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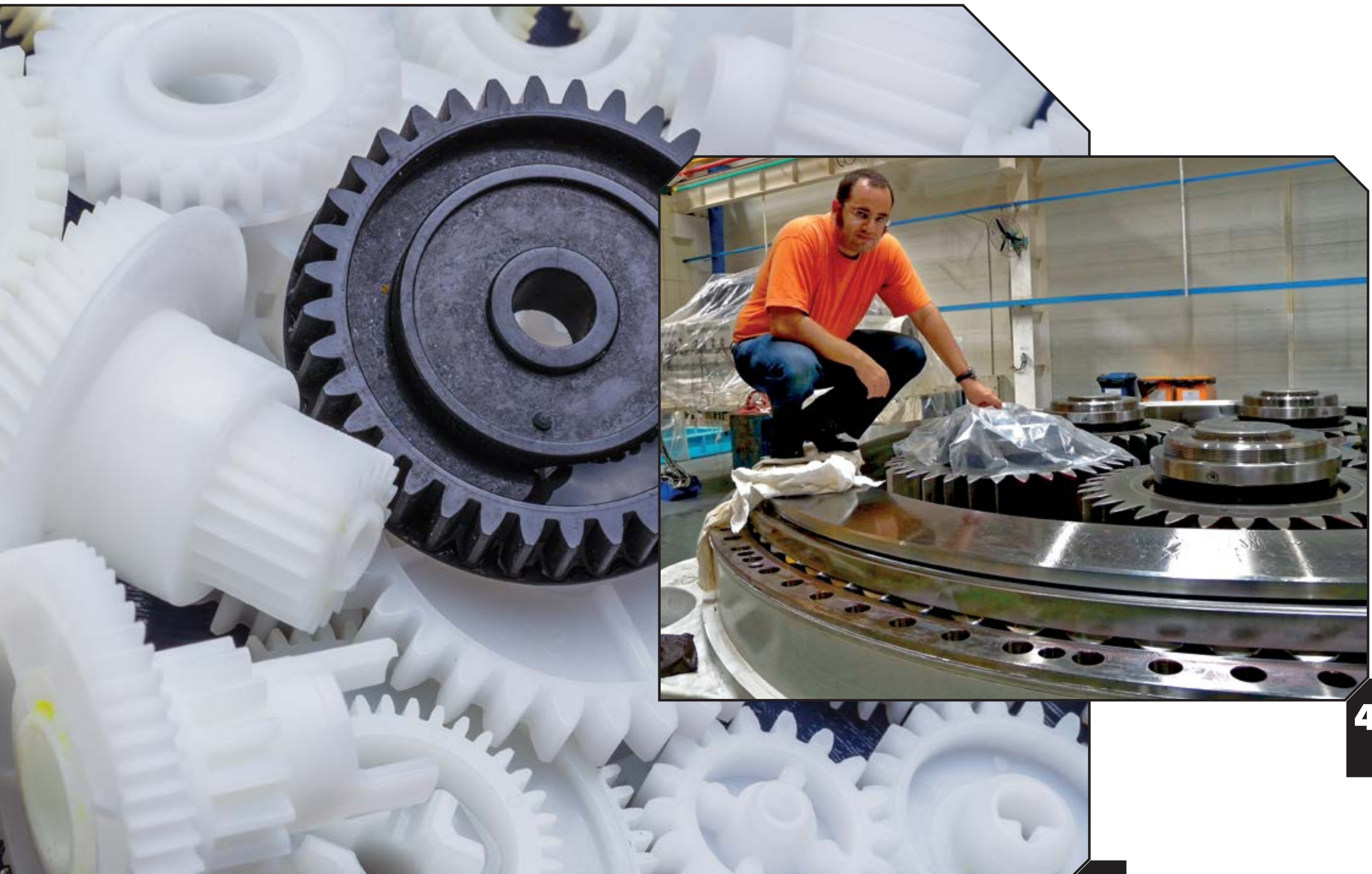

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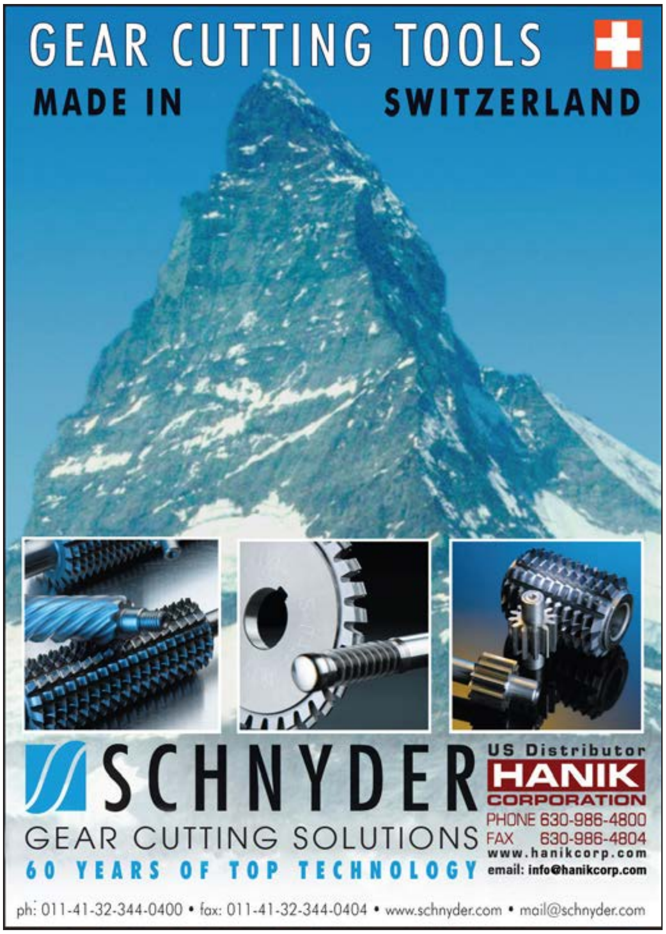

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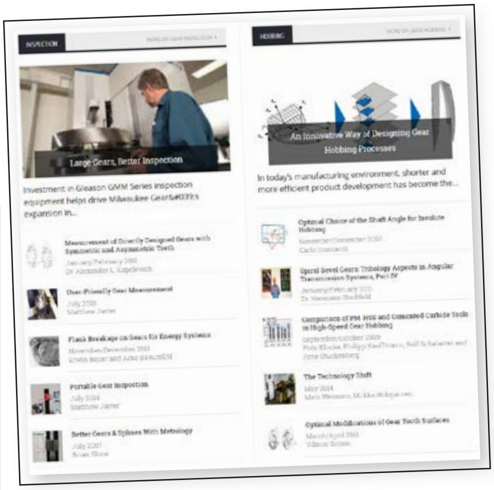

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Gear Talk

Gear Technology technical editor and resident blogger Chuck Schultz weighs in on some important gear topics:

In *What Good Are the Leading Indicators*, Chuck discusses the tumultuous economic cycle facing manufacturers today and the impact it has on business.

In *New Ideas in Gears*, Chuck examines the product development challenges in gear design with some historical examples and thoughts on how to improve the process internationally.

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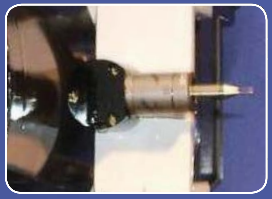

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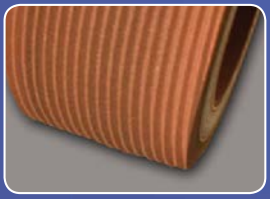

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Time to Take Off the Training Wheels

Publisher & Editor-in-Chief
Michael Goldstein

Teaching a kid to ride a bike is hard work. Sure, you can put training wheels on the bike, and the kid will be mostly safe, build some confidence and manage to get around. But it's not really riding a bike, is it?

You don't truly learn to ride until the training wheels come off. As the teacher, that means you have to spend a lot of time running alongside, coaching and encouraging. It also means you have to know when to let go.

The same is true of training employees, especially if we expect them to be the next generation of leaders who run our companies.

I read an interesting article in *Bloomberg Businessweek* about mentorship programs and what a number of progressive companies are doing to ensure that the up-and-comers will be prepared to take over when the time comes ("Chowing Down on Boomers' Brains," from the January 25-31, 2016 edition).

Unfortunately, for most of America, that time has already come, and the gear industry is no exception. Most of the Baby Boom generation has already reached retirement age. Even Generation X is getting close, which means the Millennials (those born between 1980-2000) are becoming a more and more important part of the workforce.

In fact, the article says, until last year, Baby Boomers made up the largest portion of the U.S. population, and Generation X made up the largest portion of the workforce. But today, Millennials make up the biggest portion of both categories.

The question raised by the article is whether companies are doing enough to make sure they're ready.

We all know how serious this is, and the gear industry is no exception. Every day, more of the oldest, most experienced employees leave the workforce, taking with them lifetimes of knowledge and experience.

According to our most recent "State of the Gear Industry" survey (Nov/Dec 2015), 63% of you say your companies are currently experiencing a shortage of skilled labor.

According to the *Bloomberg Businessweek* article, 78% of executives surveyed thought the threat of losing business-critical expertise was more of an issue than it was just five years ago. A whopping 84% said they frequently (24%) or sometimes (60%) lose top managers or other experts without successors.

So what are we supposed to do?

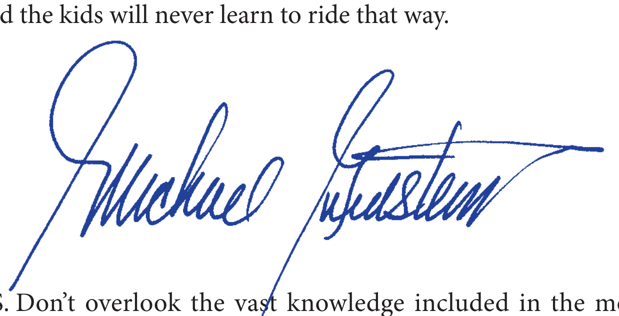
It all comes down to figuring out a way to transfer the knowledge, the article says. Major companies like BAE Systems, General Motors, General Electric and others are coming up with ways to formalize and encourage that transfer via mentorship programs, training initiatives and special task forces.

At BAE, for example, a knowledge-transfer group of about a half-dozen people is assigned whenever the company learns that an employee with deep institutional knowledge is planning to retire. The teams meet regularly over months to talk and exchange advice. The article also mentioned one manager who demoted himself prior to retirement so he could let a younger manager step in. The two worked together on a number of key projects during the transition, and the younger manager was fully prepared when the time came.

All the companies mentioned in the article benefitted from these knowledge transfer programs. They saved money in training costs. They completed projects more successfully, and they maintained their competitive advantage.

It seems clear that we can't afford to just let knowledge walk out the door. The next generation needs the coaching, encouragement and insight that the older generation can provide. And they need to take on the responsibility that the older generation may be reluctant to give up. Sure, it can be a lot of work for the older generation, who might prefer to be left alone, and who might prefer to leave the youngsters to their own means.

But doing nothing is akin to leaving the training wheels on, and the kids will never learn to ride that way.



P.S. Don't overlook the vast knowledge included in the more than 2,000 technical articles we've published in the last 31 years, organized by subject, in the GT LIBRARY on our website at *www.geartechnology.com*.

Critique of the ISO 15144-1 Method to Predict the Risk of Micropitting

This is About Micropitting — Not Nitpicking

From the Editors

Great minds think alike — but not always at the same time.

Indeed, arriving at a consensus of "great minds" can be tricky — like the shepherding cats thing.

Witness proposed ISO/TR/TR Standard 15144-1 — Method to Predict Risk of Micropitting — as a perfect example.

As far as international standards go, this one on balance is not particularly controversial; it does not seek to reinvent the wheel — it's about micropitting, after all.

Not, on the other hand, to minimize what has been a very serious gearing issue — especially in such vital sectors as the wind industry — on and offshore.

The following Voices submission is a Robert Errichello opinion piece (and a virtual micropitting tutorial) regarding a portion of the mentioned work-in-progress micropitting standard — 15144-1. (*Full disclosure: Errichello is a both a longtime Gear Technology Technical Editor and contributor*.)

It will be followed by a joint ISO/TR-AGMA statement addressing this issue.

Some brief backstory for perspective: Errichello is of the opinion — along with 20 fellow peer reviewers — that the proposed micropitting standard is "flawed." And his submission on the issue that you are about to read explains in great detail his opinion why this is so.

By going public, is it possible Errichello runs the risk of perhaps being perceived by his colleagues as "gearing's gadfly?"

Regardless, *Gear Technology* is certainly not here to judge — nor even to referee. We simply thought gear folk might find some behind-the-scenes back-and-forth on how standards are drafted to be of some interest. Again, Errichello's statement is followed by a brief ISO/TR/AGMA joint statement.

Robert Errichello

Introduction

There exists an ongoing, urgent need for a rating method to assess ***micropitting risk,*** as AGMA considers it a "a very significant failure mode for rolling element bearings and gear teeth — especially in gearbox applications such as wind turbines."

In response, ISO Technical Report ISO/TR 15144-1 has been proposed as an International Standard for rating *gear micropitting risk*. Currently, it is a Technical Report that is being tested by several members of ISO and AGMA technical committees. Because micropitting is a very complex failure mode that is influenced by a vast array of parameters, the AGMA decided to conduct a peer review of ISO/TR 15144-1 by recognized tribologists specializing in elastohydrodynamic lubrication (EHL). Reviewers were selected for their expertise in EHL and micropitting. All reviewers had published technical papers in peer reviewed journals and many of the reviewers are tribologists who have conducted research at technical universities or industrial laboratories. Their affiliations are located in the US, UK, and France. The invitation was sent to 39 potential reviewers and 22 accepted the invitation. Ultimately, as of the date of this report, 20 reviews were completed and submitted.

Critique of ISO 15144-1 Method to Predict Risk of Micropitting

ISO 15144-1 (Ref. 1) is technically flawed. Its postulate that Blok's flash temperature reduces the elastohydrodynamic lubrication (EHL) film thickness is fundamentally wrong. A peer review of the document concluded that the postulate flies in the face of established science. Therefore, I recommend that ISO 15144-1 be withdrawn.

AGMA Peer Review Process

The peer review (Ref. 2) was performed by world-renowned tribologists; they were encouraged to review the entirety of ISO 15144-1, but were asked to focus their review on the novel feature of ISO 15144-1 — i.e., the sliding parameter $S_{GF,Y}$. The results of the review showed that ISO 15144-1 is technically flawed.

What is the problem? The heat generated within the EHL film by shearing of the lubricant and rubbing of asperities does not affect the inlet temperature once the bulk temperature reaches equilibrium. Consequently, the temperature rise due to frictional heating within the Hertzian zone only affects film thickness indirectly by influencing the gear tooth bulk temperature, and it does not change the EHL film thickness, which is determined by the gear tooth bulk temperatures in the inlet zone to the EHL contact. Therefore, the ISO 15144-1 postulate that Blok's flash temperature reduces the local film thickness is fundamentally wrong.

What, in fact, is the proper way to account for sliding? Tribologists have found that it is not the sliding within the Hertzian zone that influences EHL film thickness, but rather it is the sliding in the inlet zone to the contact that controls EHL film thickness. In the inlet zone, the lubricant that is adsorbed on the surfaces of the contacting bodies is

Robert Errichello, PE heads his own gear consulting firm, GEARTECH; is the designer of GEARTECH Software, Inc.; is a longtime AGMA member and contributor and winner of its TDEC award; its E.P. Connell award; its Lifetime Achievement award; a winner of the STLE Wilbur Deutch Memorial award; STLE Edmond E. Bisson award; AWEA Technical Achievement award; and for many years an invaluable Gear Technology and Power Transmission Engineering magazine technical editor.

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entrained into the EHL contact by the rolling motion of the bodies. Entrainment of the lubricant is greatly facilitated by its viscosity increase because the high viscosity resists flow, makes it more difficult to squeeze the lubricant out, and viscous drag forces cause it to move with the surfaces into the Hertzian zone. As a result, the inlet pumps the film up to a thickness sufficient to separate the opposing bodies.

EHL film thickness is determined by the viscosity and pressure-viscosity coefficient of the lubricant in the inlet zone. For gears, the lubricant that is entrained into the inlet is molecularly bonded to the surfaces of the pinion and wheel teeth and consists of thin boundary layers that immediately take on the bulk surface temperatures of the pinion and wheel teeth. Consequently, EHL film thickness is determined by the equilibrium bulk surface temperatures of the pinion and wheel teeth in the inlet zone before the lubricant reaches the Hertzian zone.

Why is inlet shear heating important? In a fully flooded EHL contact, only a fraction of the lubricant can pass through the contact. Therefore, some of the lubricant is rejected and reverse flow occurs in the inlet. Furthermore, if there is sliding in addition to rolling, heat is generated by shearing of the lubricant. Churning and shearing generate heat that increases the lubricant temperature above the average bulk surface temperatures. Therefore the temperature that controls lubricant viscosity and EHL film thickness is the temperature of the lubricant in the inlet. Although it is well known that inlet shear heating reduces EHL film thickness, and there are published thermal correction factors for accounting for inlet shear heating, ISO 15144-1 neglects inlet shear heating.

What about sliding within the Hertzian zone? Sliding friction within the EHL film increases the bulk temperature of the gear teeth from a cold start by accumulating heat from each tooth engagement. The bulk temperature of the gear teeth increases until the heat input is equal to the heat loss to the surroundings. Once the bulk temperature reaches equilibrium there is no further change in gear tooth bulk surface temperature unless the operating conditions change. The heat input is confined to the immediate area of the Hertzian zone and its duration is only a fraction of a millisecond long. Consequently, the heat produced by frictional heating within the EHL film is removed by conduction through the film into the tooth surfaces and by convection as the hot oil exits the outlet zone. Due to the short contact time, the heat penetrates only a shallow distance into the gear teeth and is rapidly dissipated. And so as the contact point moves on, the heat input disappears immediately and the surface temperature of the gear teeth returns promptly to the equilibrium bulk temperature. After one revolution of the gear, a particular point on the gear flank comes into engagement with essentially the same bulk temperature as the previous engagement. Although frictional heating does not directly alter the film thickness within the Hertzian zone, any increase of the bulk surface temperatures due to frictional heating indirectly reduces film thickness by decreasing the viscosity of the lubricant in the inlet zone.

The sliding is significant because it generates traction forces that result in energy losses. If the lubricant behaved like a Newtonian fluid, the high viscosity would lead to extremely high traction force. Fortunately, however, when subjected to

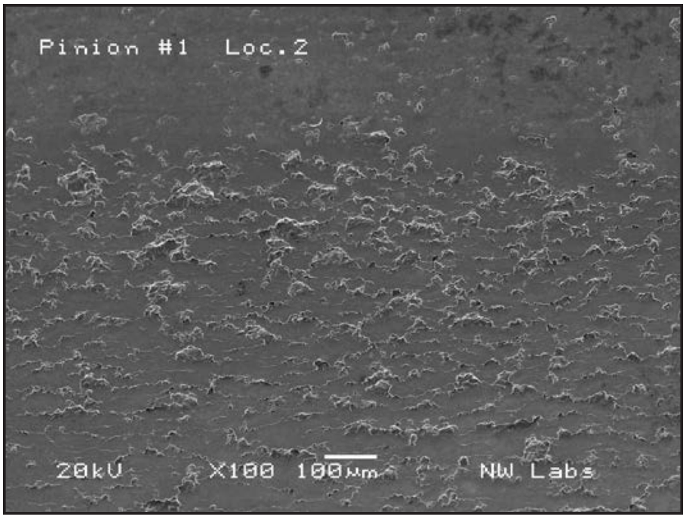

Figure 1 SEM image of micropitting on wind turbine pinion at 100X magnification.

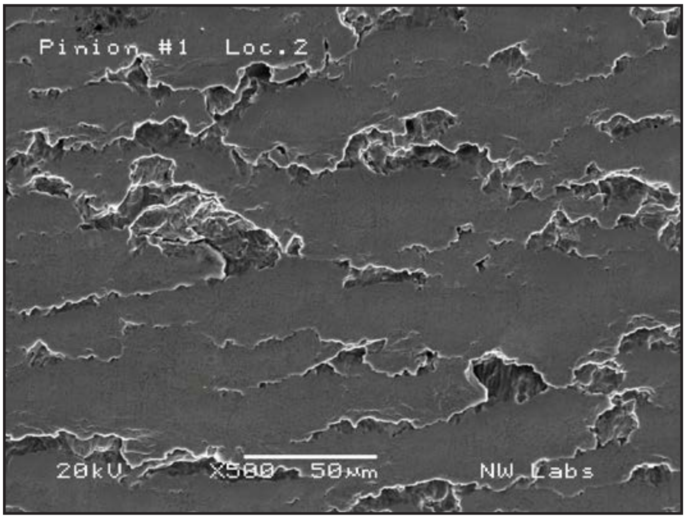

Figure 2 Same as Fig. 1—but at 500X magnification.

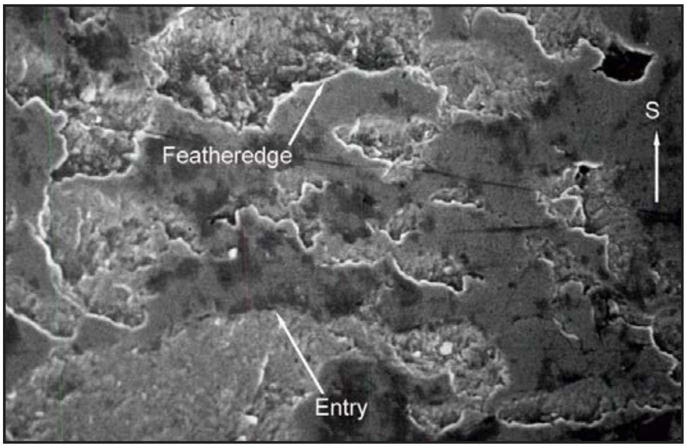

Figure 3 Detail of micropitting on wind turbine pinion at 1000X magnification (Courtesy of AGMA Standard ANSI/AGMA 1010-F14; Figure 56).

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high shear stresses the lubricant behaves like a plastic pseudo-solid with limited shear strength that is characterized by its traction coefficient. The bulk surface temperatures are controlled by heat generated in the Hertzian zone, and the temperatures can vary significantly, depending on the molecular structure of the lubricant base stock — which influences a lubricant's solidification pressure, shear strength, and traction coefficient. Furthermore, depending on antiwear and antiscuff additives that may be in the lubricant, the sliding and heat generates boundary tribofilms that help to prevent adhesive wear.

What about Blok's flash temperature? Blok defined the contact temperature as the sum of the bulk surface temperatures of the gear teeth and the flash temperature rise associated with frictional heating in zones of asperity contact. Blok's theory of scuffing proposes that scuffing occurs when the maximum value of the contact temperature reaches a critical temperature; he predicted the surface temperature based on the following assumptions:

1. The surfaces are in intimate contact or perfectly insulated
2. All the heat is removed by one-dimensional conduction, straight down into the surfaces
3. The two bulk temperatures are identical

Assumption 1 is violated if an EHL film is present; assumption 2 is violated if the speed of either surface is too slow; and assumption 3 is violated for a high gear ratio because the pinion typically runs hotter than the wheel. Therefore Blok's flash temperature theory applies only to the boundary lubrication regime where the EHL film is non-existent, and the only protection against scuffing is any tribofilm deposited by lubricant additives. Once the tribofilms fail the only remaining protection is the natural oxide layer on the gear teeth. As a result, Blok's flash temperature is not applicable to the mixed-film or full EHL regime that is considered in ISO 15144-1.

Quoting (anonymously) one of the AGMA peer reviewers:

"The use of the flash temperatures for the calculation of the properties for the sliding parameter $S_{GF,Y,}$ presume that mixed or boundary lubrication occur; in which case, what is the point of calculating a film thickness reduction?"

Thus, ISO/TR 15144-1 incorrectly uses Blok's flash temperature to reduce the EHL film and contradicts Blok's assumption that the surfaces are in intimate contact without an EHL film.

The heat generated within the EHL film by shearing of the lubricant and rubbing of asperities does not affect the inlet temperature once the bulk temperature reaches equilibrium. So the temperature rise due to frictional heating within the Hertzian zone only affects film thickness indirectly by influencing the gear tooth bulk temperature; it does not change the EHL film thickness, which is determined by the gear tooth bulk temperatures in the inlet zone to the EHL contact. Which means that the ISO 15144-1 postulate that Blok's flash temperature reduces the local film thickness is fundamentally wrong.

What film thickness is relevant to micropitting? ISO 15144-1 calculates the minimum EHL film thickness at the exit to the EHL contact. In contrast, AGMA 925-A03 (Ref. 3) calculates the central film thickness in the center of the EHL contact. The minimum film thickness is not relevant to micropitting because there is little interaction between surface asperities because the width of the exit zone is narrow, and the film pressure is very low in the exit zone. Conversely, there are more stress cycles on asperities and much greater film pressure in the central zone of the EHL contact. Result: the central film thickness is relevant to micropitting. And: ISO 15144-1 uses the wrong film thickness equation and AGMA 925-A03 uses the correct one.

