, Aachen; (2001–2002) Dean of the Faculty for Mechanical Engineering; (2006) Honorary Ph.D. by the University of Hannover; (2007–2008) President of the International Academy for Production Engineering (CIRP); (2009) Honorary Ph.D. by the University of Thessaloniki; (2010) Honorary Ph.D. by the Keio University; Award of Fraunhofer Medal; (2012) Fellow of the Society of Manufacturing Engineers (SME); (2014) Eli Whitney Productivity Award (SME); and (2014) Fellow of RWTH Aachen University.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3DEO

POSTS TRIPLE DIGIT GROWTH BY DEMOCRATIZING MANUFACTURING

3DEO started as a 3D printing company with its revolutionary metal 3D printing technology, Intelligent Layering, at the core. But in order to compete in high-volume traditional manufacturing, the company evolved into a vertically integrated, next generation factory. This new business model meant manufacturers could gain the cost savings, design freedom, and manufacturing flexibility they need to compete—without having to shell out millions of dollars for a metal 3D printer and the supporting infrastructure.

As evidenced by 3DEO's success metrics for 2019, this paradigm shift could be a forerunner to building the factory of the future.

"We are very proud of the growth that was accomplished over the last year. It is clear that 2020 will be another record-setting year for 3DEO as our pace of adoption across all industries is accelerating. More than a metal 3D printing company, 3DEO is a solutions provider helping our customers tackle their most challenging manufacturing problems. What's more, almost every customer we are working with is using metal 3D printing in production for the first time. We are in the trenches with our customers, and our growth curve is a testament to the demand for these solutions. In the end, our mission is to do for manufacturing what Amazon's AWS did for the internet by offering low-cost access to flexible, scalable, and world-class manufacturing infrastructure," Matt Sand, the company's president, said.

"We're doing things in manufacturing that previously couldn't be done," Matt Petros, 3DEO's CEO, said. "And we're doing it by leveraging several enabling technologies that are converging right now in manufacturing—in a way that finally allows metal 3D printing to shift the serial production paradigm."

Amidst a downcycle in manufacturing jobs in America, 3DEO's new solution-focused business model is creating new jobs. High-tech production workers work with robotics and automation. The most noteworthy employee increase was in the R&D department. With over 25 engineers, 3DEO is continuously improving core processes and technology up and down the production line. (*3deo.com*)

DTR USA Corp.

MOVES TO NEW LOCATION

DTR USA Corp. is moving to a new office located at 1261 Wiley Road, Unit K, Schaumburg, IL 60173. DTR offers a complete line of coarse pitch to fine pitch hobs including involute, worm, chain sprocket, timing pulley, serration, parallel spline or special tooth shape, shaper cutters and milling cutters and broaches for auto, aerospace, wind, mining, construction and other industrial gear cutting applications.

Hobs are manufactured to AGMA, DIN, JIS and ISO standards, modules ranging from 0.5 to 32, available in AGMA Class A, AA and AAA tolerances. Every hob is precision-made with the latest in coatings and high-speed steels, premium powder metal and carbide, giving the best possible tool to achieve superior cutting. DTR uses top of the line equipment including Reishauer CNC hob grinding and Klingelnberg CNC sharpening and inspection equipment. (*www.dtrtool.com*)

Höganäs

DONATES 165,000 SURGICAL FACE MASKS TO SWEDISH HOSPITAL

Höganäs in China recently sourced 165,000 surgical face masks, the kind that are used by hospital staff when caring for Covid-19 infected patients.

"Through the Swedish Chamber of Commerce here in Shanghai, we were able to ship and donate the masks to Örebro University hospital in Sweden," says Mark Braithwaite, who heads continent APAC. "If only so little, we are happy to ease the burden on the Swedish national healthcare."

In February, during the peak of the corona crisis in China, Höganäs co-workers in China received a lot of support and care from colleagues around the world. Also, Höganäs in China together with its co-workers donated 184,000 CNY ($25,000 USD) to support the Wuhan district through a charity foundation.

"Then during March, Höganäs in China sent more than 38,000 masks to different Höganäs countries to support maintained operations," says Terry Chen, who heads the operations at Höganäs' plant in Quing-Pu, Shanghai. "It became apparent

that there was good availability of face masks in China, but shortages in many other parts of the world. We thought we could help."