ISO 15144-1 uses a linear sum to combine the surface roughness of the pinion and wheel. However, AGMA 925-A03 — and all current tribology literature — use a root-mean-square sum to combine the roughness of the pinion and wheel. Therefore ISO 15144-1 is not consistent with the science of tribology.

What's wrong with ISO 15144-1? The peer review disclosed not only the fundamental flaw in ISO 15144-1 that assumes Blok's flash temperature reduces film thickness, but also disclosed many other shortcomings of ISO 15144-1:

- Postulate that Blok's flash temperature reduces EHL film thickness is incorrect
- Blok's flash temperature applies only to boundary regime, but not mixed-film or full EHL regimes
- The mathematical derivation of sliding factor $(S_{GF,Y})^{0.22}$ technically flawed
- Sliding factor $(S_{GF,Y})^{0.22}$ is without mathematical basis
- Exponent derived by regression analysis, but details not given
- Shear heating in the Hertzian zone contributes to bulk temperature — but does not reduce EHL film thickness
- Derivation doesn't include analysis of flow rate to ensure mass conservation
- Derivation uses form of Reynolds' equation that is unsuitable for thermal analysis because it excludes temperature variations throughout thickness of EHL film
- Coefficient of friction highly dependent on film thickness, temperature, traction coefficient, and tribofilms; therefore a thermally coupled analysis required to determine consistent estimates of friction, temperature, and film thickness
- Minimum film thickness calculated rather than the more relevant central film thickness
- Composite surface roughness is incorrectly defined
- Derivation assumes Newtonian fluid, but in high-speed gears fluid is non-Newtonian
- P-V coefficient applies only to low-pressure inlet zone and not high-pressure Hertzian zone
- ISO adopts engineering approach that is excessively convoluted
- ISO definition of micropitting failure is ambiguous
- Micropitting depends on many factors other than EHL film thickness
- Running-in neglected
- Inlet shear heating neglected
- Shear thinning neglected
- Non-Newtonian behavior neglected
- The bulk temp assumed to be same for both pinion and wheel, but actually different for gearsets with high gear ratio
- Single value of thermal conductivity is used, but actually varies with gear steel

Can ISO 15144-1 regain credibility? ISO 15144-1 cites the Elstorpff dissertation (Ref. 4) as the source for the sliding factor. However, several mathematically inclined peer reviewers (Ref. 2) analyzed Equations 7.18–7.24 of the Elstorpff dissertation and they unanimously agreed that the derivation of the sliding factor $S_{GF,Y}$ is mathematically flawed and has no basis in Reynolds' equation. As such, it is clear that the analytical basis for the sliding factor is unsound. Without an ana-

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lytical foundation for the sliding factor, it might be justified via regression analysis that empirically derives the sliding factor by comparing isothermal and thermal EHL analyses for a large range of gear examples. Furthermore, the Elstoropff dissertation mentions that the exponent for the sliding factor was derived from a regression analysis, but no details of the analysis are given. Therefore a minimum revision of ISO 15144-1 would include adequate documentation of the regression analysis. Furthermore, the software used for the regression analysis should be made available to AGMA members so that they can validate the software and replicate the calculations. The scientific method requires that empirical results be replicated by independent researchers. ISO 15144-1 cannot be considered creditable without such replication.

Is there a path forward? *Quoting from recent research on micropitting* (Ref. 5): "The use of a 'specific lubricant film thickness' (similar in definition to the λ ratio) as the basis of a numerical aid to avoid micropitting is embodied in a current ISO standard (Ref. 1). The document recognizes that other specific factors, including lubricant chemistry, have an influence, but it is appreciated that the science has not developed sufficiently to allow such factors to be included directly in a calculation method. Thus the specific lubricant film thickness is recommended 'as an evaluation criterion when applied as part of a suitable comparative procedure based on known gear performance.' It is therefore clear that gear practitioners recognize the need for a better understanding of the phenomenon of micropitting before it will be possible to provide a truly comprehensive design method to prevent it."

Hence, because micropitting is such a complex phenomenon, any analytical method cannot be based solely on specific film thickness if it is expected to reliably predict the risk of micropitting.

A subcommittee of the AGMA Helical Gear Rating Committee is currently updating AGMA 925-A03 (Ref. 3). The subcommittee includes tribologists, chemical engineers, gear engineers, gear consultants, lubrication engineers, lubricant formulators, and end users of gears. One of the goals of the subcommittee is to develop a method to predict the risk of micropitting. AGMA 925-A03 is consistent with the state-of-the-art in gear tribology, whereas ISO 15144-1 has many shortcomings. I therefore believe the shortest path to a reliable method to predict the risk of micropitting is to withdraw ISO 15144-1 and develop the update of AGMA 925-A03 through collaboration between AGMA and ISO members.

The updated AGMA 925-A03 could then become an international standard—upon approval by all ISO delegates.

References

1. ISO 15144-1. *Calculation of Micropitting Load Capacity of Cylindrical Spur and Helical Gears—Part 1: Introduction and Basic Principles*, Second Edition, 2012-12-20.
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3. AGMA 925-A03. "Effect of Lubrication on Gear Surface Distress," 2003.
4. ISO/TC 60/SC 2/WG 15, N 147. "Translation of Elstorpff Thesis," pp. 94–97, 2014, 12–16.
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Joint Statement on Current State and Future Activities on ISO 15144-1 & AGMA 925

Prepared by, Robin Olson, Chairperson, AGMA Sub-Committee Revising AGMA 925 and **Dr. Ing Thomas Tobie,** Head of Department, Machine Elements, FZG-TUM.

AGMA and ISO Working Group 15 applaud the efforts of *Gear Technology* magazine to educate the gear community on ISO 15144-1 (Calculation of micropitting load capacity of cylindrical spur and helical gears—Part 1: Introduction and basic principles). The document is a technical report—not an international standard—which means that it is an informative document. It has been available since 2010 and was recently updated with a second revision at the end of 2014.

ISO/TR 15144-1 predicts the risk of micropitting through the use of a safety factor that is the ratio of the *minimum* specific lubricant film thickness to the *permissible* lubricant film thickness (Ed. italics added). The minimum specific lubricant film thickness is calculated in the contact zone of the gear mesh—taking into account tooth surface roughness and geometry; lubricant; load; and relative sliding between the pinion and gear. The permissible value can be determined by running similar gears—or an adequate test—until micropitting just occurs. This method has been used with various FZG test gears, with gears in wind turbine applications and some other industrial applications. ISO Working Group 15 is working to make the method applicable to a broader set of gear applications in preparation for the re-designation of ISO 15144-1 as an international standard.

AGMA 925-A03 (Effect of Lubrication on Gear Surface Distress) is an information sheet that describes micropitting, but does not contain a method to predict risk. A subcommittee of the AGMA Helical Gear Rating Committee has been formed to review the document and develop a method to calculate a percent of risk, rather than a safety factor. This is consistent with the existing methods that evaluate scuffing and wear in the same document.

Each of these documents is a collaborative effort between members of the ISO Working Group and the AGMA Helical Gear Rating Committee, with a focus on developing a method that can be used to predict micropitting for a broad range of gear applications.

Respectfully submitted by: Robin Olson
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Gear Group | Rexnord Corporation

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Head of Department- Machine Elements, FZG- TUM
Garching, Germany

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LIEBHERR DEVELOPS DISTORTION-FREE GENERATING GRINDING METHOD FOR TOOTH-LEAD MODIFICATIONS

Twist-free generating grinding is a proven industrial production method, first registered by Liebherr-Verzahntechnik GmbH as a patent for Dr. Gerd Sulzer's invention in 1987. Since then, grinding worms featuring length-modified profile angles have been used to correct the natural twisting that occurs during generating grinding of gear teeth featuring tooth-lead modifications. During the diagonal generating grinding process, the grinding worm is guided past the workpiece in an axial motion, enabling each section of the grinding worm to come into contact with the workpiece successively. This eliminates twisting.

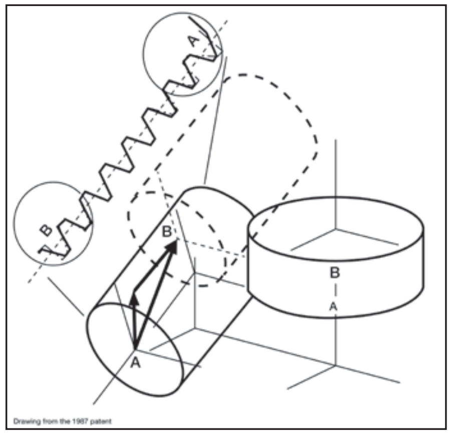
"But what this method does not eliminate are geometrical errors," said Dr. Robert Würfel, technical mathematics at Liebherr-Verzahntechnik. In Figure 3, the twisting has been corrected, but an unwanted concave crowning occurs in the profile (Figures 1 to 3).

Dr. Hansjörg Geiser, head of product development and design engineering, illustrates the helical gearing distortion issue using a practical example featuring a rounded end-relief detail (Figures 5 to 7).

The modification can only be accurately achieved by the pitch circle diameter. "Topological gear measurement shows significant distortions — too much material is ground off in two corners, and too little in two other corners. This impacts the load capacity and noise generated by the gears," Dr. Geiser said.

Low-twist grinding alone does not solve the problem

Simple, low-twist generating grinding only partially solves the problem. Geometrical variations continue to exist (see Figure 8), and the modification is ultimately only achieved correctly at the pitch circle diameter. One option of correcting such distortions would be to topologically dress the grinding worm. It would be dressed line by line, but dressing time would be considerably extend-



Drawing from the 1987 patent.

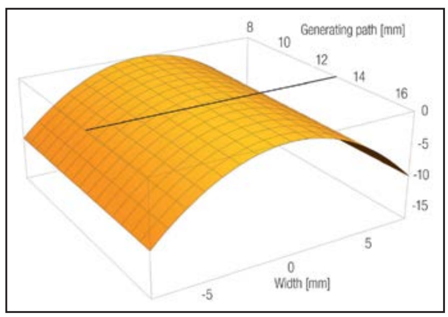


Figure 1 Twist-free tooth-lead crowning specification.

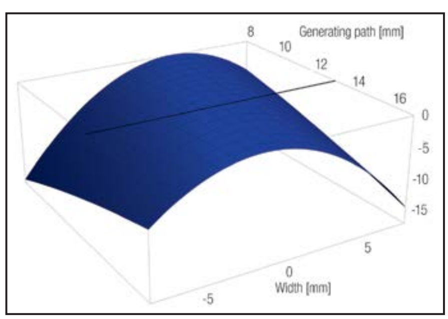


Figure 2 Naturally twisted.

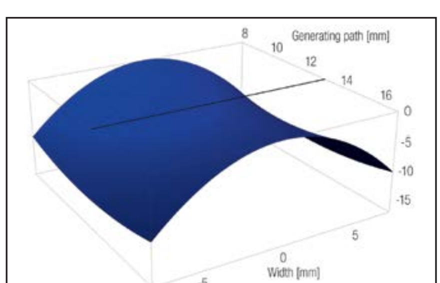


Figure 3 Twist-reduced.

Figure 4 Distortion-free generating grinding is feasible on all Liebherr generating grinding machines.

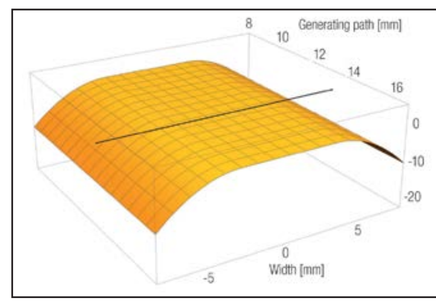


Figure 5 Rounded end-relief detail specification.

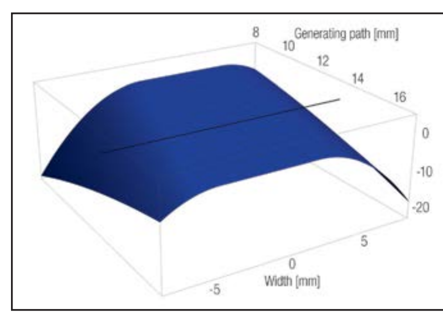


Figure 6 Results following standard generating grinding.

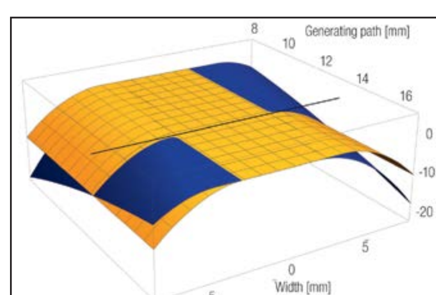


Figure 7 Illustration of end relief that's too small/distortion.

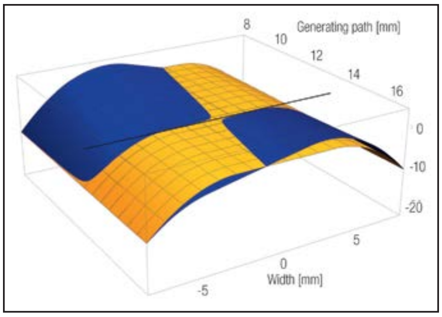


Figure 8 **Discrepancies can also occur in simple low-twist generating grinding.**

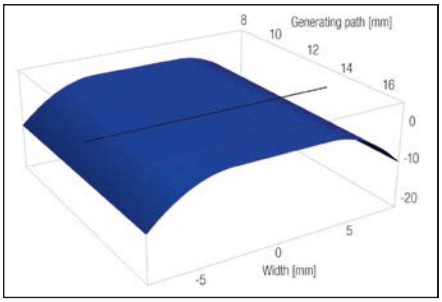


Figure 9 **Results delivered by Liebherr's distortion-free generating grinding method.**

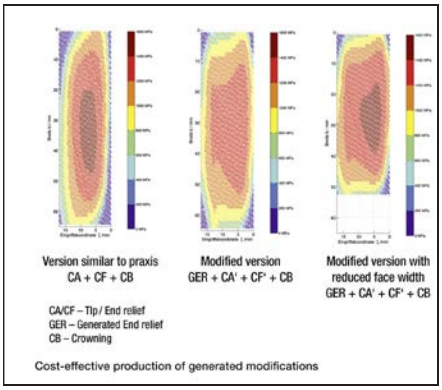


Figure 10 **Cost-effective production of generated modifications.**

ed. This would make a cost-effective process impossible. "Liebherr has developed a new grinding method, which prevents this predicament," Würfel said.

Liebherr's distortion-free generating grinding method

Liebherr's new method enables absolutely distortion-free generating grinding tooth-lead modifications. "We haven't exactly reinvented generating grinding, but we are well aware of what it involves," Geiser said. The results delivered by the new method correspond one-to-one with specifications (Figure 9).

"The new mathematical method enables modifications to be accurately achieved of all measuring diameters," Würfel explained. At the same time, grind and dress times correspond to those of low-distortion grinding. No special tools are required to achieve this; the standard dressing unit is all that's needed to do the job. "We have developed a cost-effective method for serial production. Our method can be used for all free-form tooth-lead modifications," Würfel added.

For load-capacity reasons, this patent-pending method is of major interest for gearbox applications.

Generated modifications (GER)

In addition to grinding free-form tooth lead modifications, the method described above can be adapted to enable generated modifications as well. The benefits of such triangular end-relief details (generated end relief) in terms of load capacity have been debated in the gearing industry for many years. Practical application has not been feasible to date because no cost-effective production method was available. Liebherr has therefore cleared one of the last

remaining hurdles (Figures 11 and 12).

Excitation-enhanced modifications

Another application is excitation-enhanced modifications. Time-variable gear tooth rigidity causes a periodic transmission error with amplitudes between two paired gears, which has a major impact on noise levels. During the last few years research into the use of sine-shaped modifications to reduce these errors has been successfully conducted by the Gear Research Centre (FZG) at Munich Technical University's Institute for Machine Elements. This targeted degree of undulation, which typically has a μm-range amplitude, has no impact on load distribution (Figure 13 and 14).

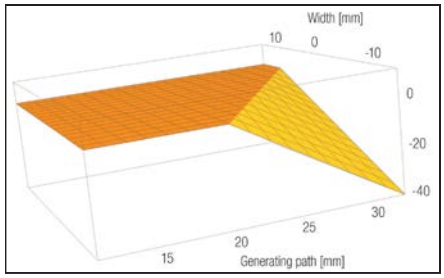


Figure 11 Triangular end-relief specification.

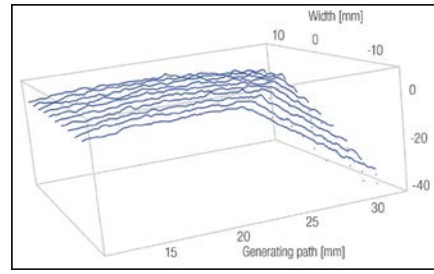


Figure 12 Triangular end-relief readings.

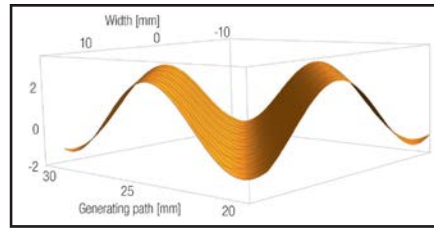


Figure 13 Targeted undulation specification.

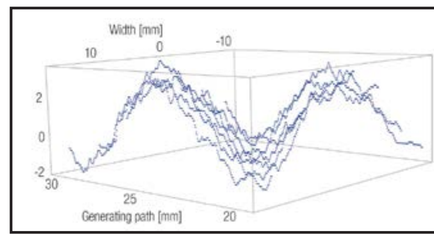


Figure 14 Targeted undulation readings.

Conclusion

Liebherr's distortion-free generating grinding method can also be used to produce tooth-lead modifications with relatively large adjustments and short gear-tooth widths — free of errors and distortions. Here, grind and dress times correspond to those of low-twist grinding. Liebherr grinding machines facilitate cost-effective, large-scale production of generated modifications; the same applies to excitation-enhanced modifications. Other applications are already being developed.

For more information:

Liebherr Gear Technology, Inc.
Phone: (734) 429-7225
info.lgt@liebherr.com
www.liebherr.com

MS3D Gear Inspection

CREATES 3D SCAN OF GEARS IN UNDER 10 SECONDS

French manufacturer Mesure-Systems-3D (MS3D) has developed a contactless inline testing system for gears. With GearInspection, a gear with 23 gear teeth can be fully measured in 3D in less than 10 seconds. With 3D inline testing, the manufacturer obtains real-time information about the effects any changes to the production parameters will have.

MS3D's 10 second inspection makes sure that no faulty part gets through to final assembly and offers information about defects in the process parameterization. Cylindrical straight, helical and bevel gears can be checked and measured using five sensors, which may be positioned differently depending on the diameter, module and helix angle of the gear. Each of the sensors digitizes part of the tooth flank surface, generating a dense cloud of points at the rhythm of 700 data points per four thousandths of a second.

One sensor measures the gear axis while the other four generate the points, which are then stitched together to get the complete surface data of all teeth flanks. Within a second, millions of data points are generated, from which a 3D model can be calculated. This point cloud is then used to identify the profile of the gear teeth, helix angle, helix curvature, diameter on flank, thickness of teeth and the pitch between the gear teeth.

The challenge of the geometry calculation using a cloud of points generated by lasers is that the raw data is very "noisy" due to reflections of the laser on other areas (e.g. the opposite flank) or the high gloss of the surface (e.g. honed surfaces). If not eliminated, this noise leads to measuring imprecision and poor repeatability. This issue has been successfully overcome by specific algorithms developed by MS3D thanks to its 10 years' experience in dealing with the inline non-contact inspection of complex metallic parts.

Saving the time spent to assemble a faulty gearbox, testing it, dismounting it, checking every gear individually to identify the faulty one and mounting the gearbox anew is one of the major benefits of using MS3D GearInspection inline. Return on Investment is estimated to be only a few months. Therefore, not only can manufacturers generate considerable savings, they can also give their customers a zero-defect guarantee. As the specifications of gears can differ according to applications, the machine has been designed with automobile manufacturers in mind, as well as gear subcontractor suppliers requirements. GearInspection is

currently suitable for gear diameters between 30 and 90 mm. Besides this, further development for inline testing of gear axles is planned for 2016.

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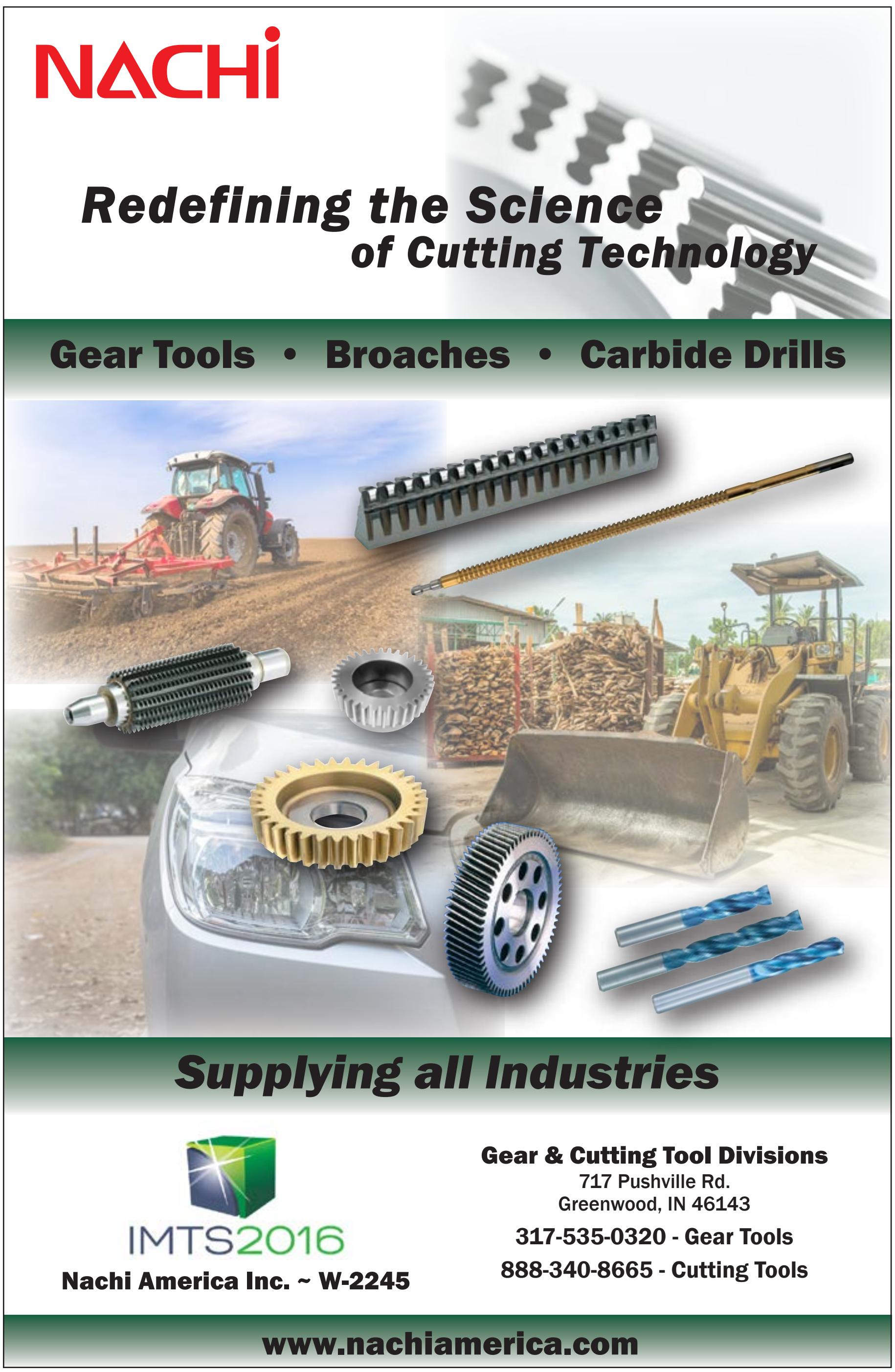

Exsys Tool Swissclamp

ALLOWS MOUNTING OF MULTIPLE WORKPIECES

Exsys Tool Inc. has expanded its offering of ultra-high precision products to include the pL Lehmann SwissClamp modular clamping system. This new system allows operators to mount multiple workpieces on machine tool tables for uninterrupted production and unmanned operations.

For use with rotary and standard tables on vertical or horizontal milling machines, the Swiss-manufactured SwissClamp modules mount on face plates or directly on worktables. The system extends a shop's potential part-clamping range from 90 mm to 200 mm — a 40 percent increase in workpiece capacity within the same clamping length.

SwissClamp's four basic modules enable more than 240 possible configurations, including both mono clamping, requiring only one basic body, and duo clamping, where two mono clamps are mounted opposite one another. Configuration options include creating a clamping tower/tombstone on a fourth axis, a horizontal clamping cone that is overhung or with counter bearing, or a clamping bridge on a trunnion table set up where both sides require a different design with mono and duo systems. Operators can also create clamping

modules on the fourth or fifth axis.

Suitable for a variety of mass production applications in automotive, aerospace, medical/dental and micro technology industries, SwissClamp can be utilized for either strong gripping or light finish clamping applications. For strong gripping, the system achieves rigid, pull down clamping to depths of 3 mm or 6 mm via a mechanical grid on its jaws.