With the recent rapid spread of corona virus across the world, including Sweden, Höganäs in China decided to donate face masks to hospitals in need. Through reaching out to the Swedish Chamber of Commerce in China in mid-March, Höganäs was introduced to the brothers Fabian and Aron Fredriksson. They have an extensive business network in the Chinese medical equipment market and supported in identifying hospitals in Sweden in critical need of face masks and ensuring that approved masks were supplied and able to be exported.

"The whole process took a little longer than expected to finalize, but we managed thanks to support from colleagues in Sweden for the shipment. We were very pleased when the 165,000 face masks finally left Shanghai on 11 April," says Richard Molin, Continent APAC Operations.

The masks arrived safely at Örebro University Hospital in late April and were approved for use.

"We are immensely grateful for this gift and the engagement it represents. The large number of face masks is a valuable contribution and supports us in supplying a good and safe healthcare," comments Claes-Mårten Ingberg, medical director in Region Örebro County.

"We continue to team up with the Swedish Chamber of Commerce in Shanghai to find more Swedish companies in China that want to join the fight against the corona virus. The situation is changing quickly, and it will become more difficult to secure needed protection equipment as more and more countries are recommending use also for individuals," says Braithwaite. (*www.hoganas.com*)

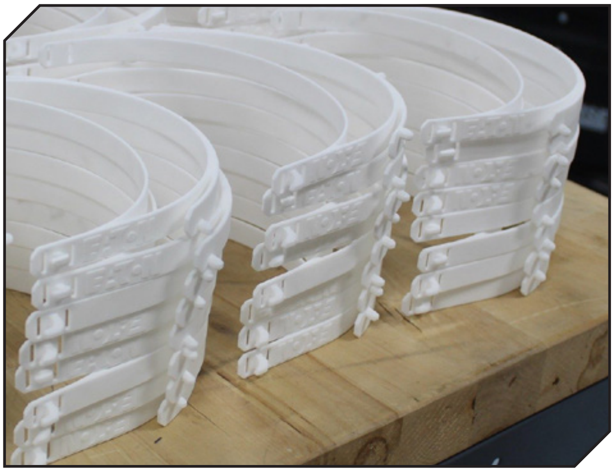
Eaton

COLLABORATES WITH THOGUS ON FACE SHIELD DESIGN AND PRODUCTION

The global COVID-19 crisis is placing unprecedented demands on government and healthcare organizations, driving a critical need for front line workers' access to personal protective equipment (PPE). Power management company Eaton is using its manufacturing, 3D printing expertise and partner network to fulfill a JobsOhio order for rapid production of 360,000 reusable face shields to strengthen the state's fight against the virus.

Eaton collaborated with multiple hospitals and Cleveland's Manufacturing Advocacy and Growth Network (MAGNET) to optimize the face shield design for production. Now, Eaton is working with Thogus, a local family-owned custom plastic injection molder, to rapidly produce the critical equipment at scale.

"Ten business days ago, this project was just a concept. Today, we're moving forward with production and looking to expand further," said Michael Regelski, senior vice president and chief technology officer, electrical sector at Eaton. "By leveraging our advanced manufacturing capabilities and strong network of partners, we're helping Ohio quickly respond to current inventory challenges and maximize accessibility of critical PPE resources for front line teams combatting COVID-19."



Eaton's additive manufacturing capabilities are instrumental to fast-paced design incorporating customer feedback and ability to easily scale production to meet the immediate needs of communities around the world. (*www.eaton.com*)

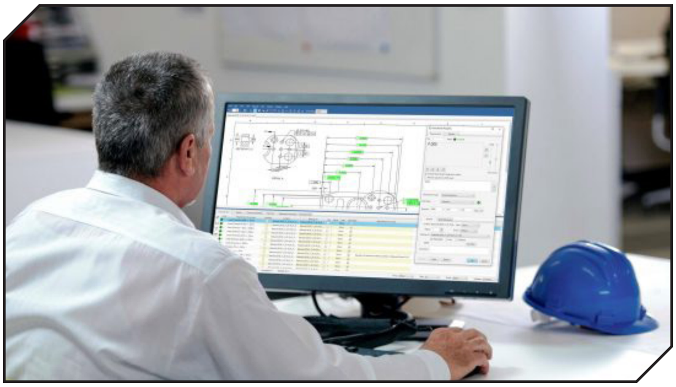
Discus Software

SELECTS ADAPTIVE CORPORATION AS U.S. DISTRIBUTOR

Discus Software Company, headquartered in Columbus, OH, has announced a premier authorized partnership agreement with Adaptive Corporation. Adaptive will sell and support Discus' First Article Inspection (FAI) software solutions to businesses operating in aerospace, defense, automotive, medical and various other manufacturing industries that have stringent quality requirements.