When used for finish clamping, SwissClamp's finish jaws achieve non-rotating, precise parallel clamping with a clamping stroke of approximately 1 mm that prevents indentations and ensures high surface quality. The system enables finish clamping to a depth of 6 mm.

For more information:
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Seco Tools T-Style Inserts

EXPAND ROUGHING AND SEMI-FINISHING PERFORMANCE

Seco has expanded the roughing and semi-finishing performance capabilities of its Secomax CS100 sialon ceramic grade by adding inserts with T-style edge preparation to the line. Featuring a free-cutting, extremely sharp geometry, the new inserts bring strength, stability and performance longevity to the machining of nickel-based superalloys in unstable conditions.

Well suited for turning applications that require tight tolerances and low cutting forces, the T-style (chamfered) CS100 inserts are available in 20-degree chamfers that range from .002" – .004" (0.05 mm to 0.1 mm) in width. The sharp, negative reinforced cutting edges on these inserts absorb some of the high cutting force and pressure that would otherwise be placed on the machine setups and workpieces. As a result, these inserts eliminate the risk of workpiece deformation, especially in thin-walled components, as well as reduce excessive vibrations that shorten tool life and negatively impact surface finish.

The characteristics of the T-style inserts complement the existing S-style (chamfered and honed) CS100 products designed to handle high cutting forces in rigid, stable machining conditions. Collectively, the T-style and S-style inserts in the CS100 line have high abrasion resistance and superior toughness that extends tool life and allows for high cutting speeds when processing challenging materials such as Inconel, MAR, RENE and Waspaloy. The inserts are ideal for achieving high productivity, consistent quality and a low cost per part in the aerospace and power generation industries.

Furthermore, Seco has added new N-class (Quick-Line) ceramic insert holders to its comprehensive product portfolio. Available in standard shaft and Seco-Capto styles, these holders have special pocket designs and clamping systems that easily accommodate the different thicknesses and missing center-mounting holes that are common with these types of inserts.

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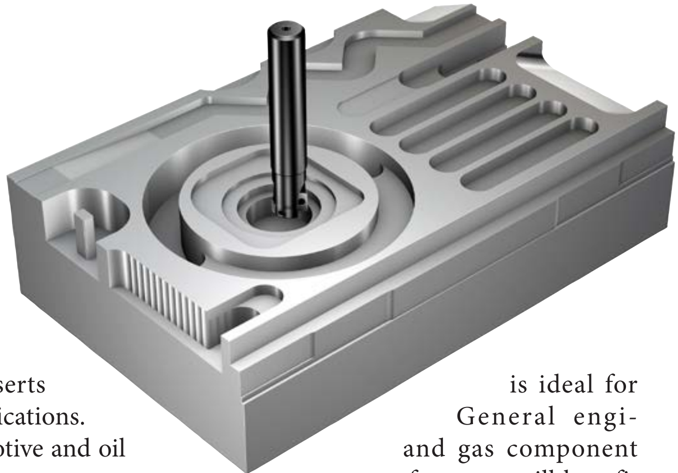
Sandvik Coromant CoroMill 390

DESIGNED FOR SMALL DIAMETER PROJECTS



Sandvik Coromant offers a new end mill for small diameters. The CoroMill 390 with size 07 inserts is a versatile cutter that is ideal for shoulder milling, deep shoulder milling, edging, linear and helical ramping, plunge milling, slot milling and face milling.

Suitable for all machine types, the CoroMill 390 with size 07 inserts is ideal for mixed production and can be used with different materials and applications. General engineering shops, as well as specialized business segments, such as automotive and oil and gas component manufacturers, will benefit from its universal capabilities.

Grades for the CoroMill 390 with size 07 inserts are available for all materials. The new insert grade GC1130, produced with Zertivo technology, gives this cutter an extra dimension of security when milling steel. The smaller inserts deliver higher cutter-teeth density for superior productivity.

A unique feature of this tool is the torque key that is specifically designed for size 07 inserts. This key provides consistent clamping every time. It has built-in spring functionality that allows you to mount inserts with the correct clamping force for reliable and consistent tool life. Coolant-through technology is standard on the CoroMill 390 with size 07 inserts for additional heat and chip control.

Troy Stashi, milling product specialist for Sandvik Coromant, says, "The CoroMill 390 with size 07 inserts is the most versatile small diameter end mill on the market today. It's beneficial for anyone who machines small features in any size component including medical, automotive, and oil and gas parts."

For more information:
Sandvik Coromant
Phone: (800) 726-3845
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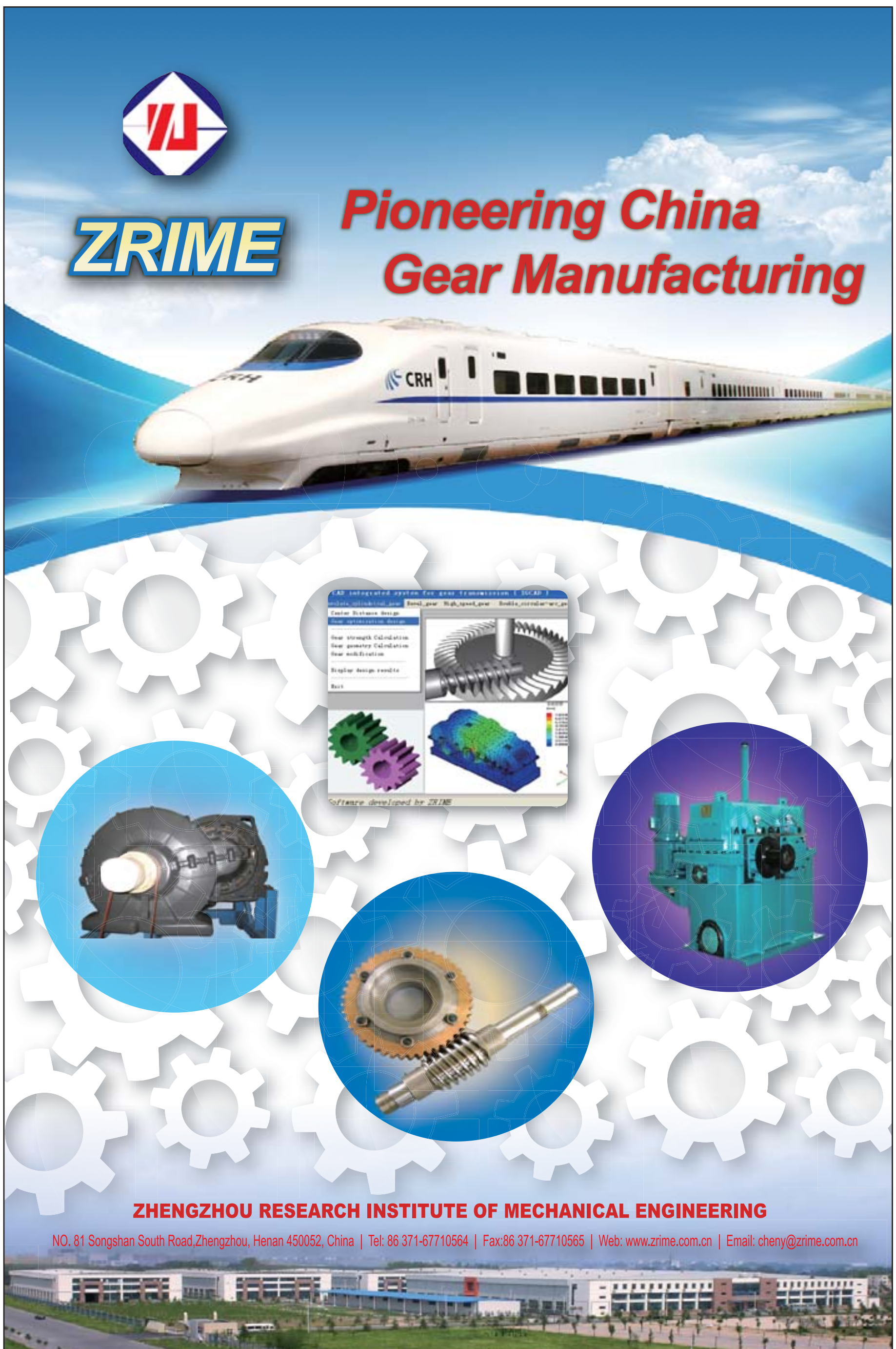

Mahr Federal

PLANS TO INCLUDE MARSHAFT SCOPE AND MARCATOR INDICATORS AT MFG4

Mahr Federal will feature the MarShaft Scope 250 plus and MarCator Wireless Digital Indicators at Mfg4, May 3–5, 2016, Connecticut Convention Center, Hartford, CT, Booth #1605.

Competitively priced and designed to provide fast, accurate, fully automatic measurement of smaller shafts and turned parts directly on the shop floor, the MarShaft Scope 250 plus features a highly accurate matrix camera with four million pixels. The system measures parts up to 250 mm in length and 40 mm in diameter with an MPE (Maximum Permissible Error) of less than 1.5 microns + L/40 when measuring diameter and an even more impressive 3 microns + L/125 when measuring length.

Also featured will be Mahr Federal's broad line of mechanical comparative gages which can now be configured for wireless data transmission with the addition of a MarCator 1086 or 1087 wireless digital indicator. The line includes a wide array of snap gages, ID & OD gages, fixed and adjustable bore gages, as well as depth and comparator stands. The addition of wireless digital indicators makes these gages faster and more productive than ever before.

The combination of Mahr Federal's robust, easy-to-use, high performance comparative gages with an economical, user-transparent wireless data collection system provides the easiest way to upgrade and implement data collection for existing gages or new gaging requirements. The delays and errors associated with manually collecting and recording data are eliminated, and the measuring process can run at its maximum speed and with the most secure collection format.

The MarVision QM 300, a new video measuring microscope with image processing capability designed for the measurement and/or dimensioning of geometric elements, the Millimar C1200

Digital Amplifier, MaraMeter mechanical comparative gages, Wireless MarCal calipers with Marcom Software, Dimensionair air gaging will also be on display. Selections from Mahr Federal's broad line of surface measuring instruments, including both portable roughness measurement devices and computer based stationary surface measuring systems will also be shown off. In addition to the new PocketSurf IV, there will be the MarSurf PS1 and a growing line of application specific surface measuring fixtures. Mahr's stationary system line includes the MarSurf XR 1, which combines mobile surface metrology with the advantages of *MarWin* evaluation software; and the XCR 20 *MarWin*, a new generation of combined roughness and contour measurement systems. A full range of other Mahr Federal handheld gages and other dimensional metrology products will also be on display.

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GMTA

OFFERS RASOMA MACHINE TOOLS IN NORTH AMERICA

German Machine Tools of America (GMTA) now offers a full line of Rasoma machining centers, including vertical turning centers, four-axis shaft turning centers, end machining, double spindle and various special purpose machining centers with full automation.

Rasoma is a large machine tool builder, founded in 1919 and based in Döbeln, Germany, who provides contract manufacturing to some of the best known brands in the global auto industry, as well as its own brands.

Gear machines for milling, hobbing and shaping are available in a variety of configurations and the GMTA application engineering team can assist interested parties to determine the best solution.

Rasoma machining centers offer high rigidity, due to separate X and Z slides plus the machine head is designed as a monoblock with polymer concrete fill. Thermal stability is enhanced by cooled motor spindles and the rapid traverse on these centers ranges up to 60 m/min at high acceleration, with feed and removal speeds to 120 m/min, less than 6 seconds from part to part and turret indexing typically under one second.

Full option packages include robotic handling and part articulation, integrated metrology onboard, working inside or outside the work envelope, full tool measurement and monitoring systems and driven tool packages, all controlled by a single Siemens CNC.

GMTA President Walter Friedrich comments, "This alignment dovetails perfectly with our other lines of gear-making, laser and finishing machines and systems. It will enhance our value proposition considerably in our current market of primary automotive and will also open other market opportunities for our company. We have made substantial investments in new personnel and floor space, both here in the U.S. and at our Mexican facility, to support these new additions to our portfolio of quality German machine tools."

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Dürr Ecoclean EcoCDuty Cleaning System

BUILT TO PROCESS LARGE LOADS

Dürr Ecoclean has developed a solvent-based cleaning system, the large-chamber EcoCDuty, for heat-treating contractors, metalforming shops and companies from the automotive and aircraft industries looking for cost-efficient part cleaning and degreasing equipment capable of handling high capacities. This machine is designed for loads measuring up to 1250 × 840 × 970 mm and weighing up to 1 ton. Operating with hydrocarbons or modified alcohols, it provides high cleaning quality and process reliability at fast cycle times. Additional benefits of this modular unit include its ease of operation and attractive design.

This large-chamber cleaning machine uses hydrocarbons or polar solvents (modified alcohols) and operates under full vacuum. Its modular design ensures adaptability to individual user needs. Configured as a steam degreaser in its standard version, the system is additionally available with one or two stainless steel flood tanks — e.g., for a process comprising steam degreasing and injection flood washing or steam degreasing, injection flood washing plus a preserving step. Vacuum drying is standard on all three versions. Chlorinated metalworking fluids can be effectively removed by means of appropriately stabilized solvents following oil compatibility testing. Moreover, the unit is suitable for cleaning off sulphur-containing oils.

The EcoCDuty is provided with a new pre-degreasing feature using steam. This technology directs the oil-laden solvent straight into the distillation circuit, thus minimizing oil enrichment of the solvent and oil deposits in the flood tank for superior cleaning performance. This is made possible by a powerful distillation system capable of handling as much as 400 or even 500 litres/hour, depending on the solvent employed. The oil collected by distillation is automatically removed via the standard oil discharge system which has a capacity of four litres per hour. Customers who encounter high oil input rates can add a second unit, thus doubling the capacity of the oil discharged system to eight litres per hour. To remove particulate contaminants from the solvent as well, the distillation system is preceded by a filter unit

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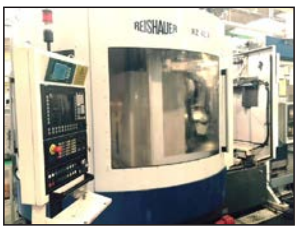
- UNION, 1984/2011, spindle 110 mm, table type, table 1600 × 1400 mm, latest DRO



GEAR MACHINES
- CNC REISHAUER RZ 400, 2002, in state-of-the art, gear grinder gear-Ø/module 400/8 mm
- CNC REISHAUER RZ 150, 2004, in state-of-the-art, gear grinder gear-Ø/module 150/3 mm
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with bag or cartridge filters.

On EcoCDuty versions with a flood tank, quick flooding and draining of the work chamber and tank is ensured by powerful frequency-controlled pumps. This technology reduces non-productive times and speeds up cleaning processes, thereby reducing costs. Furthermore, these versions comprise a separate filter circuit for each tank. Full-flow filtration of the solvent is provided in the supply and return flow lines by means of three filter units per flood tank. These can be fitted with bag or cartridge filters. As a result, even exceptional cleanliness specifications can be reliably met.

When designing the EcoCDuty, Dürr Ecoclean placed great emphasis on low operating costs and high availability. This starts with the new 7 inch color display with self-explanatory pictographs. The stainless steel flood tanks have a smooth surface and come without internal heating components. This design prevents the formation of chip and dirt pockets which could re-contaminate the parts. Customers who do not yet own a steam heating source can order an optional external steam generator to heat the distillation unit. The flood tanks are heated exclusively by waste heat from the distillation system, i.e., no additional energy input is necessary.

When it comes to part feeding, the EcoCDuty again adapts flexibly to customer needs. Depending on the equipment configuration, it can be loaded manually using a pallet truck or forklift. Moreover, custom loading solutions ranging from semi-automatic single-station to fully automatic multi-station systems are supported as well.

Large maintenance openings offer an additional advantage, as they provide easy and fast access to all service-related components. This minimizes system downtime for maintenance work. To protect the system from dirt and heat in harsh production conditions, a roof with internal ventilation is available.

For more information:
Dürr Ecoclean
Phone: (248) 450-2064
www.durr-ecoclean.com

Mitutoyo

RELEASES RENEWED IP67 COOLANT-PROOF CALIPERS

Mitutoyo America Corporation recently announced the renewal of the 500 Series IP67 Absolute Digimatic coolant-proof calipers. This product incorporates Mitutoyo's Absolute measurement system. The automatic power on/off shuts down the LCD after 20 minutes of inactivity, but the ABS scale origin is unaffected. Power is restored to the display when the slider is moved. In addition, it can be integrated into statistical process control and measurement systems. A 9 mm large LCD provides a 22 percent increase in height for improved visibility. The extended battery life of five years has been achieved due to low-current integrated circuit. The calipers are easy to operate with advanced ergonomic design that uses only one button. Mitutoyo IP67 Absolute Digimatic coolant-proof calipers can be used in workshop conditions exposed to coolant, water, dust or oil. 100 percent air-leak test ensures every caliper conforms to IP67.

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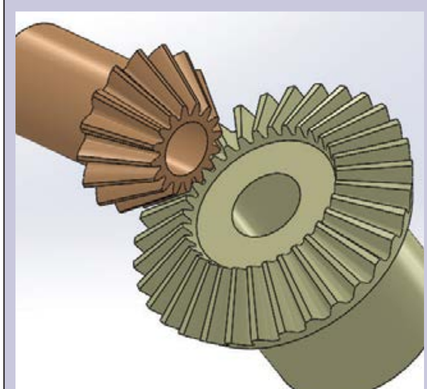

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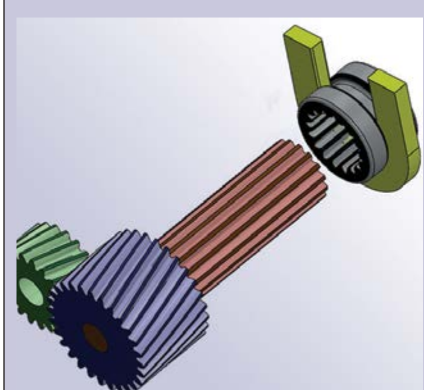

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Defying the Oil Ripple

Heat treaters are staying afloat in spite of a troubled oil industry.

Alex Cannella, News Editor

The oil industry is (pardon the pun) tanking. That may conjure up horrific images of other industries following suit in a domino effect of collective collapse into the overabundant oil slick the industry is currently drowning in, but not everyone is getting knocked down alongside the oil sector. The heat treatment industry is, in fact, staying afloat. Automotive sales are up, some believe as a direct result of dropping oil prices, and companies that work alongside the industry, such as EMAG Eldec and Applied Process, are benefiting. For those without a stake in the light vehicle industry, business has taken a bruising, but most companies are still afloat. Of the companies we interviewed, the situation has at worst given people pause, but has yet to stop them in their tracks.

Outside of the oil industry's ripple effect, there are two new forces in the heat treatment industry. One is MedAccred, a new and growing accreditation targeted towards the medical industry from the same group that oversees Nadcap. The group has ironed out the details of its prerequisites and started awarding certifications to those early adopters jumping on board, including Solar Atmospheres.

The second force is the Industrial Internet of Things, which you may have heard about as it has gained prevalence in other industries. Up until now, it hasn't really been a factor in gear hardening. The Industrial Internet, however, is starting to break into the heat treatment industry, and it's something to keep an eye on.

For the most part, however, the industry continues its course. The ripples from the oil market are rocking the boat, but they aren't destabilizing it yet, and so the hatches remain unbattened for now.

Oil is Down, but Automotive is Up

The oil industry's ripple effect through related industries is palpable. Many manufacturers are reporting flat sales at best, and there's always the possibility things get worse in the future. In the midst of the oil ripple, however, there's actually one industry that is currently on the upswing: automotives. And as the auto industry rises, so do the heat treaters that support it.

"Low fuel prices have empowered the American consumer, and this has driven light vehicle sales," said Vasko Popovski, director of sales and marketing at Applied Process. "We think this will continue at a high level for another year or two."

As the rest of manufacturing is taking a hit from the oil ripple and stumbling, the auto industry is up, and in a stroke of irony, its rise could at least in part be attributed to the decreased price on oil.

"We haven't really seen a downturn overall," said Dennis Beauchesne, general manager of ECM USA. "So our business is better than flat."

According to Beauchesne, automotive sales make up somewhere between 40–60 percent of ECM's sales worldwide, but in the U.S., that number is closer to 80 percent. That, combined with the market's increasing interest in ECM's equipment to heat treat up-and-coming nine- and 10-speed transmissions, has kept the company profitable despite the rest of the industry's woes.

EMAG Eldec is another company riding auto market growth. They produce equipment to heat treat and harden various parts with induction, from fuel reduction system parts to chain wheels and steering and drive pinions for the auto industry. Their success is compounded by the Simultaneous Dual Frequency (SDF) generator, a generator that can heat components at both medium and high frequency at the same time. The generator's unique feature has proven popular with auto manufacturers, especially for gears.

Outside of those supplying the auto industry, the picture isn't as clear. Amongst the companies feeling a pinch is Solar Atmospheres, which has customers that directly supply the oil industry, but according to Solar Atmospheres' Principal Engineer, Trevor Jones, the downswing isn't "significant enough" to alter the company's business strategy.

"We do not believe the downswing will be nearly as bad as the most recent recession in the late 2000's," Jones said.

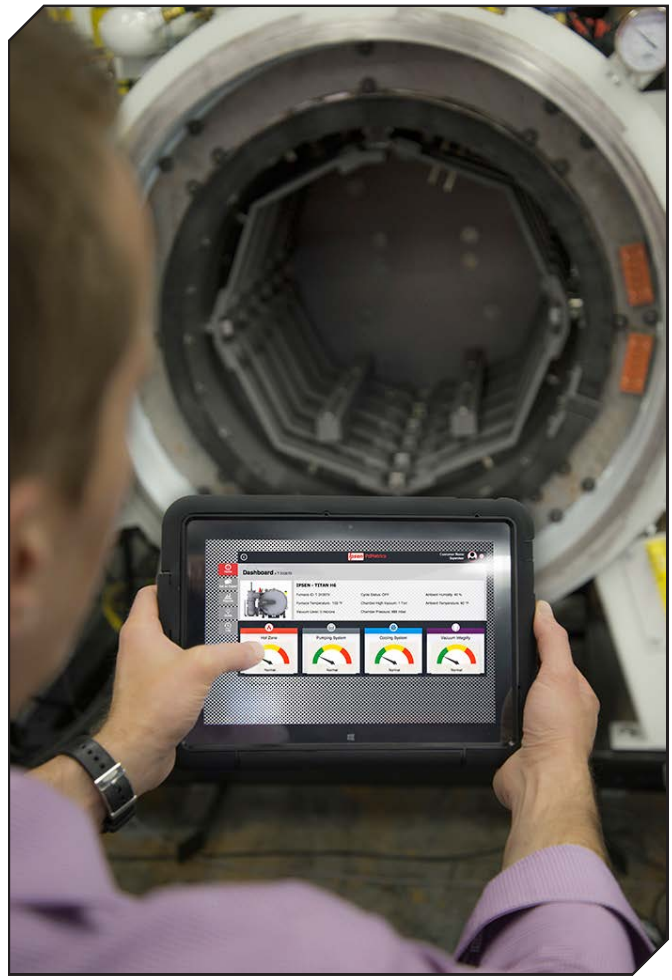
PdMetrics: The Industrial Internet Breaks In

Across every industry, the Industrial Internet of Things (IIoT) is becoming an increasingly recognizable term. Every year, the latest in the ongoing dialogue about Industry 4.0 filters out of Germany, either from headlines on the country's industrial policy or from trade shows like Hannover Messe, and every year, more American manufacturers jump on the bandwagon and start adopting the Industrial Internet.

For the uninitiated, the IIoT is an umbrella term encompassing numerous new technologies, from new applications for sensors and RFID tags to new analytics and predictive maintenance technology. The core theme that connects all of these different technologies together is increasing and improving communication in the machinery we use. For example, a machine could monitor itself and warn a technician when a part is in critical condition and in danger of failing without the technician ever having to crack open the machine and halt production. But it's also about making machines communicate with each other — transmitting orders, enabling one machine to carry out multiple tasks or make modifications to a product as specified by a customer, automatically recording and adjusting for abnormalities or mistakes in the manufacturing process, and so on — and through doing so, decreasing turnaround time and cost.

Ipsen is incorporating many of these concepts with its PdMetrics, a software platform that takes some of the cornerstones of the Industrial Internet — predictive maintenance and data analytics — and brings it to the heat treatment industry.

PdMetrics integrates with critical systems (e.g. hot zone,



pumping system, cooling system and vacuum integrity) and provides real-time monitoring and diagnostics that help ensure the furnace runs smoothly. As soon as maintenance or further action is required, the software can notify a technician before that problem causes the furnace to break down or become faulty. The program also has some other bells and whistles, such as the ability to integrate with multiple furnaces across multiple facilities, but the main draw is the proactive, predictive maintenance it brings to the table. PdMetrics is also backwards compatible. The software is an add-on that isn't integrated with the furnace PLC, so it can be installed not just on new furnaces, but also retrofitted onto older equipment and installed on non-Ipsen brands.

"Ipsen's PdMetrics software platform is the first of its kind for the Thermal Processing industry," Janusz Kowalewski, director of business development at Ipsen, said. "With that in mind, we have seen a large outpouring of interest for several reasons. One, being that it provides insights about heat treatment equipment and processes that customers have not been able to obtain before. Two, being that none of our competitors have a product like this on the market."

But even if Ipsen is the first to start tapping into this new tech, it's unlikely that they'll be the only ones, or that they'll just stop there. Kowalewski sees the IIoT as holding vast potential.

"When we think of the Internet of Things (IoT), whether it's for consumer or industrial applications, we believe it has the ability to transform the ways companies operate," Kowalewski said. "…However, it also opens the door to a multitude of possibilities and new opportunities for growth. As more companies begin to realize the possibilities of the IoT, I believe we will continue to see it emerge in ways that positively impact the productivity, efficiency and operations of industries around the world."

Big and Little: ECM's Nano and Jumbo Gas Quench Furnaces Push Boundaries of Maintenance

Another interesting product in the realm of maintenance is ECM's newest gas quench furnace, the Nano system. The furnace has two features that ECM is pushing: smaller cavities for small batches and a dual-tower system that allows for more flexible and less costly maintenance.

According to Beauchesne, the smaller load allows for faster turnaround. The obvious benefit is, of course, sidestepping the bottleneck of waiting for enough parts to do a single large load, and since the furnace features six separate cavities, multiple small batches can be run at any given time.

"Instead of being a 2,000-piece load, maybe you're only talking about 20 pieces in a load, so that we would run the load at a higher temperature and we could quench them out faster," Beauchesne said. "And then this 10- or 20-piece load can be robotically loaded and unloaded faster and simulate a single-piece flow arrangement rather than waiting for 2,000 pieces to be in a load."

The other feature, the furnace's dual-tower system, also focuses on decreasing downtime. Instead of having to shut down your entire production line to perform maintenance on a furnace, the Nano allows mechanics to shut down one tower to work on it while the other continues working as normal, only halving productivity instead of shutting it down entirely.

"You can shut off half of your capacity, do maintenance on it while you're running the other half and then, of course, vice versa," Beauchesne said.

The Nano system is literally just breaking into the industry, with the first furnace being shipped at the end of April. In the meantime, however, ECM's other furnace, the Jumbo, is already on sale.

The Jumbo is a modular system that can accommodate up to 12 cells and is capable of both gas and oil quenching. The furnace system's biggest feature marks a shift in how ECM's products work. Up until now, most of ECM's products used a tunnel system with a robotic loader, but the Jumbo moves the loader to a shuttle car, which means individual cells can be loaded or unloaded separately, instead of having to shut down the entire system for one cell. Much like the Nano, the Jumbo allows for partial maintenance while the system is still running.

"The new Jumbo system and Nano systems will change the way low pressure carburizing equipment is implemented and maintained," Beauchesne said. "The larger 250 KW motors on the new gas quench cell have improved quenching capability and will bring gas quenching into more scenarios than in the past."

A Rising Accreditation

Solar Atmospheres holds accreditations like a field marshal bears medals: in copious amounts and with great pride. Many (Nadcap, ISO and AS, to name a few) are common within the field, but they recently picked up a first: Their Souderton plant became MedAccred certified last April, making them the first business to successfully achieve certification.

"MedAccred is to the medical industry as Nadcap is to the aerospace industry," Trevor Jones, principal engineer for Solar Atmospheres, said.

And when Jones says MedAccred is the medical industry's Nadcap, he means that in more ways than just function. It's run by the same organization, the Performance Review Institute, as Nadcap is, and uses the same accreditation-via-audit system. It also covers more than just heat treating. It also has standards for sterilization, wiring, etc. It's been a steadily growing force in the medical industry, with over 30 companies now listed as actively participating in the program, and Solar Atmospheres is spearheading the effort, which they believe will pay dividends in the future.

"At this time it is a 'lead the pack' or 'first adopter' approach on the part of Solar management," Ed Engelhard, vice president of corporate quality at Solar Atmospheres, said. "The true value of accreditation will expand rapidly as OEM's flow down the requirement to become accredited. We think 2016 will be a watershed year for the program."

MedAccred certification is a big step for Solar Atmospheres, and not just because of the parallels it draws with Nadcap as a gold standard. Even without the accreditation, Solar Atmospheres had already built up a customer base within the medical industry, but MedAccred brings an extra level of legitimacy that execs believe will put them head and shoulders above the competition going forward.

All of these certifications don't come cheap, however. According to Jones, "maintaining accreditations such as Nadcap, ISO and AS is very time consuming and expensive to preserve… To maintain these accreditations and deal with other business related items requires comprehensive employees that are dedicated to their jobs and experienced in these fields constantly looking for methods to reduce costs and/or keep costs associated with these difficulties at a minimum."

The question then becomes: If the cost is so high, is it worth it? While MedAccred is gaining traction, it's still a young program, only a few years old. Some of its more specific certifications (such as, for example, one for sterilization) were only just finalized in the past year. While it may aim to become the same universally recognizable standard that Nadcap is, it has yet to reach that industry-wide level of recognition. In the short term, becoming MedAccred approved is voluntary. Even though it's been a year, Engelhard noted that it's still too early to tell if Solar Atmospheres is seeing any returns on their efforts.

Solar Atmospheres' view has, however, been on the long term, and in the long term, MedAccred approval looks viable. The program's gaining steam and it's entirely possible it will indeed become the medical industry's equivalent of Nadcap.

"Every company has to make that business decision for themselves," Engelhard said. "But I would point out the following; look at what has happened to the value of Nadcap accreditation over the years."

The Neverending Hunt for Talent

Fresh talent is continually at a premium in most of the industries we cover. The dearth of incoming talent seems to be a

constant woe across time and industry that affects everyone, regardless of how well the company's doing.

Unfortunately, the problem isn't going away. In fact, according to Beauchesne, it's been getting worse. So bad, in fact, that ECM has opted to start training employees from its own ranks to fill more specialized positions, teaching them everything they need to know starting with the very basics.

"We've taken more of an attitude of training somebody from scratch," Beauchesne said. "So hiring somebody in the warehouse, getting them familiar with the parts and the drawings and how the equipment works, and then training them into service people from there."

Training began less than a year ago, and according to Beauchesne, it's still too early to tell how well the training program is working. ECM has considered expanding the program, but has opted to maintain the program at its current level for now.

"We're satisfied with the number of people we have onboard," Beauchesne said.

Applied Process has also felt the talent shortage, particularly with metallurgical engineers, and they've been taking more traditional measures to try and bring fresh faces into the industry.

"Applied Process has consistently hosted interns from a variety of backgrounds, including metallurgical engineers," Popovski said. "Beyond this, we feel a responsibility to work with colleges to support their programs via groups like ASM and AFS."

Sailing Ahead

The oil industry may be haunting the minds of some people, but the ripple effect hasn't been enough to sink the heat treating industry. Even if sailing isn't smooth for everyone in the industry, it *is* steady. Companies are still investing in innovation, the conversation is still on increased productivity and reduced turnaround times and the talent pool is still too small.

Blips such as the advent of MedAccred show up here and there in the industry, and the Industrial Internet of Things will almost definitely continue to grow in relevance, but overall, the industry continues business as usual.

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Jack McGuinn, Senior Editor

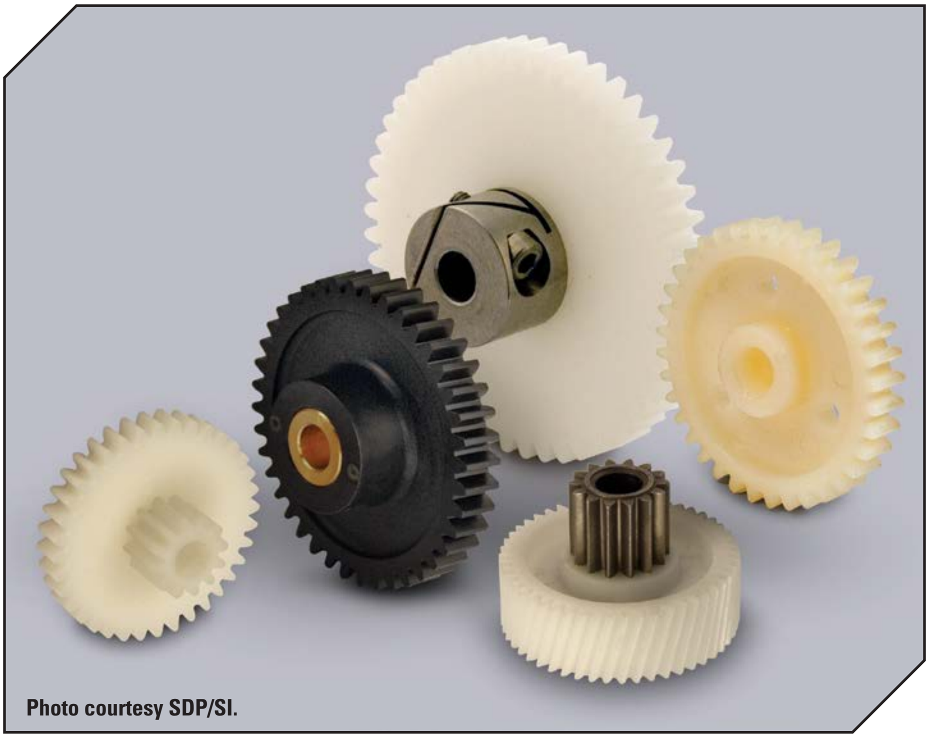
Photo courtesy SDP/SI.

Plastic gears are everywhere today—throughout your car, at the oceans' lowest depths, in deep space. The question, when is a metal gear a candidate for plastic conversion, can be addressed in three words, i.e.—what's the application? One can argue whether conversion to plastic gears remains application-limited. Not a problem—there exist many current and potential applications for polymer, waiting to be tapped, according to George Zollos, Celanese Corp.'s tribology segment market manager, engineered materials. This applies, for example, to applications like medical. "High-precision gears for medical applications are the next frontier for plastic gears," he says. "Medical applications require high-precision, tight tolerances, outstanding reliability and durability, and they need to be small, light and quiet. They must also be approvable for medical use. These are demanding requirements, but they lend themselves well to the capabilities of high-performance, engineered plastics."

Fact is—plastic gear technology is all about the less-is-more dynamic—as Zollos cites. What plastic in some applications cedes to metal in load limits is offset by the benefits of those applications where, say, lighter parts, lower cost and lower noise reset the bottom line.

In other words, you'll see plastic gears not only in all the old familiar places, but also—as the ability to convert progresses—in "any application where precise motion transfer is required," according to Glenn Ellis, senior engineer for ABA-PGT, Inc.

Some 50, 60 years since the first plastic gears started popping up in watches, office equipment, toys, household appliances and sundry gadgets of varying usefulness, they are now literally all around us—used in craft and equipment from the lower depths to the heavens. But are you going to see plastic gears in your car's drivetrain anytime soon? No. As Cris Ioanitescu, SDP/SI Engineering manager succinctly nails it, "If two gears of identical size and configuration are made from plastic and metal respectively, the metal gear will be stronger. Metal gears can be heat-treated to improve strength, but for plastic gears it is entirely material-dependent." Plastic gears do indeed dislike heat, being, according to George Diaz, general manager, The Gleason Works—Gleason Plastic Gears, the "No. 1 reason for (plastic) gear failure in high-torque applications."

But Ioanitescu then offers up a Top-10 list of solid reasons why plastic (and PM) gears continue in the conversion from their metal mates with each new design and material improvement:

1. Cost-effectiveness of the injection-molding process
2. Elimination of machining operations; capability of fabrication with inserts and integral designs
3. Low density: lightweight, low inertia
4. Uniformity of parts
5. Capability to absorb shock and vibration
6. Ability to operate with minimum or no lubrication
7. Relatively low coefficient of friction
8. Corrosion resistance
9. Quietness of operation
10. Tolerances often less critical than for metal gears, due in part to their greater resilience
11. Consistency with trend to greater use of plastic housings and other components
12. One-step production; no preliminary or secondary operations

And you can bet there are many new conversions, the "as yet unconverted" you might say, being earmarked for plastic gears as they continue usurping their metal-made progenitors. Indeed, metal-to-plastic gear conversion is keeping material suppliers in full-time R&D mode.

Adds Zollos, "The development of Celanese's Hostaform SlideX POM represents a significant breakthrough for plastic gears and bearings because it has extremely low wear and friction properties, but unlike other polymers, it also slides easily on itself. This is significant because it enables engineers to utilize the mechanical and physical properties of POM in both sliding components (surface and counter-surface) without negatively affecting wear, friction and noise performance. Hostaform SlideX even provides outstanding tribological performance, when paired against glass-filled POM."

Scott Paulot, sales and engineering manager, VictrexUSA/Kleiss Gears, says his company "has many material design and manufacturing innovations in development and in production, while Diaz offers that, "Gleason Plastics is actively involved in (gear) material testing efforts. Our 'no-weld-line' technology continues to deliver superior plastic gear quality levels."

Material aside — there is nothing without a plan — more to the point regarding plastic gears — a *design*. Without that, regardless of the material quality, the result will be garbage in, garbage out.

So what goes into making a good — or bad — metal-to-plastic gear conversion? (*Also see sidebar page 38 — Metal-to-Plastic Conversion Precautions: Three Traps to Avoid.*)

"The gear design is the first step to develop a stronger gear," says Ellis. "If the design for strength is not adequate, then a review of the material is required. If the selected material is molded improperly, then the properties will suffer and strength will be reduced.

"(But) the design of the gear is only one part of many influences that can cause noise in an assembly; a properly designed gear mesh will help reduce mesh noise. This design is only as good as the final molded gear. A good, molded gear is the result of a quality mold and a quality injection-molder."

Zollos adds that "Stronger material strengths can possibly result in better gear performance. But with plastics, significant improvement in gear performance can be achieved from the plastic's greater flexibility and elongation resulting in greater load sharing. So, an unreinforced plastic can have better gear performance versus a glass-reinforced plastic than a comparison of their tensile strengths would indicate.

Photos this page courtesy ABA-PGT.

"Design can also affect gear performance. For example, the gear designer should take advantage of the fact that a custom gear mold must be cut to account for shrinkage variations by modifying gear teeth beyond standard proportions to increase contact ratios and load sharing. Additionally, full-round gear tooth roots should always be used to minimize stress concentrations and molded-in stresses that can compromise gear performance. Molding can likewise affect plastic gear performance. Poor crystallinity as the result of low mold temperatures and hastened cycle times can compromise plastic gear strength. Poor molding conditions can also create residual molded-in stresses than can cause dimensional changes after gears are put into service."

Says John Winzeler, owner-operator of Winzeler Gear, "Gear strength starts with optimum gear geometry for the application. The design of gating systems that determine flow paths can impact the durability of plastic gears. The strength of plastic gear materials is influenced by process variations. Optimization of the process for the material is essential for best performance."

"The gear design phase is critical in the development of an optimal gear," Diaz stresses. "In this stage critical design conditions are developed to address the gearbox requirements (material selection, increase contact ratio, decrease sliding ratios, etc). During the tool design and fabrication phase, one must ensure that the gear cavity geometry is sized properly to accommodate for plastic shrinkage. Finally, during the injection molding process development phase, one must also develop a robust process (following decouple molding practices) to ensure consistency in the manufacturing process."

Regarding noise, that's a definite deal breaker, given that less of it is supposed to be a leading attribute of plastic gears.

Zollos explains. "Most plastic gear noise is the result of bad geometry; either from bad initial design, poor manufacturing (including mold making and molding), and resulting dimensions, or both. Tribological material performance also contributes to overall gear noise. One of the biggest oversights in plastic gear design is the failure to account for thermal expansion differences between the gears and their mounting geometry. Plastics have an order of magnitude greater thermal expansion than metals. These differences can result in significant variations in the effective center distance, contact ratio, and load sharing that, when gets too bad, will create tooth impacts, noise and premature failure."

ABA-PGT's Ellis raises another caveat — uniform material testing procedures — or the industry's lack of them, more precisely. "Material manufacturers do not have a common procedure for testing their products," he says. "This makes it difficult to compare some materials to find the best fit for the application. Some gear programs have material properties to compare when designing a gear mesh. However, this list is very limited, so in many applications the material you would like to review is not available."

Regarding the rich veins yet to be mined in the automotive industry, we've already addressed the drivetrain gear conversion possibility—which is nil. But of course that's only a small part of the number of car parts in play. But to actually produce those parts, says SDP's Ioanitescu, "Future developments in material science could create hybrid materials which will combine the best properties from plastics and metals. The fact that plastics are self-lubricating materials eliminates the need of using grease and oil for two gears in mesh."

Ask Gleason's Diaz about the further potential for metal-to-plastic conversion in automobiles—you'd have to say he's all-in.

"The day will come when we will drive an all plastic *automobile*! Gleason's 2011 plastic gear acquisition is a long-term commitment in support of this trend. Over the next 10–20 years, new polymer resins will be developed to withstand increased loads / temperatures. We do not see steel gears in drivetrain going away, (but) there are an increasing number of plastic gears used for a variety of applications outside of drivetrain applications."

Offering a more restrained, yet positive view is Celanese's Zollos. "In the near future, there are just too many parts requiring materials with widely different performance properties to expect that one type of material could be used for (every auto part). However, as the move toward electric vehicles continues, the demand for lighter, stronger materials will result in an ever-increasing percentage of plastics being used in cars."

Victrex/Kleiss Gears' Scott: "This is a very wide scope question. Clearly significant performance improvements and cost savings are available if plastic is utilized in more under-the-hood applications. CAFE standards will drive this forward." And Diaz further adds that "In general, metal-to-plastic transformations typically yield a weight reduction that directly impacts energy efficiency performance. Plastic gear transformations also can offer dampening gearbox responses as well as noise reduction advantages."

And, finally, what of lubrication? True, in most cases it is not needed for plastic gearing. But when it is…

"One of the most important drivers for converting from metal to plastic gears and bearings in many applications is the ability to eliminate the need for lubrication," says Zollos. "The lack of lubrication is a key factor in premature gear and bearing failure, whether it's due to inadequate maintenance, breakdown of the lubricant due to temperature, dirt or other contaminants, or simple depletion of the lubricant over time. The development of new and better performing tribological polymers will allow more and more metal gears and bearings to be converted to plastic and potentially eliminate the need for lubrication in those applications. That is why Celanese is continually developing new grades and compounds to improve tribological performance of gears and bearings in all applications and across a wide range of industries."

"It is very important. Plastic gears offer more flexibility for lower viscosity lubrication or no lubrication than metal," Scott agrees, with Diaz pointing out that "In general, lubricated applications may offer a cooling benefit to the gearbox system. One must also ensure proper compatibility between the lubricant and the plastic resin. We see nanoparticle technology as a major technology breakthrough in both resins and lubricants."

"Lubrication—internal or external—is a science in itself," Winzeler points out. "The appropriate lubrication system is critical for optimum performance of a plastic gear system, which is no different for metal gearing. Many plastic gear systems can meet life requirements with only initial application of grease. We engage lubrication engineers in our design process."

Metal-to-Plastic Conversion Precautions:
Three Traps to Avoid

Courtesy Victrex/Kleiss Gears

With a constant demand for performance improvements and cost reductions, the conversion of metal gears to plastic in high-performance applications is a growing sector in the marketplace. Following are some common pitfalls to be avoided when you are asked to make the conversion:

Trap No. 1—Direct replacement. The earliest and easiest trap is the convenience of a direct replacement: i.e.—the metal gear works, so why not quote making the "same part" from plastic? There are times where this direct replacement would be acceptable and a plastic gear designer will perform that analysis for you; however, many times the gear needs some redesign work. The good news is this trap is easily avoided by sharing the current design along with requested improvements with your plastic gear designer to see what solutions—including direct replacement—may be available.

Trap No. 2—Failure to optimize for plastic. This leads to the next pitfall, which is not giving the plastic gear design enough flexibility at the onset of the redesign. The original design was optimized for a *metal* gear, so changing the gear material warrants a redesign for the *plastic* gears—which may extend beyond the design of the gears alone. Plastic gear optimization is the key to removing unwanted weight, cost, NVH and other undesirable elements, so specific concerns should be discussed with plastic gear designers early in the conversion process. Plastic gear designers can work with project engineers to develop a solution tailored for the unique operating conditions of any system; this is necessary to select the correct material and optimize the gears to meet the functional requirements throughout the entire operating environment. Because the part is converting to plastic, other design elements may be present that were not before, such as designing an insert for over-molding, combining multiple parts into a single component, and removing secondary operations.

Trap No. 3—Prototype testing setbacks. Once a plastic gear design is agreed upon, the design must be built and tested. The prototype testing phase of the conversion process is usually seen as a pass/fail test of the plastic design, but therein


Photo courtesy VICTREX USA/Kleiss Gears

lays the trap. The reality is the prototype testing phase should be an iterative process during which improvements can be made that take full advantage of the plastic redesign opportunity. Plastic material properties have been generated through repeated lab tests which follow precise standards, but the prototype plastic components are not operating in a lab environment. Because this is a new technology, gear reference tables at different temperatures and loads do not exist for each resin. This can lead to setbacks in prototype testing during alpha/beta testing. Though undesirable, unexpected results in prototype testing are not uncommon: often these results lead to a refinement of actual environmental conditions that expand the specified ranges. If a gear does fail during testing, find the root cause and properly account for it in subsequent designs and tests.


Photo courtesy VICTREX USA/Kleiss Gears

Countless opportunities for metal to plastic conversion are present in the automotive and aerospace industries. The medical industry also offers abundant applications ideal for plastic gears. Whether you are looking for durable replacements for large metal gears or small disposable gears, plastic gears can provide a valuable solution to bring your product successfully to market. Any plastic gear solution can offer advantages that, when realized in new applications, may revolutionize the standards in that industry. Great innovations are close at hand with plastic gears in the toolbox, so start researching if you have gears suitable for plastic conversion.