Discus specializes in automation of the first article inspection process. "We selected Adaptive as our first U.S. premier authorized partner because of their ability to deliver a closed-loop solution for FAI, as well as additional services such as the capture and tracking of statistical process control (SPC) data," says Jake Hart, director of sales and marketing for Discus.

"Our complete package provides not only First Article Inspection, but support for other production/inspection processes as well," says Frank Thomas, Adaptive's metrology line business manager. "At Adaptive, our metrology solution portfolio helps our customers significantly reduce first article inspection costs by automating the data collection and reporting process."



First article inspection is a common practice in a wide variety of industries for reviewing products before volume production. Many manufacturers spend an inordinate amount of time converting customer data packages (CAD models, drawings, specifications, etc.) into the necessary internal documentation. Quality engineers create inspection plans and FAI reports; manufacturing engineers create process plans. Manual transcription of such data is laborious, can be redundant and is subject to human error.

Compliance with the various FAI expectations (i.e. AS9100 in aerospace, PPAP in automotive) of customers is essential for manufacturers. Discus' modular software tools greatly reduce the labor effort for AS9100, PPAP, TS16949, and Part 820 quality and manufacturing planning. The software is compatible with many of the requirements used by companies like Boeing, Lockheed, BAE, Aerojet, Honeywell, Collins Aerospace and others.

"Discus is an industry-leading product that is used heavily in automotive and aerospace companies of all sizes, which are a primary focus for Adaptive," says Thomas. "Together we have a common market and business focus on enhancing product quality and time-to-market and it made sense to partner in sales and support of Discus software moving forward."

"The Discus-Adaptive partnership is a powerful combination given Adaptive's extensive experience in FAI and metrology and Discus' industry-leading software," says Hart. "Adaptive will help grow and support Discus' expanding customer base here in the US." (*www.discussoftware.com*, *www.adaptivecorp.com*)

Gear Motions

PLEDGES TO KEEP PEOPLE SAFE AND FACTORIES RUNNING

In coordination with the Manufacturers Association of Central New York (MACNY), Gear Motions has joined a group of CNY manufacturing companies pledging to keep employees safe and factories running.

Supported by a peer-to-peer review process, the pledge combines the experience, skills, and knowledge of the founding organizations with best practices from noted authorities such as NYS DOH, CDC, OSHA, and WHO.

GEAR MOTIONS

Precision in Motion

The pledge includes steps that go above and beyond to keep factories safe for employees and the community. Components include:

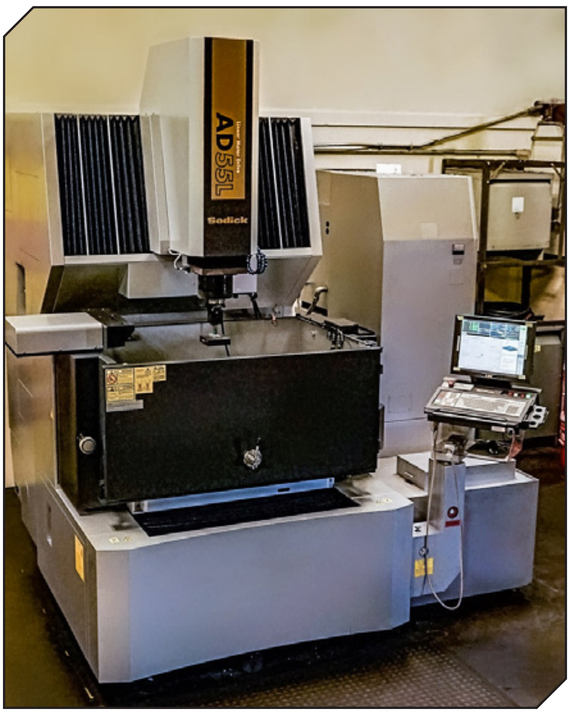
- Controlling site traffic
- Enhanced hygiene
- Social distancing and reduced density
- Emergency response and quarantine procedures
- Robust communication

Message from Gear Motions: "Keep People Safe and Factories Running. We have instituted significant operating enhancements to mitigate the risk associated with the spread of the Novel Coronavirus. We remain committed to, and align with, NYS DOH, CDC, OSHA and WHO guidelines." (*gearmotions.com*)

Atlas Pressed Metals

ACQUIRES NEW SINKER EDM FOR PM MANUFACTURING

Electrical Discharge Machine (EDM) is a machining method primarily used for hard metals or those that would be impossible to machine with traditional machine tools. A Sinker EDM is especially well-suited for cutting intricate contours or delicate cavities that would be difficult to produce with a grinder, an end mill, or other cutting tools. Atlas currently does most all repairs to tooling in house, the Sinker EDM is an integral part of the company's tool repair and replacement program.