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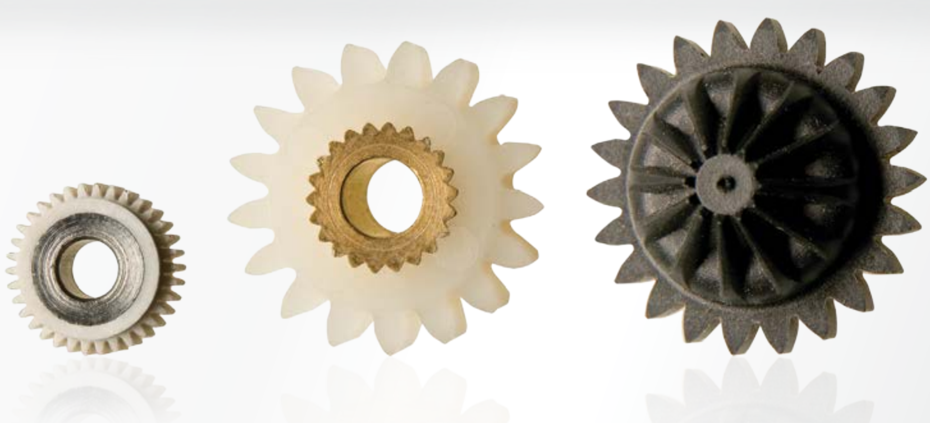

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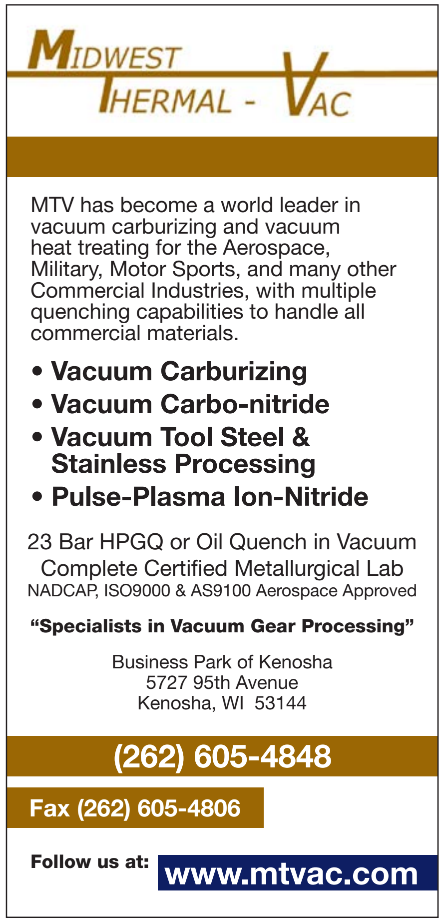
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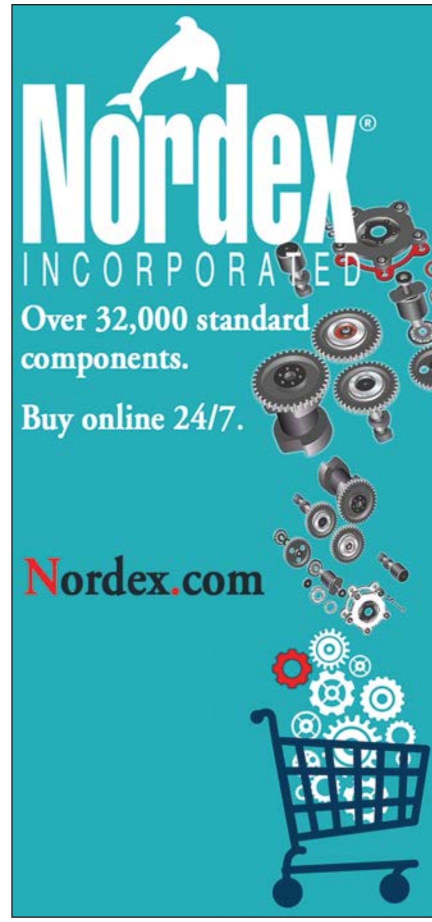
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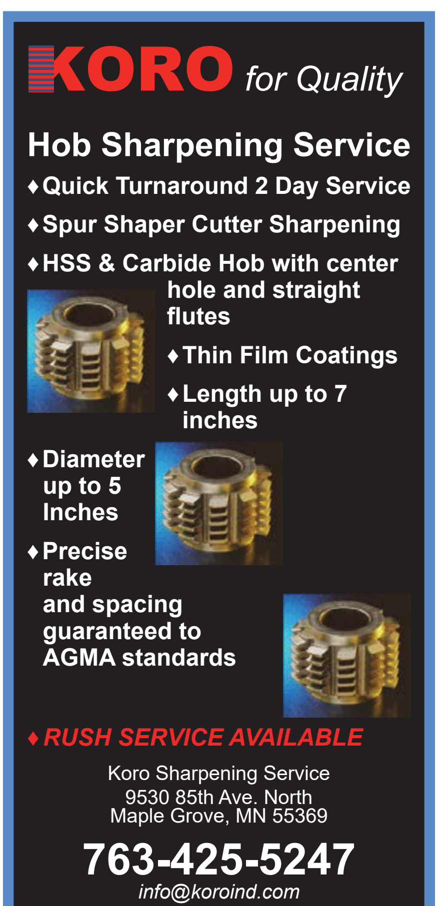
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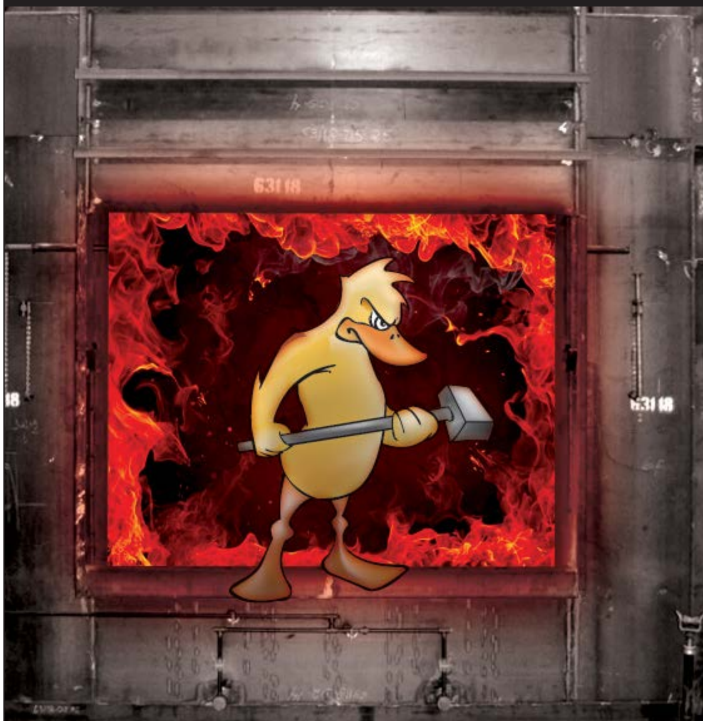

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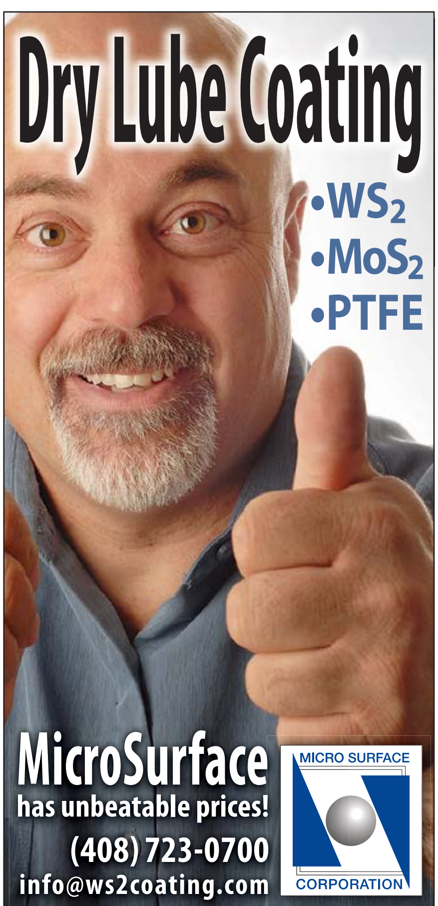
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Taking on Tight Margins in Wind Energy

Three Factors Influencing Gearbox Technology in Wind Turbines

Matthew Jaster, Senior Editor

Onshore and offshore wind turbines boast some of the most critical assets in order to run effectively. If the motors, bearings and gears fail, the result is expensive maintenance costs, operator safety concerns and the end of that warm, happy fuzzy feeling, according to Brett Burger, product marketing manager at National Instruments. "We don't often start with that warm, happy, fuzzy feeling at the beginning, but our goal is to get there by providing the hardware and software tools that are specific to the user's requirements."

The gearbox is largely considered the heart of a wind turbine, according to Fernando Catalão, chief WTG engineer at SMT Portugal. It converts the slow rotation speed and high torque of the rotor through the transmission in the gearbox to a high speed and low torque in the generator. In the same way that wind turbine companies request new concepts and higher quality gearboxes, the gearbox manufacturers ask subcomponents suppliers for advancements in bearings, heat treatment and lubrication systems.

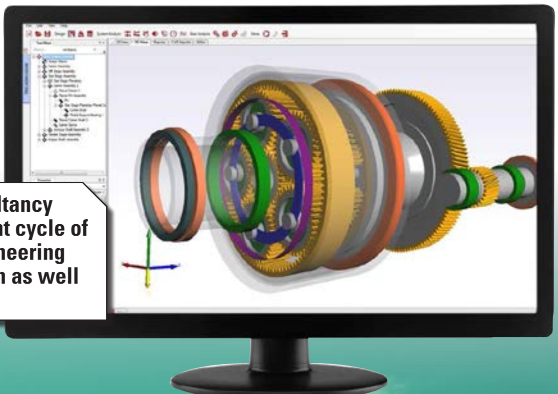
"The gearbox manufacturers and designers have learned lessons from other industries. Better maintenance regimes, condition monitoring/management, better oils and oil care have all played their part as well as powerful CAE software modelling, advanced manufacturing technology, improved materials and a greater understanding of the turbine operating environment," he added.

Companies like Smart Manufacturing Technology Ltd. (SMT), KISSsoft, Romax and National Instruments play a significant role in advancing wind turbine technology today. These companies recently addressed the key factors influencing gearbox technology such as meeting the challenges of gearbox design, properly testing the equipment and developing a condition monitoring system to improve gearbox performance and limit production downtime.

#1 Meeting the challenges in gearbox design

The predominant influencers on the design of wind turbine gearboxes have been driven by the requirements of the market itself. "This includes cost, weight, reliability and noise requirements," said Stephen Brown, vice president, engineering design at Romax Technology. "Bigger rotor diameters are increasing in popularity from OEMs. The resulting load and torque increases, combined with lower weight and cost requirements, are dominant driving factors in new product gearbox design."

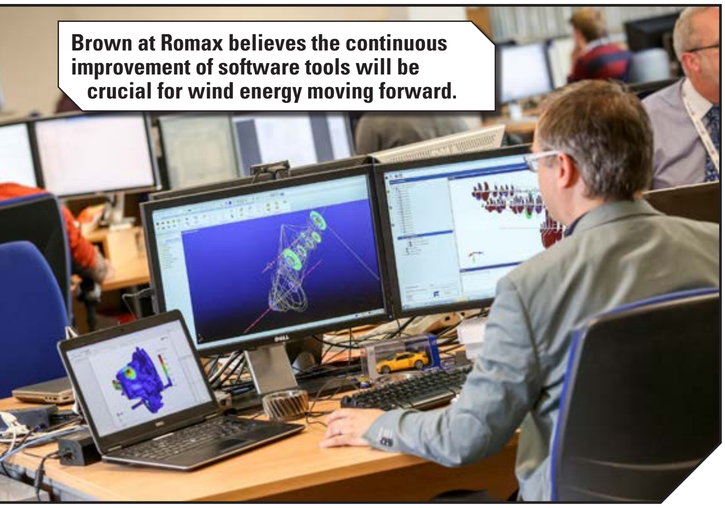
Catalão believes several factors play a role in improving gearbox design including reduced maintenance time/costs; simplified and modular designs; lighter weight; higher reliability components and lower manufacturing costs. "SMT has developed a wind turbine gearbox



SMT provides engineering design and consultancy services that cover the complete development cycle of wind turbine drivetrains with extensive engineering expertise in transmission and gearbox design as well as analysis and manufacture simulation.

for offshore applications that can avoid planetary systems and take into account the modularity and size of the components. This concept can decrease the costs of the manufacturing due to the simplicity of the shafts and a reduced number of components. Also, this gearbox design makes it possible to replace all components in place without the need to disassemble the gearbox from the nacelle, dramatically reducing downtime and repair costs," Catalão said.

The predominant point is the data collection and analysis to understand failure mechanisms, according to Brown. "These are ultimately fed into designs (and software) to enhance reliability at the design stage. The continuous improvement of software tools through data integration, reports, supply chain, manufacturing and product management will be crucial moving forward."



Brown at Romax believes the continuous improvement of software tools will be crucial for wind energy moving forward.

For KISSsoft Gmbh, the engineering tools have evolved rapidly over the last five to ten years. All of the challenges involved in wind applications can be boiled down to managing design processes. "This requires a total system approach where designers are focusing on details and have little experience or exchange with manufacturing or quality control," said Hanspeter Dinner, consultant, EES KISSsoft Gmbh. This means training new engineers must go beyond the basics of the software design package. "We inform engineers on theoretical background, principles of gear and bearing design, conduct seminars on drivetrain technology and perform onsite design reviews," Dinner said.

Feedback from the load test to the design engineers is crucial. "Of highest interest is the correlation of the tooth contact patterns as predicted/calculated to what is observed in the field. Here, it is imperative that designers are closely involved with the testing and get access to the gears (and other gearbox parts) in the workshop," Dinner added.

#2 Testing Equipment

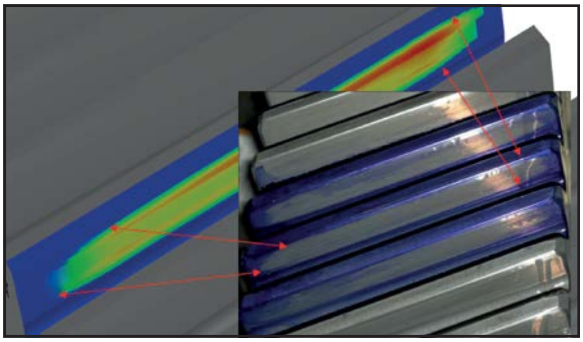
Testing is important in wind turbines because the margin between being profitable and not profitable is so slim. "It's a very tight margin," Burger said. "You're setting up government subsidies to get going, for example, and then driving down the costs of the technology over time as those subsidies roll off. It is important that when you deploy a standard wind turbine it will last as long as it can or in the case of a new technology on a wind turbine, you want it to be as efficient as possible so that it will catch on. I think in both those scenarios, testing is an absolute necessity."

National Instruments tests everything from control systems to structural testing (thermodynamics, structural engineering). "When you have your simulation model in the computer and your real model deployed in the field instrumented with sensors, the customer can compare the two and make sure what they expect to happen is actually happening. When those two line up we're back to that warm, fuzzy feeling again," Burger added. "When they don't line up, that's when engineering and part design get together and attempt to remedy any discrepancies."

Testing capabilities are one of the key ingredients if you want to be taken seriously in the industry, added Dinner at KISSsoft. "Running full load and overload tests are industry standard and a good correlation between analytical prediction of contact patterns and strain gage measurements are achieved nowadays. It is also relevant when purchasing/designing gearboxes not only to supervise the test itself, but also the assembly of the gearbox prior to testing (to see whether damages were present even before the test) and the disassembly after the testing (it is tempting to hide damaged parts from the customers or certification body's eyes). The key challenge in testing from a supplier point of view is to shorten times between test runs, that is, to shorten the time needed to install and de-install the gearbox in the test bench."

Brown agreed, "Full scale testing has been driven by certification agencies to make a requirement to validate design. It has also been used as a compliance validation following a gearbox rebuild that has already been in service. The industry is seeing three and four DOF (Degrees Of Freedom) test rigs emerging that provide close-to realist trials and results. Testing will always play an important role in the wind industry because of the costs associated with failure in operation, particularly offshore."

"Full scale testing is crucial for technological and system innovation because this kind of test makes it possible to see the potential weak points that can come to the surface for each component of the system," Catalão added.



The loaded tooth contact analysis (LTCA) in KISSsoft has been refined over several years and is now showing outstanding match to contact patterns observed in full load tests performed using a master and slave gearbox in back-to-back arrangement. Combined with the load spectrum calculation and the KHβ calculation along ISO6336-Annex E as required to obtain certification along GL guidelines, it is a most powerful, easy to use and accurate tool to optimize the load sharing and hence the power density of any wind gearbox. The above image taken from such a test confirms the comparability between load patterns from analysis and real world conditions.

#3 Condition Monitoring

The main objective of condition monitoring is to determine the current technical status of the component—the health of the gearbox. "Condition monitoring and failure analysis can be a vital tool to decrease/reduce the operation and maintenance costs, as well as, provide important information (sensors data) to predict upcoming failures," Catalão said.

In Europe, the condition monitoring system (CMS) is now mandatory for offshore, and factory-fitted to all new turbines, and it is becoming more common for onshore turbines in Europe as well as North America, with CMS increasingly being retrofitted in the field. "Early detection of gearbox problems saves operators a large amount of money, so understanding condition monitoring reports and being able to interpret the data can be cost-saving at the least, and performance improving at best," Brown said.

Dinner at KISSsoft wants to see an additional approach in the engineering analysis of gearboxes in the future. "We need to use statistical methods to predict MTTF (mean time to failure) or similar values. This is opposed to the current approach where for a 20 year lifespan a safety factor is calculated even though we all know the calculation methods are not valid or reliable for 20 years of operation. For the prediction of MTTF values, using only the theoretical approaches available in standards is not sufficient as they are often based on different concepts or different inherent failure probabilities. Here, feedback from the field (be it failure analysis or condition monitoring) needs to be considered and used as a basis to make predictions, as it is done

Determining root failure cause: Endoscope inspection of a wind turbine gearbox.

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in other industries (helicopter or vehicle transmissions for example). Obviously, the condition monitoring approach has an advantage here as all data is readily available for processing and statistical analysis.

"Gearboxes have been around much longer than wind turbines," Burger said. "One of the advantages of the technology that is currently happening with the Industrial Internet of Things (IIoT), you can bolt on this high-end performance, computing node and not only do you have the ability to monitor the gearbox through its life, you can log data and determine how to improve upon it in the future."

National Instruments has customers that are the owners of the assets eager to plan and prepare for any unplanned outages. They also have customers that are gearbox manufacturers.

"The condition monitoring equipment becomes a black box of sorts for these customers, logging data in order to process hitches or spikes or additional anomalies in the equipment. The customer can then use this data to determine if the problem is environmental, something in the manufacturing process or problems with the initial design."

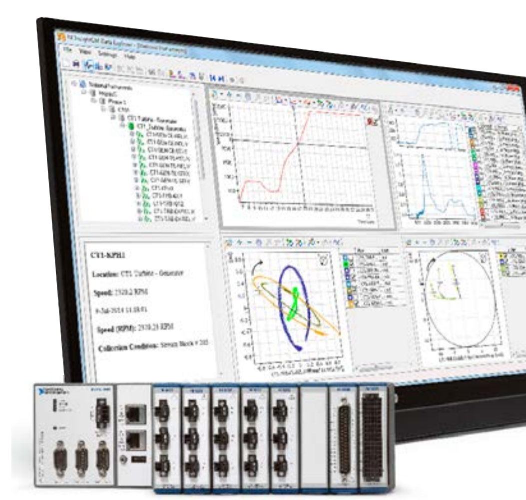
Never-ending innovation

While these three factors only scratch the surface of gearbox technology, the truth is the hardware and software tools available in this growing market are as dynamic as the equipment they are monitoring.

"The development process never stops," Catalão said. "This means that gearboxes will continue to be complex and highly-reliable components in the drivetrain of new wind turbines. This reliability, however, does not mean gearboxes will be completely trouble-free. Replacing a gearbox will still come at a very high cost. In other words, replacing a shaft or a bearing is cheaper and quicker than replacing the whole gearbox and engineers will opt for systems with better interchangeability for components."

Future integration between CAE software packages for design, manufacturing and testing will help close gaps in development loops and ensure an engineer's time is spent innovating rather than processing and migrating data," Catalão said.

The gearbox is the link between the rotor and generator, Dinner added. "Its design will be driven by those components, the gearbox has to fit in, that's all. So, the requirements on the gear-



box will evolve with new technologies applied there. In testing, we expect more transient tests to be done besides the standard load and overload tests. Also, application of hub loads like bending moments or axial forces is something we expect to happen more often in the future."

Brown at Romax said that industry is looking towards life prediction as a dominant factor in wind turbine operation. "The benefits include operation and maintenance cost management, outages and service intervals that can be easily predicted and managed, the education of reliability factors, the opportunity of increasing power production through control system refinements and the opportunity of asset life extension."

Burger at National Instruments sums up the future of hardware and software tools like this. "Right now, we're brownfield. There's a huge inventory of commissioned assets out there," he said. "10 to 15 years from now, you're going to see more of the sensing technology, the processing and measuring technology built directly into these assets. It will be more common in the future to have a smart or intelligent gearbox that can self-diagnose problems. This will make it so much easier for a gearbox manufacturer to alert a wind farm when turbine components need to be shut down and serviced immediately in the field."

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Early Wind Turbine Developments

In the early 1980s, wind turbines went into mass production to be used as commercial generators of energy. Since then, a wide variety of wind turbines emerged in the market. "The Danish wind turbine concept, three-bladed, fixed speed, stall-regulated turbine became the dominant model in the market at rated power levels of less than 200 kW. As installed capacity has increased, wind energy technology has evolved towards machines with longer blades and higher power ratings," Catalão said.

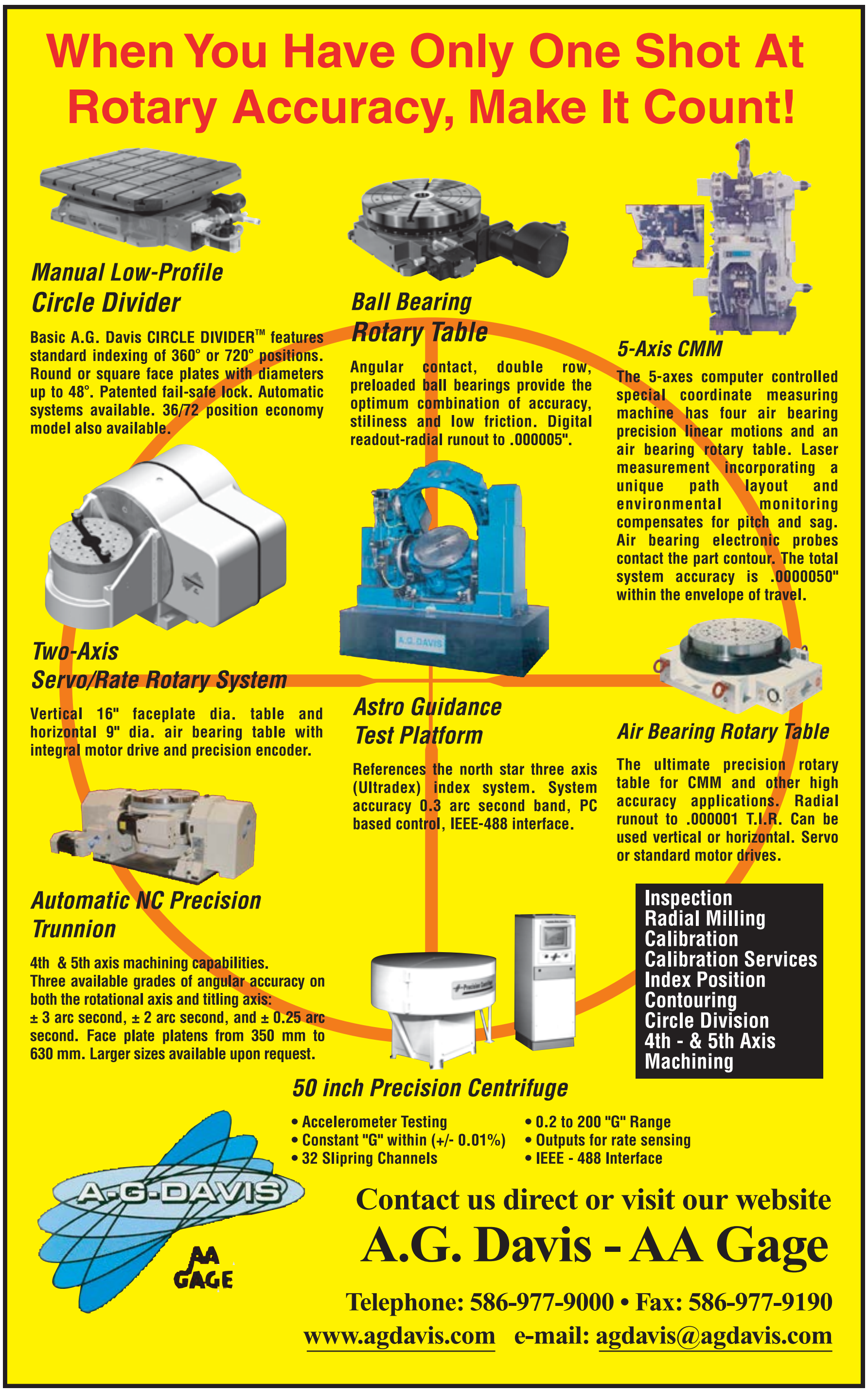
This increase in capacity has led to more stringent regulations and the need for the gears and gearboxes to keep pace and adapt to these requirements. "Gearbox manufacturers therefore have been pushed to design and develop more reliable and competitive products," added Catalão.

In general, the gearboxes can be separated in low, medium and high speed applications with one, two or three stages respectively. "A wide range of other designs have been tried and applied, e.g. compound planetary (e.g. by RENK), differential planetary (e.g. by Bosch Rexroth), helical gearboxes with multiple pinions driving several generators (e.g. by Clipper or Winergy) and even gearboxes including bevel differentials (e.g. by Kowintec)," said Dinner at KISSsoft Gmbh.

"Other non-standard gearbox designs would use flexible planet supports, hydrodynamic bearings instead of rolling bearings or double helical planetary gears. Still, two planetary stages plus one helical stage is the industry standard, ratios are now going up to e.g. 1:110. We do see a trend towards medium speed gearboxes where the generator is in line with the gearbox, resulting in lower generator speeds and less difficulties to align gearbox and generator (e.g. SCD 3 MW and 6 MW by Aerodyn, Multibrid, Winergy HybridDrive and Moventas Exceed)," Dinner added.

In the early stages of wind turbine development, these gearboxes were little more than adaptions of those used in industrial or agricultural applications with a very simple configuration; two or three stage spur gear drives between the input and output. "Modern gearboxes are now complex and highly efficient drivetrain systems and their reliability in recent years has significantly improved," Catalão added.

The wind industry has long debated the benefits of both direct drive (DD) and geared solutions for wind turbine drivetrains. DD solutions became increasingly popular following reliability challenges from MW-scale gearboxes. "As it would currently seem, the industry is swinging towards geared solutions (high speed output-generator for smaller MW machines and medium speed for larger," said Brown at Romax Technology. "This could be explained by improving reliabilities being enjoyed as well as better cost competitiveness, provided by geared drivetrains."



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Hard-Finishing Spiral Bevel Gears

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QUESTION

Could you explain to me the difference between spiral bevel gear process face hobbing-lapping, face milling-grinding and Klingelnberg HPG? Which one is better for noise, load capacity and quality?

Expert response provided by Dr. Hermann J. Stadtfeld.

Face hobbing lapping. Spiral bevel gears have no length sliding between the flank surfaces while they mesh. If they are lapped, the lapping action fully depends on the profile sliding. However, at the pitch line, the profile sliding is zero and the lapping removal as well. It is therefore very difficult to lap spiral bevel gears (in contrast to hypoid gears which lap very well). The material removal principles, of the three discussed hard-finishing methods, are shown in the graphics for Figure 1.