Atlas upgraded to a brand new Sodick AD55L Rigid Linear Motor Driven Sinker EDM for higher precision, and the ability to produce finer, more intricate details on powder metal compaction tooling; to accommodate larger tools for higher compaction tonnage presses. With a maximum workpiece weight of over 2,200 pounds, and capability to accept a punch over 22 inches in length, this EDM will cover most any powdered metal (PM) tool in the entire industry; and to produce much finer finishes and reduce EDM time. With less labor-intensive hand polishing required Atlas will achieve quicker lead times, shorter press downtime, and reduced labor to improve the overall cost of its final products.

"It is very exciting to have this level of technology for tool and die work here at Atlas. Investing in an EDM of this caliber really shows that we are committed to supporting our customers and being the best at what we do," says Dan Dixon, Atlas tool shop and machining manager.

Atlas Pressed Metals is a family-owned, powdered metal parts manufacturer, that was established in 1976. (*atlaspressedmetals.com*)

VELO3D

FUNDING PAVES WAY FOR PRODUCT EXPANSION

VELO3D has announced that it has raised $28 million in a Series D funding round. New investors Piva and TNSC joined the round, along with existing investors Bessemer Venture Partners, Playground, and Khosla Ventures. This brings VELO3D's total funding to $138 million.

"With the VELO3D integrated solution of Flow advanced pre-print software, Sapphire printer, and Assure quality management software, companies can finally break free of the constraints of existing metal additive manufacturing processes," states Benny Buller, founder and CEO of VELO3D. "Customers in industries such as aerospace, oil & gas, and power generation are now able to achieve part quality for their mission-critical applications with performance levels that weren't possible before with 3D metal printing."

VELO3D plans to use the new capital to expand its product portfolio to include more machine options, compatible alloys, and enhanced software and hardware capabilities. The company anticipates that the injection of fresh capital will help them reach sustainable profitability by mid-2022.

Piva is the largest investor in the new round and has a strong heritage in industrial markets, as they are backed by Malaysia-based PETRONAS, one of the world's largest energy companies.

"VELO3D is revolutionizing the way we think about advanced manufacturing today," said Ricardo Angel, CEO and managing partner at Piva. "We have been impressed by Benny, the team and their breakthrough technology that will have a significant impact on the efficient design and manufacturing of more complex components, previously unattainable, with clear commercial traction already in the aerospace and aviation markets. VELO3D will lead a new wave of more resilient, distributed manufacturing capabilities for its most critical components, which the world will need to ensure local product availability and timeliness, while mitigating potential future worldwide disruptions."

Founded in 2015, VELO3D operated in stealth mode for the first 4 years, then announced availability of the Sapphire printer in 2019. In that first year of commercialization, VELO3D generated nearly $30 million in sales and gained seven new customers, many of which have placed repeat orders. VELO3D now has a global customer footprint that includes Japan, Korea, and Australia. (*www.velo3d.com*)

Rollomatic Inc.

APPOINTS GROUP COO

The Rollomatic Group has announced the appointment of **Joe Kane** as Group COO for both entities, Rollomatic Inc. and Strausak Inc. Kane will continue to hold his position as president of Strausak Inc. In this position, Kane will oversee all areas related to the operation of the two companies. He will personally manage the combined team of application engineers and provide leadership and training to the field service manager, parts and logistics manager and the customer solutions manager and their respective teams. Kane will also be responsible for the day-to-day running of the company, IT/IS and the facility.

"Joe's impressive track record working as president of Strausak Inc. and his ability to communicate and relate to people make him the ideal leader. Such qualities are key to expanding the brand name and drive the ever-evolving new technologies of the companies. We fully expect that his talents will support the profitable growth of the Rollomatic and Strausak business," said Eric Schwarzenbach, president of Rollomatic Inc.