Face milled spiral bevel gearsets have generating flats on their surfaces which are parallel to the contacting lines between them during meshing. The lapping process will follow the generating flats and magnify the ripple they cause if the lapping takes too long. In other words, spiral bevel gears are difficult to lap due to the missing length sliding. If spiral bevel gears are face milled, then they present a combination of obstacles which makes them rather "unlappable."

Face hobbed spiral bevel gearsets have generating flats which cross under 10 degrees to 20 degrees the contacting lines between the flanks. The lapping motion moves the lapping compound across the ripples which reduces them and makes the lapping efficient. However, there is still the obstacle with the missing sliding velocity along the pitch line. It is only possible to lap face hobbed spiral bevel gearsets for a very short time (e.g. 30 sec.) with low torque (e.g. 5 Nm). The contact before lapping must be positioned to the top-toe at the drive side and towards the top-heel on the coast side. Also, the pitch line needs to be very high (towards the topland) on the gear member.

Although the gear quality of face hobbed/lapped gears is often rated only in the AGMA 10 to 11 range, roll behavior, break-in properties and strength are very good. One of the great advantages of face hobbed/lapped bevel gearsets is the insensitivity to housing deflection and building tolerances.

Face milling grinding. The obstacles with lapped spiral bevel gearsets previously described make the face milling/grinding combination process the choice for spiral bevel gears. While face hobbed gears cannot be ground because of their epicyclical lead function, face milled sets are ideal for grinding. The grinding wheel just emulates the silhouette of the cutting blades in the soft cutting process. The direction of the generating flats has no influence to the process and the final results. It is recommended for strength reasons to avoid root grinding; however, the fillet region should show a soft blend between the ground flank surfaces and the root. Root grinding will form a slightly different fillet surface than the previous soft cutting operation with separate inside and outside blades. The grinding wheel will remove steps and fins and therefore cause "invisible notches" in the material structure. To "design around" root grinding, it is recommend-

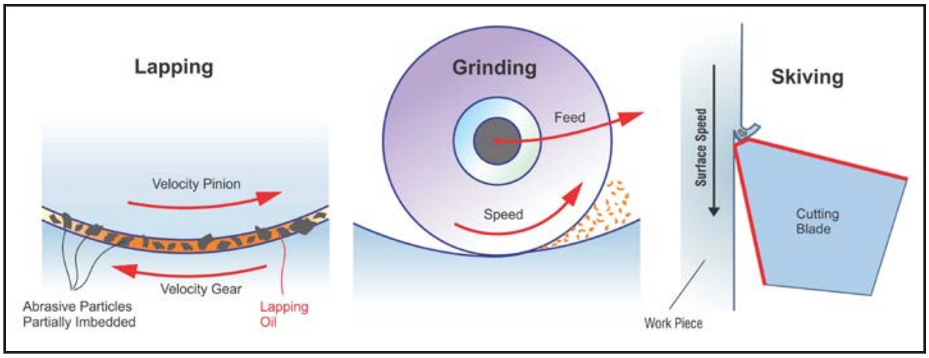

Figure 1 Hard-finishing material removal mechanisms.

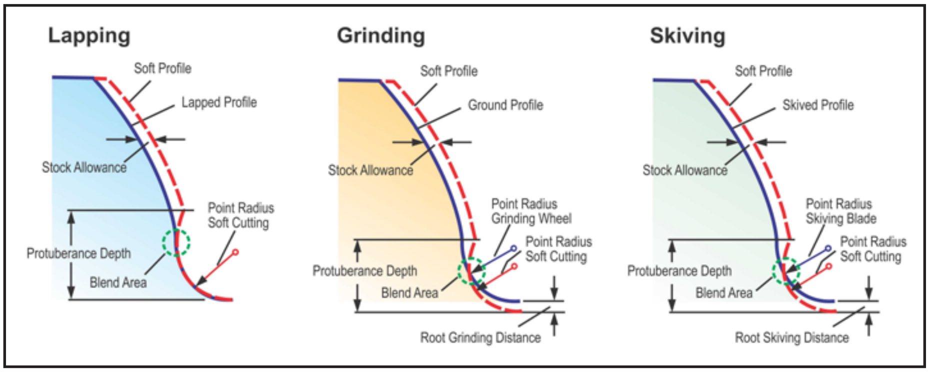

Figure 2 Semi-finish strategy.

Dr. Hermann J. Stadtfeld is vice president/ Bevel Gear Technology -R&D, and longtime contributor to ***Gear Technology*** magazine.

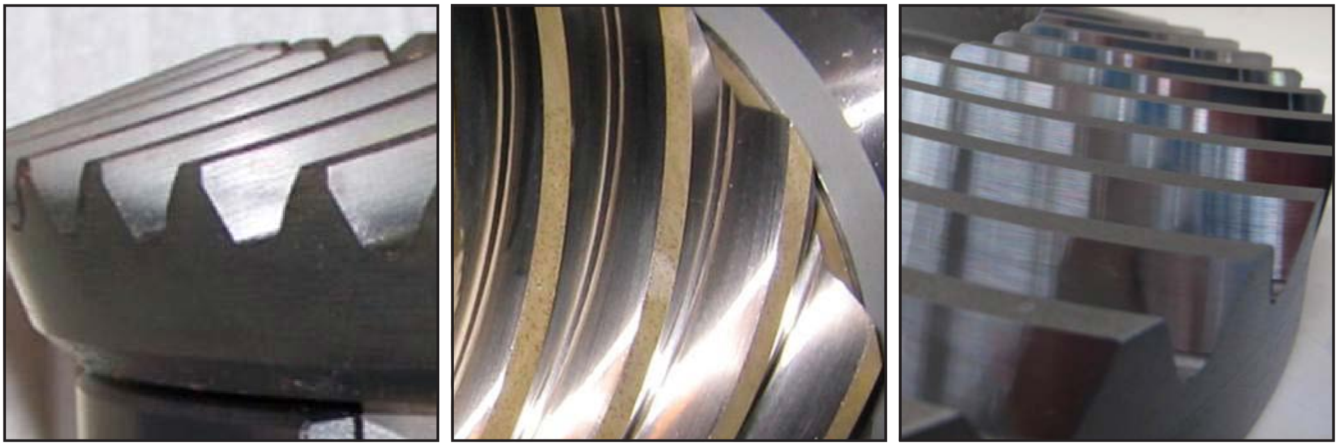

Figure 3 **Surface appearance of lapped (left), ground (center) and skived (right) bevel gears.**

ed to apply the semi-finishing geometry as shown in the center of Figure 2.

The gear quality of ground sets is AGMA 12 and 13 without extra effort. However, the surface roughness is higher than in lapping, which requires special oil properties and/or phosphate coating of the ring gear member in order to assure a good break-in result. The strength of ground gearsets with conventional geometry is equal to comparably lapped pairs. Grinding presents the advantage that higher order motions, such as *UMC* (*Universal Motion Concept*) with three pinion flank sections and additional gear end relief can be applied. *UMC*-optimized bevel gearsets have the same favorable displacement characteristic as face hobbed/ lapped gearsets, with a similar low-noise emission. Root bending strength and surface strength of *UMC*-optimized ground bevel gears is higher than the strength of their lapped or skived counterparts.

Hard skiving. Hard skiving of spiral bevel gears with Gleason Cyclocut or Klingelnberg Cyclo-Palloid HPGs is a viable process for the hard finishing of face hobbed bevel gearsets. In hard skiving, either coated carbide blades with a negative T-land (Gleason) or brazed on CBN cutting strips (Klingelnberg) are used to skim off a stock allowance of 0.10 mm to 0.15 mm, similar to grinding. The hard skiving blades should not have any cutting contact with the workpiece at their tip region. The depth of the soft cut slots therefore is 0.1 mm deeper than the depth of the hard finish cut. Just like the recommendation for grinding, the upper section of the root fillet radius should blend with the lower section from the previous soft cutting—preferably below the 30° tangent point.

The gear quality of hard skived bevel gears is in the range of AGMA 12 to 13. The flank surfaces have a mirror finish. A surface comparison between the three discussed hard finishing methods is shown in Figure 3.

While the strength is often expected to be higher than the strength of lapped gears, this is not correct. The root bending strength is comparable to lapped and ground gearsets with conventional design. Depending on operating speed and lubrication, micropitting has been found to exist along the crest of consecutive generating flats. In order to prevent surface problems during the break-in period, it is recommended to either coat the ring gear with phosphate and/or use a synthetic oil filling.

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Practical Approach to Determining Effective Case Depth of Gas Carburizing

March Li

Effective case depth is an important factor and goal in gas carburizing, involving complicated procedures in the furnace and requiring precise control of many thermal parameters. Based upon diffusion theory and years of carburizing experience, this paper calculates the effective case depth governed by carburizing temperature, time, carbon content of steel, and carbon potential of atmosphere. In light of this analysis, carburizing factors at various temperatures and carbon potentials for steels with different carbon content were calculated to determine the necessary carburizing cycle time. This methodology provides simple (without computer simulation) and practical guidance of optimized gas carburizing and has been applied to plant production. It shows that measured, effective case depth of gear parts covering most of the industrial application range (0.020 inch to over 0.250 inch) was in good agreement with the calculation.

Introduction

Carburizing is one of the most widely used case hardening techniques/treatments in the industry. It is a thermal process in which austenitized steel is brought into contact with a carbonaceous atmosphere of sufficient carbon potential to cause adsorption of carbon-bearing gasses at the surface where they dissociate, and by diffusion, to create a carbon concentration gradient. After quenching, the outer surface becomes harder via martensitic transformation, due to its higher carbon content, while the core remains relatively soft and tough. Through carburizing, the part receives enhanced surface hardness, wear resistance, fatigue and tensile strength, along with some collateral side effects (grain growth, distortion, etc.).

Gas carburizing is the most common type of carburizing and provides precise control of case depth with economical and cost-effective benefits. However, it is also a complicated process during which many chemical reactions occur simultaneously in the carburizing atmosphere. Therefore several parameters governing the process must be well controlled, such as, for example, temperature, carbon potential and cycle time. The goal is to reach a desired, effective case depth (ECD) for a specific part, as well as other acceptable characteristics such as surface and core hardness, surface carbon content, and microstructure (including retained austenite, carbide distribution, etc.).

In 1943, F.E. Harris published a paper on carburizing case depth in which mathematical analysis based on Fick's law of diffusion and experiments was performed (Ref. 1). He also computed the case depth for various temperatures and times, assuming the part maintained a saturated carbon content at the surface when carburizing; the detailed data are listed in Table V of this paper. It should be noted that the case depth mentioned in Harris's study referred to "total case depth," which is difficult to measure consistently and is quite different from "effective case depth," which can be measured more consistently and is the preferred measure today.

Later, Harris's data were published in *Metal Progress Data Sheet* (Ref. 2). Per the data and method, one can determine the carburizing cycle time based on the temperature and carbon content increase above the base carbon. To get the corresponding effective case depth — there was no such terminology at that time — one had to go through several steps using these data, curves and basic calculations. Another way is to multiply the total case depth by a factor. Depending on steels and temperatures, this factor varies from 0.60 – 0.76. Using this methodology, a Timken metallurgist in 1953 created effective case depth tables for different base carbon content steels (Refs. 3–4).

For carburized parts, total case depth refers to the maximum depth of diffused carbon. Effective case depth has a slightly different definition in ISO and AGMA standards. In ISO 6336-5, it is defined as the distance from the surface to a point at which the hardness number is 550 HV_{500}, which converts to 52.4 HRC or 583 HK_{500}. According to AGMA 923, this is measured normal to the finished gear surface to a location where the hardness number is 50 HRC (542 HK_{500} or 515 HV_{500}) by conversion from a microhardness test result (Ref. 5). Traditionally, this location has about 0.40 wt. percent carbon, which provides about 50 HRC hardness with 90 percent martensite. In this paper, the AGMA definition is adopted.

It is well recognized that the work of Harris and others provided valuable analytical and practical guidelines for carburizing. Yet neither of these tables/charts included the effect of carbon potential, nor took into account different temperatures during a complete carburizing cycle, as do most carburizers today. Furthermore, these carburizing factors have three decimal digits, which is not very accurate in predicting some thin or

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thick case depths. Currently many heat treaters purchase commercial software to determine the carburizing cycle process parameters, and get satisfactory results — most of time. However, this is costly for use and maintenance. While the program works well for routine carburizing processes, it is hard to tackle abnormal problems such or carbon potential out of control, heat treatment termination and recarburizing, etc.

In this case it would be preferred and more convenient to establish an explicit formulation to combine the effective case depth with all related parameters. This paper analyzes the relationship between effective case depth and these parameters based on diffusion theory and carburizing conditions that have been derived from decades of manufacturing experience.

Diffusion Analysis

Carburization is basically a thermal process during which carbon atoms diffuse into the steel; it can therefore be described by Fick's laws of diffusion. Since the diffusion flux and the concentration gradient near the surface vary with time due to accumulation of carbon, it is considered a non-steady-state diffusion and can be expressed by Fick's second law, which is:

$$\frac{\partial_C}{\partial t}=\frac{\partial}{x}\left(D\frac{\partial_C}{\partial x}\right) \tag{1}$$

Where C is concentration of carbon, t is time, x is position or depth below the surface of the part, D is the diffusion coefficient.

Theoretically, the diffusion coefficient of carbon in austenite varies with carbon content. For simplicity, the dependence of D on carbon content can be discarded. In this case, Equation 1 simplifies to

$$\frac{\partial_C}{\partial t}=D\frac{\partial^2 C}{\partial x^2}\Big) \tag{2}$$

When some boundary conditions are specified, this equation can be solved analytically. In other words, the carbon gradient and depth of penetration under certain conditions can be predicted.

Practically, the surface carbon concentration can be considered constant (equal to carbon potential). As long as the part is thick enough compared with the case depth (that is, the thickness of the carburized part is larger than $5\sqrt{Dt}$), it can be treated as a semi-infinite solid. When the following boundary condition assumptions are made:

- Before diffusion, the carbon atoms in the solid are uniformly distributed with concentration of C_0
- The value of x at the surface is zero and increases with distance into the solid
- The time is taken to be zero the instant before the diffusion process begins

Equation 2 can be solved and expressed as:

$$\frac{C-C_0}{C_S-C_0}=1-erf\left(\frac{x}{2\sqrt{Dt}}\right) \tag{3}$$

Where C is the concentration at depth x after time t. C_S is the constant surface concentration at $x=0$. For estimating case depth, it is assumed that this surface carbon content instantaneously takes on the carbon potential at the carburizing temperature. Expression $erf\ (x/2\sqrt{Dt})$ is defined by is the Gaussian error function, which is defined by:

$$erf(x)=\frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt \tag{4}$$

For specific carbon concentration, e.g., $c=0.40$ wt. percent, the left-hand side of Equation 3 is a constant. This implies the right-hand side is also a constant, which means —

$$\frac{x}{2\sqrt{Dt}}=\text{constant, i.e., } x=k\sqrt{t} \tag{5}$$

Traditionally, k is called carburizing factor.

Per the literature (Ref. 6), the diffusion coefficient of carbon in austenitic iron from 800° C – 1,000° C is:

$$D(C,\gamma-Fe)=16.2\cdot 10^{-6}\cdot \exp\left(\frac{-137800}{RT}\right)\ \text{m}^2/\text{s} \tag{6}$$

Where $R=8.314\ J/K\cdot mol$, T is temperature in degrees Kelvin.

Per Equation 3, we can easily get:

$$C=C_S-(C_S-C_0)\,erf\left(\frac{x}{2\sqrt{Dt}}\right) \tag{7}$$

Based on Equations 6 and 7, carbon content at any time and depth can be calculated at a certain temperature; i.e., when surface and base carbon content are known (Fig. 1).

Figure 1 shows that, assuming other conditions are the same, the depth reaching certain carbon content (e.g., 0.40 wt. percent) is deeper for high base carbon content material. In other words, steel with carbon content of 0.20 wt. percent (such as SAE 4320 steel) will always get bigger effective case depth than that with carbon content of 0.10 wt. percent (such as SAE 9310 steel).

Figure 1 also shows that carburizing with constant conditions — such as single surface carbon potential — gives rise to a quick drop of carbon content within the case. Based on the relationship between carbon content and the hardness of martensite, this implies that hardness drops quickly with depth in the case. This will limit the stock removal after carburizing (e.g., gear grinding), as the remaining surface hardness could be below the

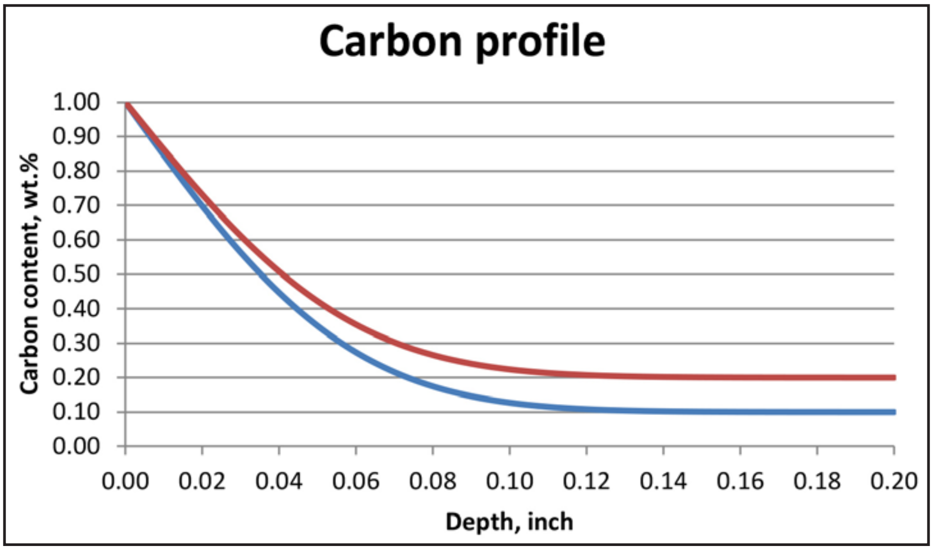

Figure 1 Calculated carbon profile with carburizing $T=1{,}725°$ F, $t=10$ hr; surface carbon content is 1.00 wt. %, base carbon content are 0.10 wt. % (blue curve) and 0.20 wt. % (red curve).

required minimum surface hardness (for gears, this is 55 HRC or 58 HRC, depending on the grade) and lead to failure of the part. Therefore, it is desirable to design a variable carburizing scenario such that the case carbon (hardness) profile is flat and allows reasonable grinding stock removal.

Carburizing Parameter Selection

Equations 3 and 7 demonstrate the relationship between concentration (carbon potential and base carbon content), position and time at a given temperature. Once the other carburizing conditions are set, the related cycle time can be calculated. But before doing that, let's analyze the role of carburizing parameters.

Temperature. Carburizing should be processed in the austenitic region. For plain carbon steels this should be above the A_{c3} line on the iron-carbon phase diagram. This temperature changes with different carbon and alloy element concentration. Equation 6 shows that temperature has a most profound (exponential) influence on diffusion coefficient and rate, as it increases the mass transfer — or more precisely, the mobility of atoms. The higher the temperature, the faster the carburizing/diffusion occurs. From a processing point of view, it is always better to set a high carburizing temperature. However, due to the constraint of the carburizing furnace (cost, maintenance, and operation life) and the grain growth that results in unexpected mechanical properties of the part, the carburizing temperature cannot be set too high; typically, it should not be over 1,800° F.

On the other hand, the temperature of the part is usually lowered after carburizing to reduce the thermal stress and corresponding distortion during quench. For most industry applications this temperature is about 1,500° F – 1,550° F. Keep in mind that at this lower temperature, carbon atoms continue diffusing into the part.

Carbon potential. Equations 3 and 7 revealed that carbon potential C_s also facilitates carburizing. We should therefore set carbon potential as high as possible at a certain temperature. This stage is called the "boost phase." Alternatively, however, carbon potential is limited by the maximum dissolved carbon content in austenite (A_{cm} line on iron-carbon phase diagram) at the corresponding temperature — otherwise the carbide network will appear. For most carburizing steels this is roughly 0.90 wt. percent – 1.40 wt. percent at 1,600° F – 1,800° F. For example, at 1,725° F the carbon potential limit is about 1.20 wt. percent for SAE 9310 steel.

As mentioned previously, in order to allow sufficient grinding removal, it is desirable to set a different (lower) carbon potential to obtain a flat carbon profile in the case; this is called the "diffusion phase." It is typically around 0.20 wt. percent lower than that at the boost phase.

When these two phases are finished, the temperature is lowered to slightly above A_{c3} temperature, such as 1,500° F – 1,550° F, to reduce quench stress and distortion. Carbon potential is targeted to 0.80 wt. percent so that 0.65 wt. percent – 0.95 wt. percent surface carbon content can be reached, as required by AGMA standard.

Suppose the boost and diffusion times are t_b and t_d, time at 1,500° F – 1,550° F before quench is t_q, then the total carburizing time $t = t_b + t_d + t_q$. Experience shows that when t_b is $(3-5)\ t_d$ — it is easy to obtain a flatter carbon/hardness distribution in the case. Figure 2 exhibits carbon distribution within the case for a single potential carburizing and an ideal carbon profile that offers adequate case depth for grinding. Obviously, the carbon profile will be in between these two curves by setting $t_b = (3-5)\ t_d$.

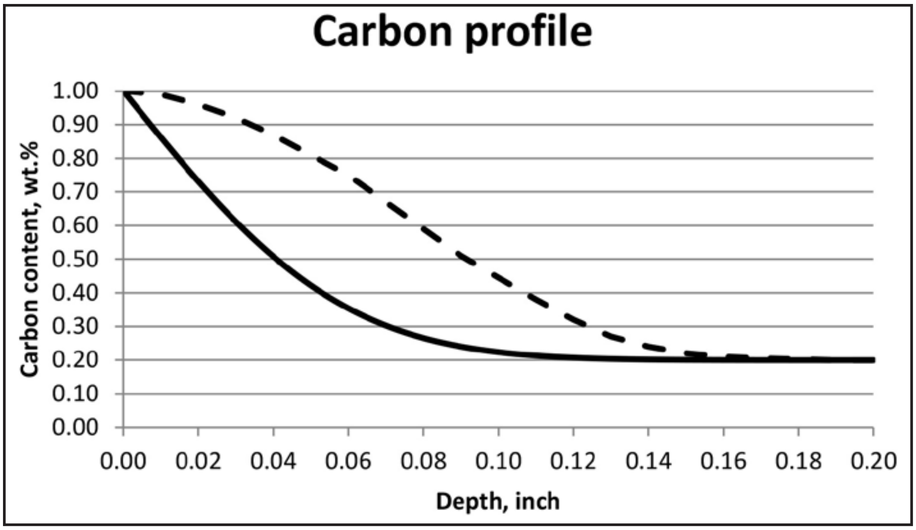

Figure 2 Ideal (dashed curve) vs. normal (solid curve) carbon profile in the carburized case for 0.20 wt. % base carbon steel at 1,725° F for 10 hours; normal carbon profile is obtained by single carbon potential setting 1.00 wt. %, while ideal carbon profile is obtained by a different carbon potential (boost and diffusion) setting.

Carbon Content at 50 HRC

Traditionally, carbon content at 50 HRC is considered as 0.40 wt. percent for carbon and low-alloy steels. This content reduces with the increase of alloying elements such as Mn, Cr, Ni, Mo, etc. Reference 7 mentioned that for medium-alloy and high-alloy steels, this is approximately 0.30 wt. percent. Reference 8 used 0.35 wt. percent for computer simulation of effective case depth.

In order to determine the carbon content at 50 HRC, a wedge-shaped carbon gradient bar is introduced to accompany the carburizing part. Carbon concentration at the surface and at different depths is measured, per ASTM E415-14 (standard test method for analysis of carbon and low-alloy steel by spark atomic emission spectrometry). Experimental statistics of the average carbon content at 50 HRC for different steels is listed in Table 1; this is in agreement with other literature.

Table 1 Carbon content at 50 HRC for different carburizing steels

Steel	SAE 9310	18CrNiMo7-6	SAE 4320
Carbon content (wt.%) at 50 HRC	0.33	0.34	0.35

Calculation and Discussion

Setting different carbon potentials in boost and diffusion phases offers good grind stock allowance. However, there is no analytical solution for

Equation 2, as boundary conditions are not simple. Further carbon diffusion at a lower temperature — such as 1,500° F – 1,550° F — complicates things. Therefore from a mathematical point of view, no functional expression similar to Equations 3 or 7 is available, making it hard to predict the effective case depth.

However, if we simplify the model and ignore some effects, we can still use Equation 5 to determine or predict the required effective case depth under designated carburizing conditions. To do this, the following assumptions are made:

- The effect of alloying elements on carbon diffusion is included in reduced carbon content at 50 HRC; no other effect of alloying elements is considered.
- Other metallurgical features, such as grain size, hardenability, etc., have no effect on carbon diffusion.
- Carbon potential is considered as constant at all carburizing stages — including at 1,500° F – 1,550° F before quench.
- Diffusion during temperature or carbon potential transition is ignored.

In this case the whole carburizing cycle can be considered as a single carbon diffusion process at the boost temperature — except that diffusion time at 1,500° F – 1,550° F should be converted to an equivalent time at boost stage since the diffusion coefficient is smaller than that at boost temperature. This can be done by multiplying a factor a, where $a = D_q/D_b$ (ratio of diffusion coefficient at temperature before quench and at boost stage). This way, Equation 5 is still valid for prediction of the cycle time. Hence, the total carburizing time would be:

$$t = tb + t_d + at_q$$

Where a is the diffusion coefficient ratio mentioned above. Based on Equation 6, the calculated a is illustrated in Figure 3; details are listed in Table 2.

For a specific base carbon content steel (C_0), preset carbon potential (C_s), and carburizing temperature (T) with carbon content at 50 HRC known, we can derive the relationship between designated effective case depth x and cycle time t from Equation 3 and get carburizing factor k for Equation 5. Results for base carbon content of 0.10 wt. percent at different carbon potential and temperature are shown (Fig. 4), revealing that k increases with temperature and carbon potential, as

Table 2 Ratio of diffusion coefficient between temperatures of 1,500° F – 1,550° F and boost stage

Boost Temperature, °F	$a = \frac{D_{1500°F}}{D_b}$	$a = \frac{D_{1525°F}}{D_b}$	$a = \frac{D_{1550°F}}{D_b}$
1600	0.477	0.578	0.697
1650	0.339	0.410	0.495
1700	0.244	0.296	0.357
1725	0.208	0.252	0.304
1750	0.179	0.216	0.261
1800	0.132	0.160	0.193

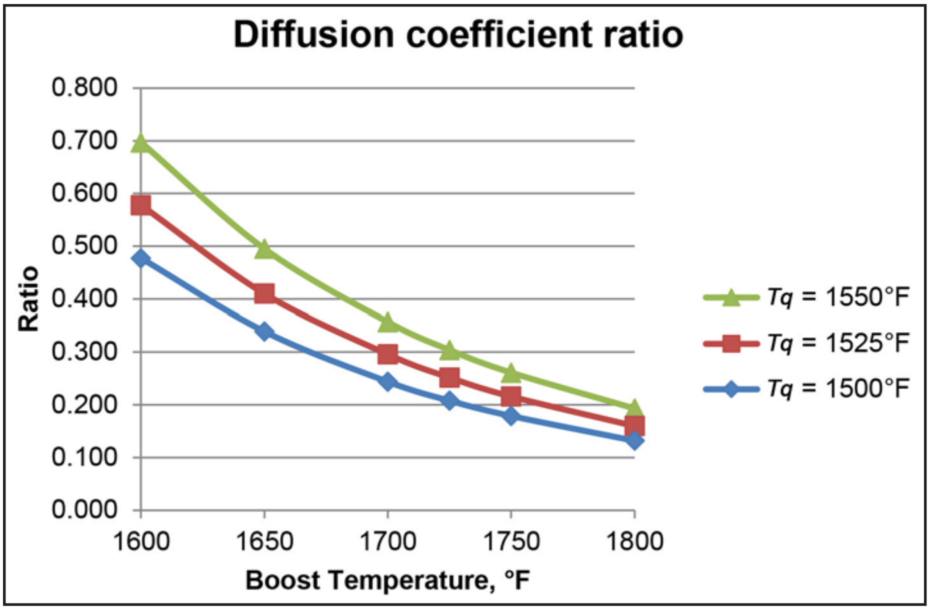

Figure 3 Calculated diffusion coefficient ratio $a = D_q/D_b$, where D_q and D_b are carbon diffusion coefficients at 1,500° F – 1,550° F, and at boost stage; T_q refers to "temperature before quenching."

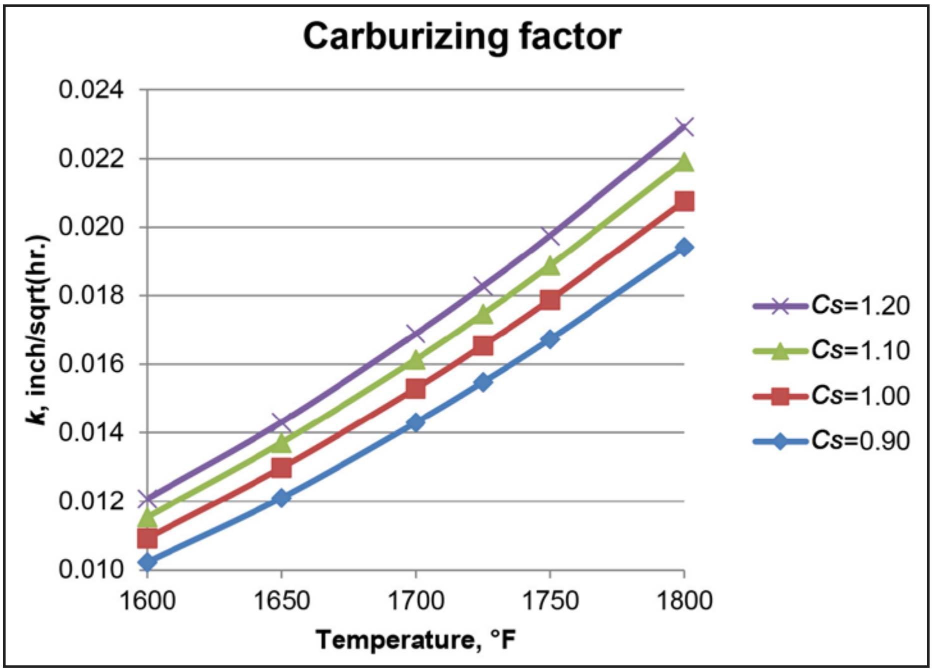

Figure 4 Calculated carburizing factor k of base carbon content 0.10 wt. % for different carbon potential and carburizing temperature.

analyzed before.

The effect of carbon potential on *k* for different base carbon content steel with a carburizing temperature of 1,725° F is shown (Fig. 5) — again showing that *k* increases with carbon potential.

Carburizing Factor k

To check the validity and accuracy of this method, let's compare some calculated results with manufacturing data.

Figure 6 is a carburizing process schematic for SAE 9310 steel in an integral quench furnace (IQF). In light of the rules mentioned in this paper, time allocation for boost and diffusion stages (i.e., carbon potential of 1.15 wt. percent and 0.95 wt. percent) is about 3:1 to 5:1. For a certain period of time, different gears/pinions with various effective case depths were carburized, and the results are shown (Fig. 7).

The tested effective case depth for different parts (cycle times) (Fig. 7) is in good agreement with the method introduced in this paper. Most of the data points are distributed along the parabolic line. Under this processing condition the calculated carburizing factor is 0.0179 inch/hr. (Fig. 5). The experimental value of *k* through statistical regression is 0.0181 inch/hr.; relative error is 1.1 percent.

Another carburizing scenario was applied to the same furnace, steel, and temperature. When the carbon potential setting is 1.00 wt. percent and 0.90 wt. percent at 1,725° F, the *k* value is 0.0166 inch/hr. by calculation (Fig. 5), while tested *k* is 0.0164 inch/hr; relative error is 1.2 percent.

Other steels, such as SAE 4320 and 17CrNiMo6/18CrNiMo7-6, were also carburized in different furnaces and settings with distinctly effective case depth ranges (about 0.025 to 0.300 inch). Historical data shows that we can consistently reach the target case depth with less than ± 5 percent relative error and flat hardness profiles (depth reaching 58 HRC from surface is at least 40 percent of the effective case depth). This indicates that the guidelines and calculations of this method are both feasible and practical. Furthermore — parts made of the same type of steel, but with slightly different yet effective case depth ranges, or parts made of different steels with distinctly effective case depths — can be carburized together, as we can precisely predict the case depth by setting the cycle time. This offers a flexible carburizing program and cost-saving benefit for manufacturing.

It should be noted that the error between measured and calculated effective case depth comes from several factors, such as the temperature, carbon potential, etc. It can be imagined that if temperature cannot be well controlled, the final case depth will deviate from the predicted target. The same is true for carbon potential control. This error normally increases with cycle time (e.g., 100 hours or longer). Another factor is the carbon content of the base steel. In this paper we simply use the nominal carbon for calculation.

For example, for SAE 9310, C0 is set as 0.10 wt. percent; as a matter of fact, it can be anywhere from 0.07 wt. percent – 0.13 wt. percent. If the real carbon content is used for each carburizing load (though this is not convenient), the prediction will be more accurate.

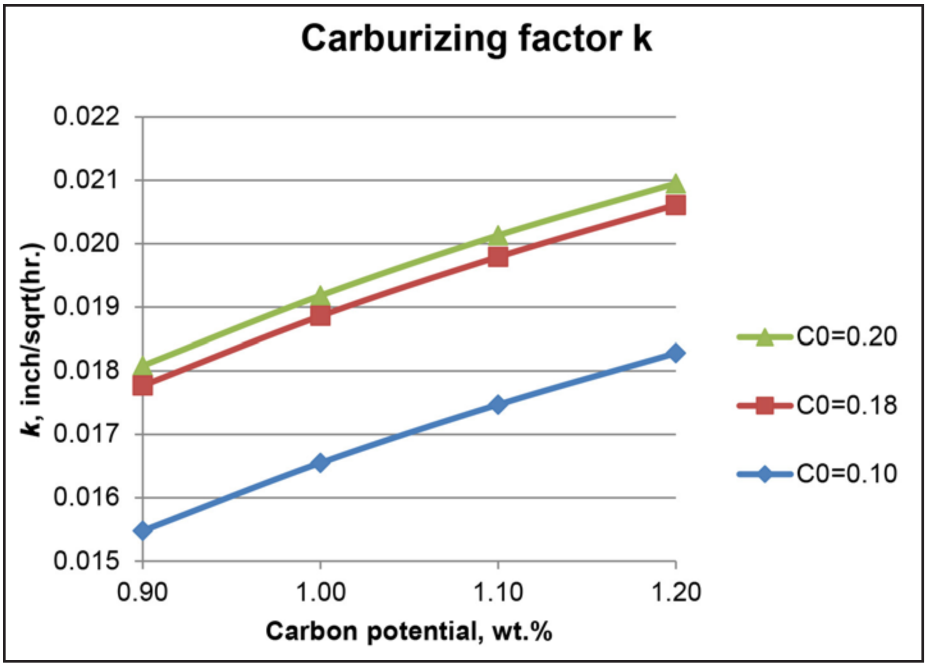

Figure 5 Effect of carbon potential (C_s) on carburizing factor *k* for different base carbon contents at 1,725° F. These different base carbon contents can be applied to SAE 9310, 18CrNiMo7-6 and SAE 4320 steels.

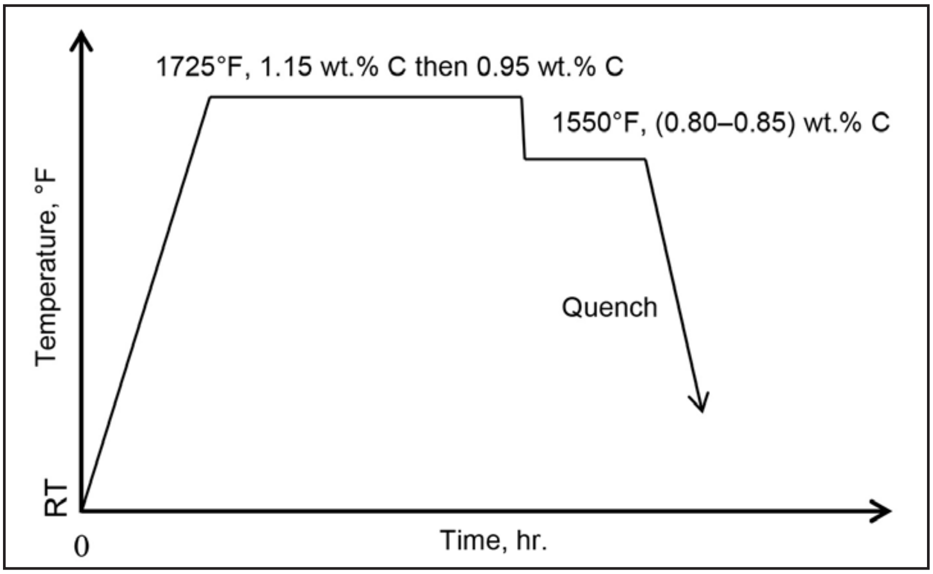

Figure 6 Carburizing process schematic of SAE 9310 steel (Note: temper, sub-zero treatment and re-temper are not included). Carbon potential is built up after 1,725° F is reached, and carburizing time starts when carbon potential reaches 1.05 wt.%. Transition time for carbon potential and temperature changes before quench is ignored.

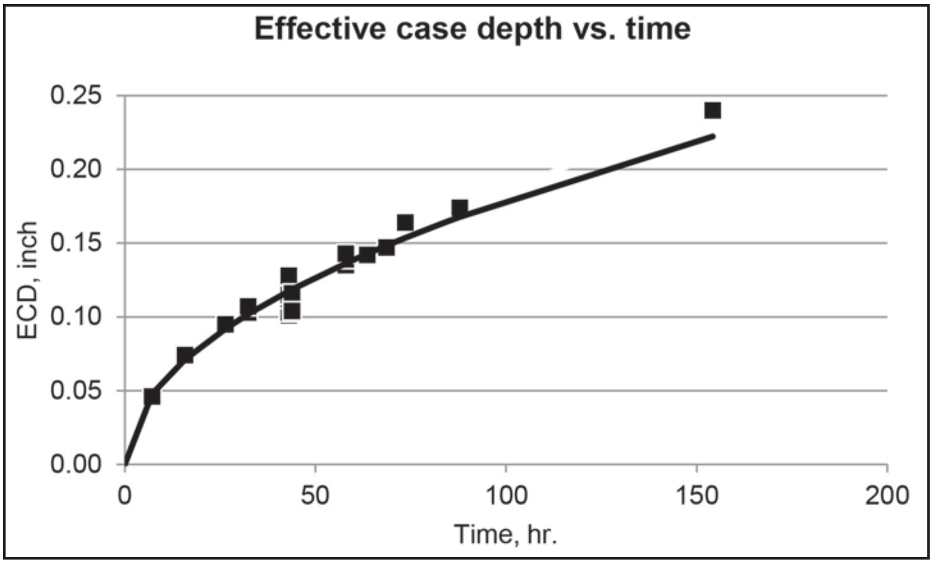

Figure 7 Effective case depth vs. carburizing time (per processing parameters, Fig. 6) for SAE 9310 steel parts. Curve is for ECD $= k\sqrt{t}$ where $k = 0.0179$ inch/$\sqrt{hr}$ (Fig. 5).

Nevertheless, experience shows that nominal carbon content can still yield satisfactory results most of the time.

Summary

This paper introduces a simple and practical method to establish the relationship between effective case depth and carburizing parameters by adopting diffusion theory and some practical assumptions. This methodology can quickly determine cycle time based on carburizing temperature, carbon potential setting, and the carbon content of the part without computer simulation. Results given by this method were checked with manufacturing data and were found to correlate well. Optimum carburizing conditions depending on the equipment were discussed as well. The carburizing processing guideline included in this method also provided an improved case profile for the final grinding operation.

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Practical Gear Characteristics: Process Characteristics of the Most Popular Cutting Methods

Dr. Hermann J. Stadtfeld

Bevel Gear Technology

Chapter 5

The geometry of bevel gears depends more than for cylindrical gears or other machine elements on the design of the tool. A face cutter with radially oriented blades will produce spiral bevel and hypoid gears with a circular lead function in a face milling process. If the blades of the face cutter are oriented with a radius and an offset in blade groups, representing a number of spirals equal to the number of blade groups, then this cutter is designed to produce an epicyclic lead function in a continuous face hobbing process. If the blades are protruding radially out on a peripheral cutter head, then this cutter can manufacture straight bevel gears or even face gears. The same, or similar peripheral cutter heads can be used to manufacture cylindrical gears in a Power Skiving process. In this case the blade front face is rotated from its tangential orientation such that it points in the axial cutter direction.

This chapter will explain the different bevel gear machining processes sorted by the different cutter head designs and the subsequently different flank geometries produced with them. The chapter also explains the different process kinematics, using simple explanations rather than formulas. In summary, the following fundamentally different bevel gear cutting methods i.e. bevel gear geometries exist:

Face Milling Generated	pinion and gear are generated
Face Milling Formate (form-generated	pinion generated, gear plunge cut
Face Hobbing Generated	pinion and gear generated
Face Hobbing Formate (form-generated	pinion generated, gear plunge cut
Straight Bevel Gears Generated & Formate	pinion generated, gear gen. or form-gen
Face Gears	face gear always generated

This chapter concludes with the table which shows the geometrical and kinematical placement of the different bevel gear cutting methods and the produced flank geometries.

— Hermann J. Stadtfeld

Plunging and Generating

The cutting process consists of either a roll only (only generating motion), a plunge only or a combination of plunging and rolling. The material removal and flank forming due to a pure generating motion is demonstrated in the simplified sketch in Figure 1 in four steps. In the start roll position (step 1), the cutter profile has not yet contacted the work. A rotation of the work around its axis (indicated by the rotation arrow) is coupled with a rotation of the cutter around the axis of the generating gear (indicated by the vertical arrow) and initiates a generating motion between the not-yet-existing tooth slot of the work and the cutter head (which symbolizes one tooth of the generating gear). The "forced" generating contact eventually results in the removal of material in the developing tooth slot (step 2). This is continued in step 3 until the cutter head (generating gear tooth) comes out of engagement with the work in step 4 (cutter is rolled out). The cutter moves now without any contact with the work—from the rolled out position back to the starting point (step 1). The work now rotates counterclockwise back to the rotational position of step 1 (plus one additional tooth spacing) in order to prepare for the cutting of the next slot.

The manufacture of a tooth slot by plunging is only possible for non-generated gears (Formate gears). Figure 2 provides a schematic explanation of pure plunging. Step 1 in Figure 2 shows the cutting blade in a position where it is not yet in contact. Step 2 shows the plunging move of the cutter head while the work gear is fixed in its position. Correct tooth form and tooth depth have been achieved in step 3. The cutter head withdraws now from the work gear until the blade clears sideways. After that, the work gear rotates about one pitch (arrow in step 1) and the plunge procedure is repeated in order to cut the next tooth slot.

It is also possible to begin the cutting of a generated pinion or ring gear with a plunging cycle in order to remove the majority of the chip volume at the beginning. The following step is a generating finishing cycle to create the correct flank form. This case, often applied in completing methods, consists of a combination of the movements shown in Figures 1 and 2.

Process Characteristics of the Most Popular Cutting Methods

Five-cut method. Five-cut is a single indexing method in which the tooth slots are cut in several steps.

- **Step one**: The ring gear tooth slots are roughed out with a cutter head that carries inside, outside, and sometimes bottom blades.
- **Step two**: The ring gear tooth slots are finished with a cutter head that carries inside and outside blades.
- **Step three**: The pinion tooth slots are roughed out with a cutter head that carries inside, outside, and sometimes bottom blades.
- **Step four**: The convex flanks of the pinion are finished with a cutter head

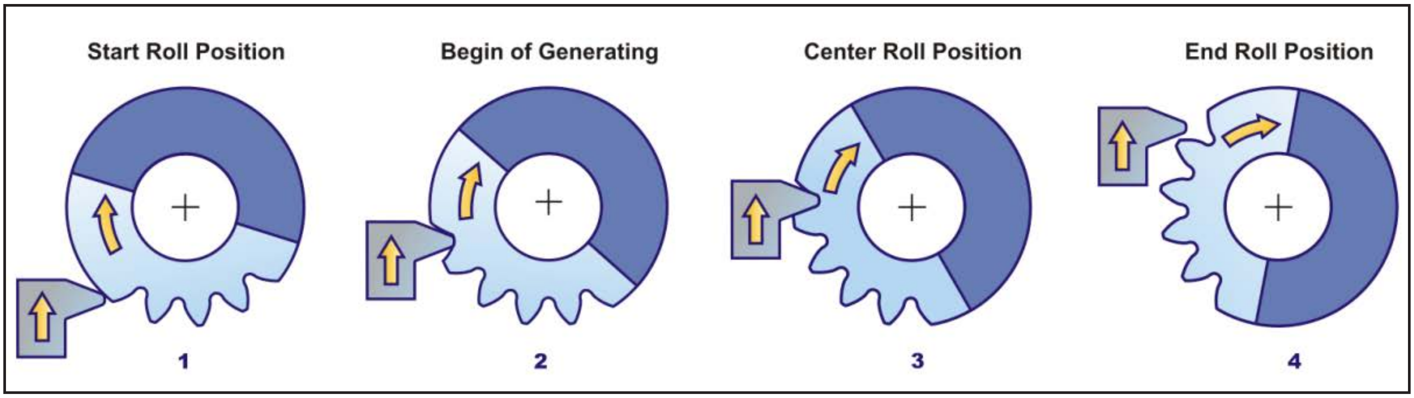

Figure 1 Cutting of a tooth slot by generating.

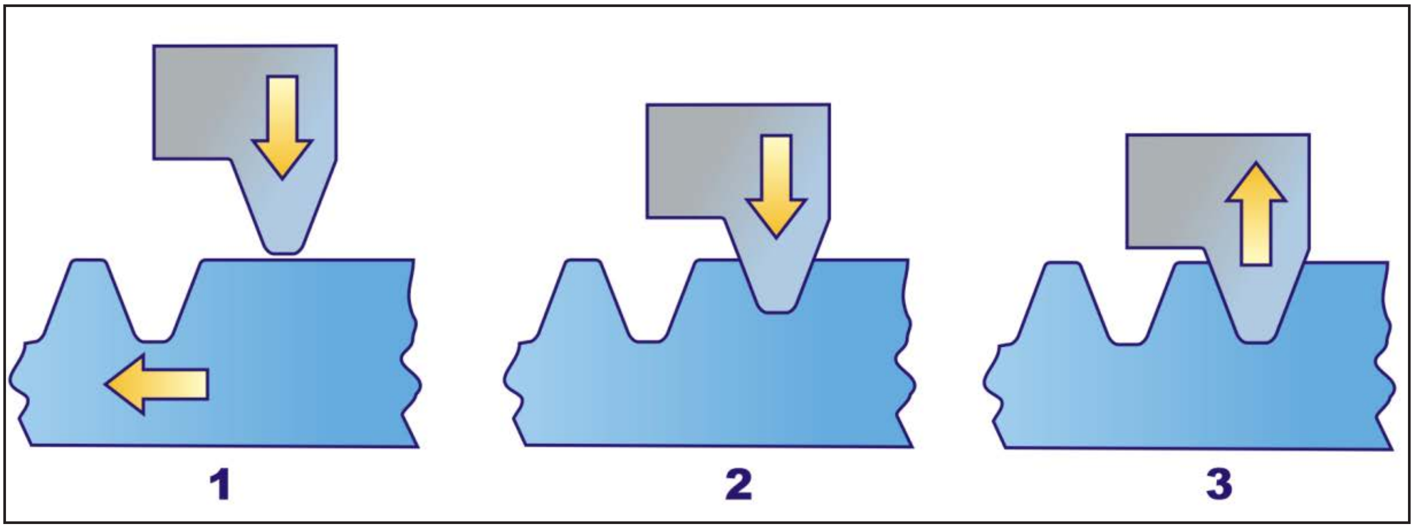

Figure 2 Manufacture of a tooth slot by plunging.

that carries only inside blades.

- **Step five**: The concave flanks for the pinion are finished with a cutter head that carries only outside blades.

The five cutting steps generally require five different machines, each of which performs one of the cutting steps. Parts have to be moved from one machine to the next, and the second and third cuts require a precise stock division in order to synchronize the 5-step slot cutting effort.

A typical cutter head used in five-cut is the Hardac cutter (Fig. 3, left). The blades have curved ground side relief surfaces (spiral relief) and are bolted to the circumference of the cutter body. Spiral relief ground blades are only ground on their front face for sharpening. This cutter head type is available for roughing and finishing of pinions and ring gears. A version with a circular blade stepping for the finish cutting of ring gears (Helixform method) is shown (Fig. 3, right). Similar cutter heads for the broaching of Formate ring gears in one cutter revolution (single-cycle method) are available under the name Cyclex; Cyclex cutters also feature stepped blades (analogous to a broach). Parallel shims and a variety of standard blade pressure angles make this kind of cutter head, with a minimum of required blade inventory, universally applicable (Ref. 1).

Due to the separate cutting of convex and concave pinion flanks, the highest possible number of freedoms exists for an independent optimization of coast and drive side. A process version with a generated pinion and a generated ring gear, and a version with a Formate ring gear and a generated pinion are available.

Length crowning is achieved with different cutter radii, while profile crowning — because of the standard blades (with mostly straight cutting edges) — is generated by modified machine settings.

Today, five-cut methods are outdated.