Kane has been president of Strausak Inc. for 2½ years where he successfully focused on accelerating Strausak's innovation and customer-focused applications in the precision grinding space for the cutting tool industry.

Prior to joining Strausak Inc., Kane spent over 14 years in the manufacturing and quality industry where he began as a metrology technician with the United States Marine Corps. He later translated these skills and expanded his career into product and sales manager positions where he set up distribution and service channels throughout North America for CNC machine tool companies specializing in automated, turnkey solutions for production machining. (*www.rollomaticusa.com*)

Blaser Swisslube

OFFERS LIVE WEBINARS AND METALWORKING FLUID TIPS

Blaser Swisslube is close to its customers in these difficult times with regular live webinars to help the machining world refresh their knowledge and learn new things. It began with a look behind the scenes at the headquarters in Switzerland, followed by a series of in-depth webinars.

Since physical meetings are hardly possible at the moment, the innovative coolant manufacturer Blaser Swisslube has quickly changed to online company tours and trainings. CEO Marc Blaser explains the background of Blaser's current training series. "From basics to expertise, from analysis to monitoring and maintenance, our machining experts and chemists help you fully capitalize on the potential of your machines and tools and turn your metalworking fluid into a key success factor—a Liquid Tool," he said.

On April 2, 2020, Blaser Swisslube began with internal online courses for further training of employees. In the first five weeks, the in-house Blaser College held in total 176 live sessions, which were attended by more than 3,200 employees as well as business partners and customers from all over the world.

Since April 30, Blaser has been offering live events for the entire machining world. In the first of a series of webinars, attended by over 1,000, Chief Technology Officer Bernhard Gerber provided a look behind the scenes at the headquarters in Switzerland. He talked to machining experts

and chemists from Blaser's technology center and laboratory about the strong leverage effect of the metalworking fluid on crucial performance indicators such as tool life, cycle time, workpiece quality and machinist satisfaction, as well as about the importance of regular monitoring and maintenance.

Visit the website below to see the schedule of live webinars for the coming weeks and months on topics such as coolant maintenance, microbiology and the underestimated leverage effect of the metalworking fluid on total costs. The recordings of live events that have already taken place are also available for viewing. Anyone interested in the power of the metalworking fluid can therefore easily refresh their knowledge and learn new things. Since Blaser Swisslube has had positive experiences with its online trainings, they will remain an integral part of the company's training plan for the future. "We will focus on online and live trainings to provide our customers and partners with in-depth knowledge and experience," concludes Marc Blaser. (*blaser.com/webinars*)

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The Death of the Cog

Clocks, Cars and Music on a Saturday Night

Matthew Jaster, Senior Editor

Free time **is an interesting term in 2020.** Sure, we can attempt to retain some of the normal day-to-day activities, but most of our schedules, procedures and hobbies have been tossed out the window and replaced by more isolated endeavors. I host a virtual game show with my friends, for example, called *Pandemic: The Home Game*, just to have some laughs and see their faces once a week. I also have taken this opportunity to hit the shuffle button on my music catalog, a fun game if you have an Apple Music, Spotify or Tidal account because you never know what is going to come next. Death metal? Acid Fusion Jazz? Christian Rap? It can be quite the interesting entertainment experiment.

I recently came across a colorful, catchy, steampunk band that released a song in 2010 called, "The Death of the Cog." I had no idea there were so many bands devoted to *spinning* manufacturing and mechanical tales about gears, sprockets, and other components, but the lyrics really spoke of things happening in manufacturing—past, present, and future—that feel very relevant. A sample of the lyrics:

"Clocks used to be such magnificent things, beautiful sprockets and dazzling springs,

but you gave the people your digital beast, and in turn now all gears are deceased!"

The Death of the Cog, by The Cog is Dead (2010)

This song discusses the invention of the first digital watch, a Pulsar prototype that arrived in the early 1970s by the Hamilton Watch Company. The move toward digital time keeping was a real buzzkill to the gear manufacturers back then that provided the components in wristwatches.

The song continues:

"How things have changed since I was a boy! Clockwork would tick and would bring me such joy. But, with your advent, there's no need to wind—everything charming has been left behind!"

The invention of the world's first digital wristwatch was announced May 6, 1970 on *The Tonight Show*. Hamilton presented the Hamilton Pulsar Time Computer: with no moving parts. Two years later, The Pulsar was launched to the general public. The display was created using LEDs activated by a button on the side of its solid gold case. Hamilton produced only 400 pieces, which sold for $2,100, more than the price of a car at the time.

In recent years, Hamilton has been designing wristwatches for Hollywood films including one used by Jessica Chastain in the film *Interstellar* and one used by Matt Damon in *The Martian*. These unique timepieces hint at the future of the technology and suggest the company will continue to innovate and inspire for years to come.

While listening to this song about how digital products took the relevance—and the momentum—away from gears and sprockets, I was immediately struck by the similarities today between gears and the automotive industry.

More electronics, less components have pretty much been the calling card for the entire transportation industry lately as gear engineers scramble to make sure they will have products to offer GM, Ford and FCA in the future. Some say it's a scary time for gear manufacturing, but it doesn't have to be.

If you look back at the history of the Hamilton Watch Company, they were manufacturing pocket watches as early as 1892. The company never gave-up on gears, they just recognized a digital evolution was coming, and they adapted accordingly.

The cog won't die, in my opinion, but it's going to look very different in many applications in the future. With all this free time lately, it might be beneficial to start thinking about how your products will need to adapt in the coming years to remain relevant in manufacturing.

(*www.hamiltonwatch.com, www.cogisdead.com*)

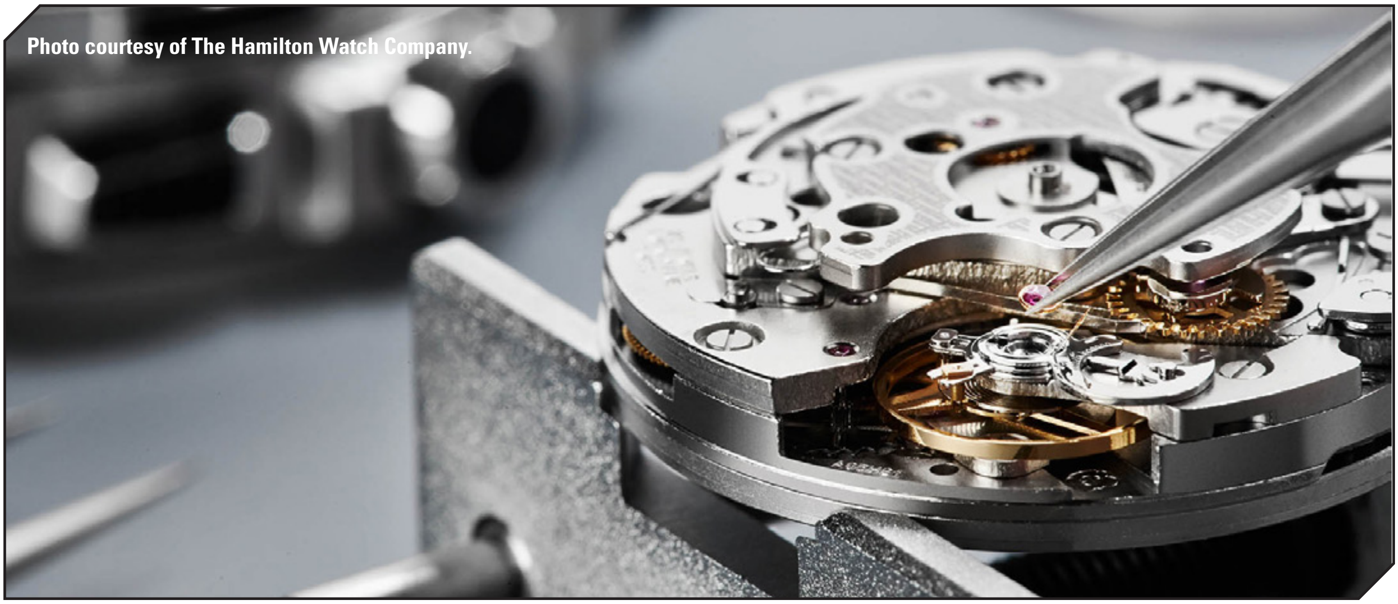
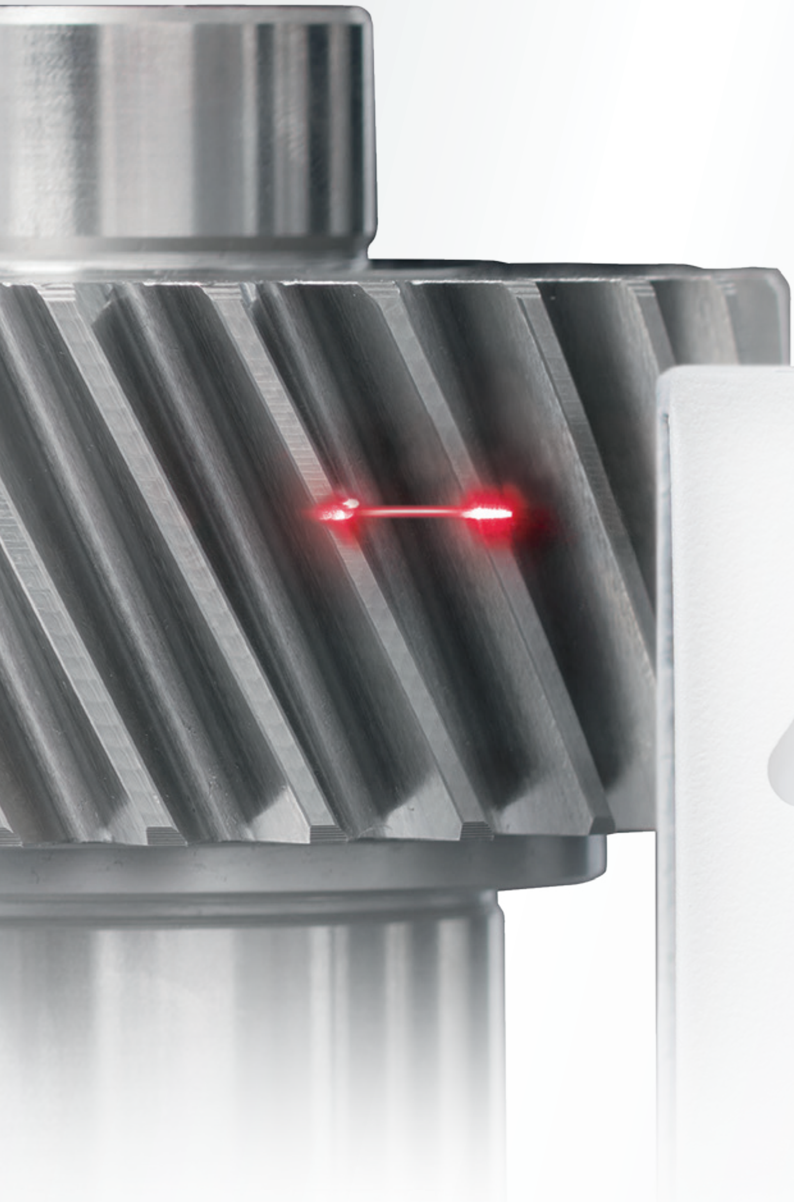
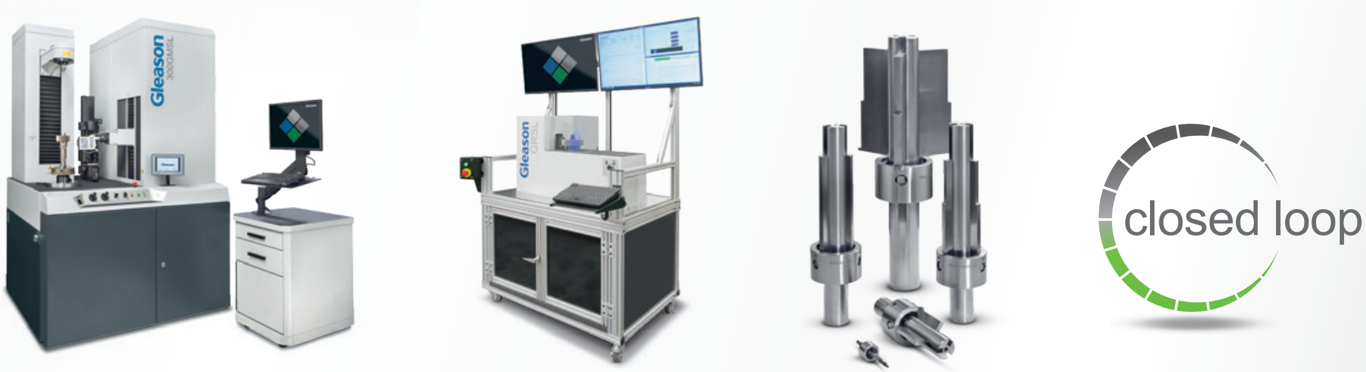


Photo courtesy of The Hamilton Watch Company.





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