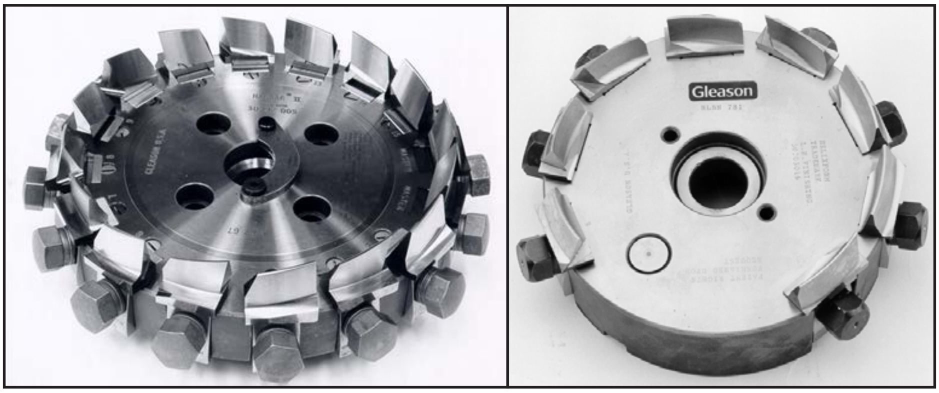

Figure 3 Hardac and Helixform cutter head.

All of them require wet cutting conditions with high volumes of cutting oil. They have been applied across all industries for the manufacturing of angular gear boxes. The five-cut methods were particularly well suited for the mass production of hypoid gears in the automotive and truck industry because the set-up changes of five machines between different jobs was not often required.

Single-indexing two-flank cutting method; face milling-RSR-completing; Pentac FM-completing. Roughing and finishing of both flanks in one slot is performed in one step (by generating, form-cutting or a combination) (Ref. 2). The cutter heads feature an alternate arrangement of inside and outside blades. The process parameters at the beginning of the chip removal cause roughing conditions, while towards the end, when the flank forming is performed, the process parameters change in order to establish finishing conditions.

With a Formate ring gear, the process parameter change from roughing to finishing is realized rather easily. With pure rolling of pinion tooth slots, it is, for example, required to start with a rough rolling from toe to heel in conventional cutting (with reduced slot depth), followed by a finish roll in full depth position in climb cutting. Another possibility is to plunge at the heel roll position (roughing), followed by a finish roll from heel to toe. Typical cutter heads as they are used in completing cutting are shown (Fig. 4).

The RSR cutter head (Fig. 4, left) is equipped with HSS stick blades that have a rectangular cross-section. The front face of the blades is pre-formed and coated. The pre-form provides a side rake angle of 20° on the entire usable length of the sticks. Only the side relief surfaces of cutting edge and clearance side are ground or re-sharpened. The individual control of the geometry of cutting edge and clearance edge (including the blade top width) allows the realization of a two-flank completing cutting. The Pentac cutter head (Fig. 4, right) uses stick blades with optimized, pentagon-shaped cross-section. Pentac blades are manufactured mostly from carbide and can be re-sharpened either on the two sides like the RSR blades, or on the sides and on the front face, which requires a re-coating after sharpening. In contrast to the five-cut process, length crowning in completing gears can be generated by tilting the cutter head with an appropriate blade angle compensation (*see also text chapters 2.6.2 and 2.7.3*). It is simple to produce any desired blade pressure angle, since the side relief surfaces are individually ground for every unique gear design. Profile crowning can be created simply by introducing curved cutting edges (*see also text chapter 2.6.3*). Because of the individual grinding of each set of blades, cutting edge modifications like curved blades and protuberance are accomplished without any additional complications or cost.

Single indexing completing methods replaced five-cut methods in those industries that use grinding as a hard finishing process (*see also text chapter 9*). RSR cutters and similar stick blade cutters with rectangular blade cross-section are well suited for applications with HSS blades and are therefore often linked to wet cutting processes. The later development of the Pentac FM cutter head system has replaced the RSR cutter system almost entirely; 80 percent of today's bevel gear production is performed as a high-speed dry cutting process, where Pentac tools show particularly good suitability (*see also text chapter 7*).

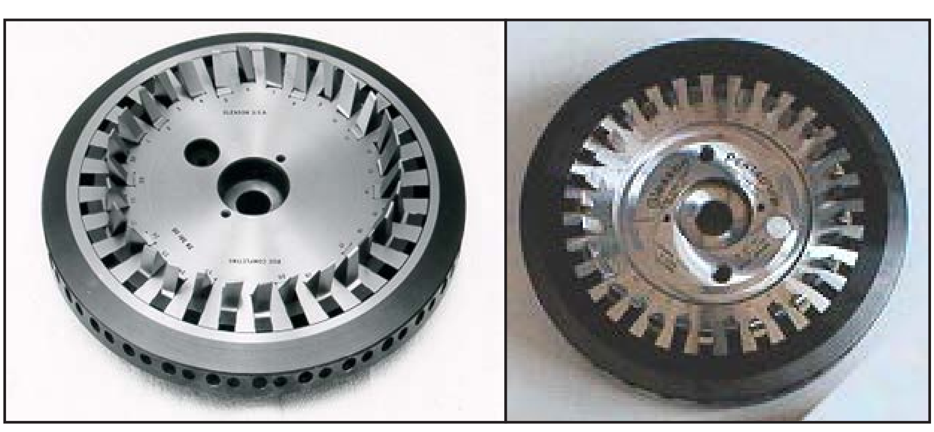

Figure 4 RSR and Pentac-FM cutter head.

Continuous two-flank cutting method; face hobbing-TRI-AC; Pentac-FH. For face hobbing methods, blades with curved ground relief surfaces have been replaced today by stick blades (Ref. 3). Stick blades helped to initiate a breakthrough for the face hobbing methods — especially for the manufacturing of axle drive units that are used in heavy trucks.

Roughing and finishing of both flanks are performed in face hobbing in one chucking (by rolling only; i.e. — plunging only with Formate gear members or a combination of plunging and rolling). The continuous cutting method is always based on a completing process kinematic (*see also text chapter 2.3*). The cutter heads consist of a number of blade groups — each of which generally has an outside blade first — which is then followed by an inside blade. The process parameters at the beginning of the chip removal are defined for a roughing operation where, towards the end of the machining operation, when the final flank form is created, the process parameter changes to finish cutting. This is easily done if plunging a Formate ring gear. With generated pinions the roughing portion begins with plunging at the center roll position, followed by a rough rolling (conventional cutting direction) from center to heel with reduced tooth depth, followed by a finish roll at full depth from heel to toe (climb cutting) (Ref. 4).

Typical cutter heads used in continuous completing methods are shown (Fig. 5). Face hobbing cutters generate flank lines that are epicycloids and have blade groups with one outside and one inside blade in an orientation showing the same distance between the outside blades to both the preceding and following inside blades (equal blade spacing). The face hobbing process kinematic — using equally spaced blades — generates an equal split of the pitch spacing angle into the tooth thickness taper and the slot width taper. The TRI-AC cutter head (Fig. 5, left) uses stick blades with rectangular shank cross-sections. The front surface of the blades is pre-formed and coated. There is a side rake angle of 12° on the re-sharpening length of the blade shank. The cutting edge and clearance side relief surfaces are the only sides ground or re-sharpened. The Pentac-FH cutter head (Fig. 5, right) uses stick blades with an optimized pentagon-shaped cross-section. As mentioned, Pentac blades are generally manufactured from carbide and can be re-sharpened either on the sides like RSR blades or on the sides and on the front face (three-face grinding). If three-face grinding, the blades must be completely re-coated after each sharpening; this generates higher cost but also leads to a significant increase in tool life.

Length crowning in face hobbing gears can be generated in similar fashion to the face milling completing method by tilting the cutter head with an appropriate blade angle compensation (*see also text chapters 2.6.2 and 2.7.3*). It is simple to realize any desired blade pressure angle since the side relief surfaces are individually ground for each different gear design. Profile crowning can be created by introducing curved cutting edges (*see also text chapter 2.6.3*). Because each set of blades can be individually ground, cutting edge modifications like curved blades and protuberance can be accomplished without complications or added cost.

Gearsets manufactured by a continuous cutting method can only be hard finished by lapping or skiving because of their epicyclical flank lines. This is the reason why, even today, no ground face hobbed bevel gearsets exist. Face hobbing methods replaced the five-cut methods in industries that continue to use lapping as their final flank surface finishing process (*see also text chapter 9*). TRI-AC and similar stick blade cutter systems with rectangular blade cross-section are well suited for the application of HSS blades, and therefore are bound to wet cutting processes that use cutting oils. The successive development of the Pentac FH cutter head system has replaced the TRI-AC cutter system almost entirely because 80 percent of today's bevel gear production is performed as a high-speed dry cutting process, where Pentac tools show particularly good suitability (*see also text chapter 7*).

Figure 5 **TRI-AC and Pentac-FH cutter head.**

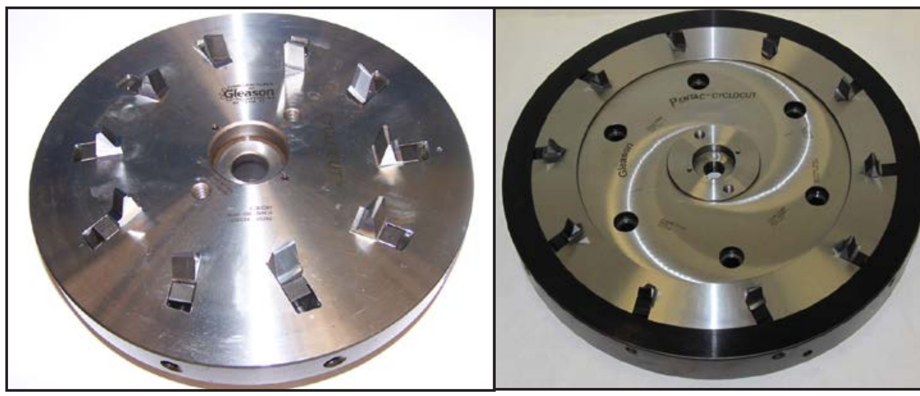

Figure 6 **Cyclocut and Cyclocut Pentac cutter head.**

The Cyclocut method. Cyclocut is a continuous cutting method similar to the one discussed in the previous section. What is different in Cyclocut is the low number of blade groups (generally five blade groups) and the unique generation and distribution of length crowning between pinion and gear.

In the Cyclocut process, roughing and finishing of both flanks is performed in one chucking (by rolling only). Cyclocut is based on a continuous kinematic and is always a completing method (*see also text chapter 2.3*). The cutter head consists of a number of blade groups, each of which generally have an outside blade first, followed by an inside blade. The process parameters at the beginning of the chip removal are chosen for a roughing operation. Towards the end of the machining operation, when the final flank form is created, the process parameters change to finish cutting. Cyclocut is always a generating method, where the roughing portion begins with a plunge at the center roll position, followed by a rough rolling (conventional cutting direction) from center to heel with reduced tooth depth, followed by a finish roll at full depth from heel to toe in climb cutting (*analog to regular face hobbing explained in text section 5.3.3*) (Ref. 5).

Typical cutter heads used in the Cyclocut method are shown (Fig. 6). Face hobbing cutters generate flank lines that are epicycloids and have blade groups with one outside and one inside blade in an orientation showing the same distance between the outside blades to the preceding, and the following inside blades (equal blade spacing). The cutter head in (*text Fig. 5.6, left*) is a sub-form of the TRI-AC cutter head that also uses stick blades with a rectangular shank cross-section. The front surface of the blades is pre-formed and coated. Formed is a side rake angle of 12° on the re-sharpening length of the blade shank. Only the side relief surfaces of cutting edge and clearance side are ground or re-sharpened. The Cyclocut-Pentac cutter head, (Fig. 6, right) uses stick blades with an optimized, pentagon-shaped cross-section. The carbide Pentac blades can be re-sharpened — either on the sides like TRI-AC blades, or on the sides and front face (three-face grinding).

The length crowning in Cyclocut is split between pinion and gear and generated by tilting the cutter head with the appropriate blade angle compensation (*see also text chapters 2.6.2 and 2.7.3*). Any desired blade pressure angle can be easily realized since the side relief surfaces are individually ground for every

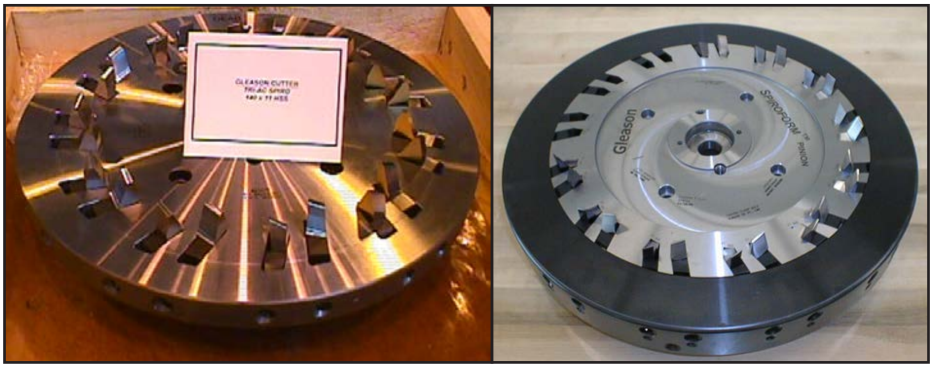

Figure 7 Spiroform ring gear cutter head (left), and Spiroform-Pentac pinion cutter head (right).

different gear design. The desired profile crowning is also split between pinion and gear and can be created simply by introducing curved cutting edges (*see also text chapter 2.6.3*). With the individual grinding of each set of blades, cutting edge modifications like curved blades and protuberance can be realized without complication or added cost.

Cyclocut bevel gearsets are hard finished after heat treatment by skiving. Soft and hard machining is therefore possible with the same cutter heads; only the blades have to be exchanged between the soft and hard manufacturing steps. Skiving is performed with three-face ground and all around coated carbide blades which require a highly negative side rake angle. The low number of required stick blades for the manufacture of a certain gear design, as well as the fact that the same machine and cutter heads can be used for soft and hard machining, makes Cyclocut the ideal method for the manufacture of a high variety of different bevel gear designs with very small batch sizes. Cyclocut is also well suited for large bevel gearsets with ring gear diameters up to 1.5m. Simple basic settings for the cutting machine summaries — together with the easy building and trueing of Cyclocut cutter heads and even split of the crowning between pinion and gear — make this bevel gear type easy to handle — even for bevel gearsets of gigantic dimensions.

The Spiroform method. Spiroform is a face hobbing method that duplicates the flank geometries of the older Oerlikon Spiroflex-Spirac methods, and like the Oerlikon methods, features a special tooth thickness and slot width taper, which alternates between pinion and gear. Because of the tooth proportions, it is possible to generate pinions with a low number of teeth and without a high potential for crossover between the inside and outside blades, thus avoiding mutilations in the pinion toe region.

In the Spiroform process, roughing and finishing of both flanks are performed in one chucking (by rolling only, plunging only in case of Formate gear members or a combination of plunging and rolling). Spiroform is based on a continuous kinematic that is always a completing method (*see also text chapter 2.3*). The cutter heads consist of a number of blade groups, each of which first has an outside blade that is followed by an inside blade. The process parameters at the beginning of the chip removal are chosen for a roughing operation; towards the end of the machining process, when the final flank form is created, the process parameters are changed to a finish operation (Ref. 6).

Typical cutter heads used in the Spiroform method are shown (Fig. 7). These cutter heads generate flank lines that are epicycloids and have blade groups — with one outside and one inside blade — in a spacing orientation that is specifically adjusted to achieve a small slot width taper and a high tooth thickness taper in the pinion member, and the opposite tapers in the gear member. The cutter head (Fig. 7, left) is a subform of the TRI-AC cutter head and also uses stick blades with a rectangular shank cross-section. The front surface of the blades is pre-formed and coated. Formed is a side rake angle of 12° on the re-sharpening length of the blade shank. Only the side relief surfaces of cutting edge and clearance side are ground or re-sharpened. The Spiroform-Pentac cutter head (Fig. 7, right) uses stick blades with an optimized, pentagon-shaped cross-section. The Pentac blades are usually manufactured from carbide and can be re-sharpened — either on the sides like TRI-AC blades or on the sides and on the front face (three-face grinding). The special blade arrangement requires, for each spiral angle direction, one pinion and one gear cutter, i.e. — four cutter heads for each cutter head size.

As previously mentioned, the modified slot width and tooth thickness taper are realized by unequal distances between the outside blade and preceding inside blade, and the inside blade in the next blade group. Spiroform cutter heads for ring gear cutting therefore have a large distance between the outside blade that enters the slot first and the following inside blade. The next outside blade that belongs to the next blade group follows with a small distance inside said blade from the previous blade group. A combined "large" and "small" distance amounts to one blade group spacing (360°/number of blade groups). The relationships of the blade spacing in a ring gear cutter head are visible (Fig. 7, left). The two blades with the large distance between them form one blade group. For the pinion cutting, the blade distance relationships between outside and inside blades have to be the opposite of the ring gear cutting. Only in this case is it guaranteed that the pinion teeth have a tooth thickness taper that fits perfectly with the slot width taper of the ring gear. The sample photograph (Fig. 7, right) shows a Spiroform pinion cutter. The blades with the smaller distance always belong to the same blade group.

Length crowning is created by cutter head tilt, with the blade angles adjusted accordingly — just as with TRI-AC. Any blade pressure angle can be realized because the side relief surfaces (that form the cutting edges) are individually ground for each gear design. Profile crowning is realized with cutting edges that have a circular curvature. Cutting edge modifications like curvature and protuberance can be realized rather easily due to individual grinding of each set of blades.

Bevel gearsets manufactured with the continuous indexing Spiroform method

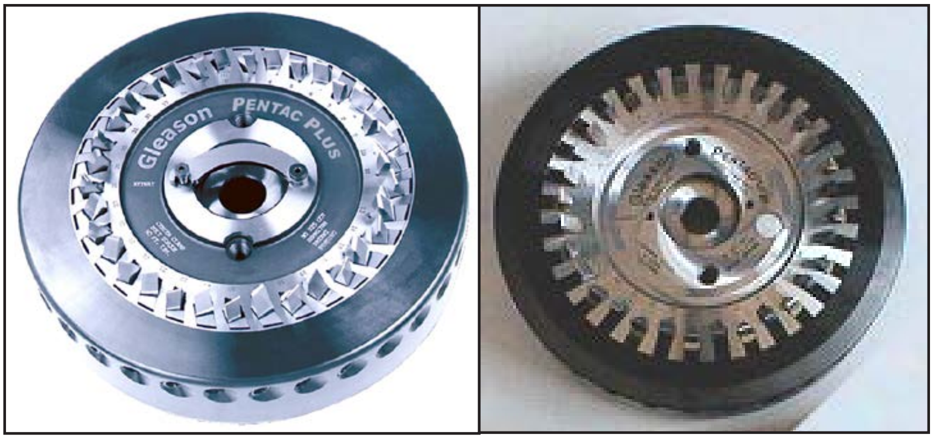

Figure 8 Pentac FH cutter head (left), and Pentac FM cutter head (right).

Figure 9 Fine-pitch Pentac face milling cutter head with large diameter.

have to be lapped or skived; grinding is not possible because of the epicyclic flank lines. The cutting methods Spiroflex-Spirac® and Spiroform have replaced the five-cut method for the manufacture of axle drive units for light, medium and heavy trucks.

The super reduction hypoid – SRH method. The SRH method is used for the manufacture of high-reduction bevel-worm gear drives from ratios 1×5 up to 1×100 (*see text chapter 4.7*). The lowest number of pinion teeth of a SRH pair is "one." SRH pinions are generated pinion worms, while the ring gears are cut and ground in Formate. The cutting process is always completing, where both versions — single indexing (face milling) as well as continuous indexing (face hobbing) — are available.

Typical cutter heads used for completing cutting of SRH gearsets are shown (Fig. 8). For the face hobbing version, Pentac FH cutter heads (Fig. 8, left) are used. For the face milling version, Pentac FM cutter heads (Fig. 8, right) are used. Standard, free-form Phoenix bevel gear cutting machines are well suited for cutting SRH gears (Ref. 7).

Length crowning of face hobbed SRH gearsets is created by cutter head tilt in the pinion cutting. With face milled SRH gearsets the naturally existing length crowning is reduced to the desired level by an evenly split, reversed cutter head tilt in both pinion and gear. Profile crowning is completed in both cases (face hobbing and face milling) with circularly curved cutting edges.

SRH gears with low requirements for noise emission and efficiency are preferably manufactured by face hobbing; the hard finishing operation is lapping in this case. The lapping time has to be limited to a few seconds (or eliminated) because of the very high number of pinion rotations during one ring gear rotation. SRH transmissions with a high requirement for quiet operation and efficiency have to be manufactured by face milling in order to allow for flank grinding after heat treatment. The major application of SRH gearsets is industrial gear boxes. With SRH it is possible to realize high ratios in a single stage reduction, enabling the design of cost-effective and efficient angular gear boxes.

The Hypoloid method. Hypoloid gears are slightly conical and look very similar to cylindrical gears (*see also text chapter 4.8*). The teeth wind under a certain spiral angle around a slightly conical base element. The face width of Hypoloid gears is significantly larger than that of comparable bevel gears. Small cutter radii lead to a borderline mesh condition in the toe region since the spiral angle increases from heel to toe continuously. Thus practical cutter diameters are about twice as large as the cutter diameters used for equal size bevel pinions. This led to the design of special, large cutter heads using fine pitch blades.

The driving pinion of the Hypoloid pair is generated while the driven gear is machined in Formate. Hypoloid gears are manufactured in single indexing completing since grinding is the only recommended hard finishing method. The gears are manufactured simply by plunging. Because of the large "rollout angle" (Fig. 1), the pinions are plunged at the toe (roughing) and then finished by rolling to the heel. A typical cutter head for the soft cutting of Hypoloid gears is shown (Fig. 9). For cutting and grinding

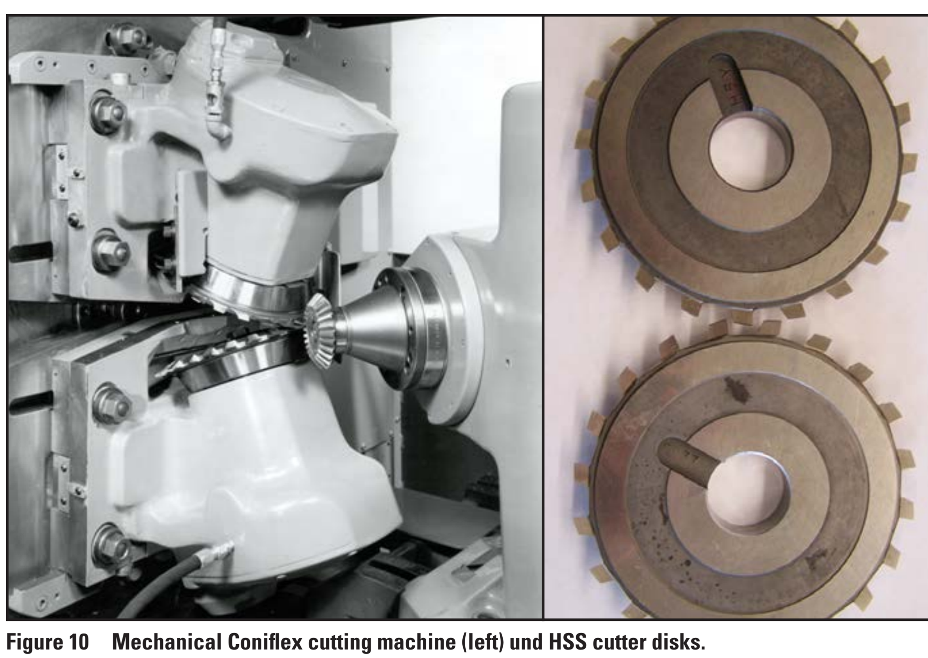

Figure 10 Mechanical Coniflex cutting machine (left) und HSS cutter disks.

machines, standard Phoenix free-form machines are utilized (Ref. 8).

The desired length crowning is created by cutter head tilt and re-adjusted blade angles. Profile crowning is realized with circular curved cutting edges. Hypoloid gearing is applied in transfer cases of all-wheel-driven passenger cars and SUVs. All of the existing applications are ground. The major advantage of Hypoloids vs. Beveloids is their very forgiving displacement behavior under high load in aluminum gearbox housings.

The Coniflex method. Coniflex is a single-indexing method used for the manufacture of straight bevel gears. The classical method uses two interlocking disk cutters from solid HSS on a special machine that applies, in most cases, a combined plunge and roll cycle.

A typical Coniflex cutting machine (No. 104) that features a cradle with two cutter spindle units is shown (Fig. 10, left). The machines are difficult to set up, and perform pre-determined cycles that are controlled with cams. Figure 10 (right) shows a pair of interlocking HSS disks with diameters of 4.25inches. These cutters are mounted in the machine under an angle that relates to the pressure angle of the part and includes certain corrections (Ref. 9).

Today's more modern method uses peripheral cutters with carbide Pentac stick blades that are applied on the same standard Phoenix machines used for spiral bevel gear cutting (*see text chapter 4.2*). The high-speed power cutting is either performed as a pure rolling process or as a combination of plunging and rolling. Figure 11 (left) shows a view of the work area of a Phoenix free-form machine with a Coniflex carbide cutter. To the right is shown the top view of a peripheral Coniflex Plus cutter head with carbide stick blades.

The desired length crowning is created by using a cutter head tilt and cutting edges that describe a cone element while the cutter rotates. For the generation of profile crowning, a machine root angle modification, or a second order ratio of roll modification, is applied. The modified ratio of roll (modified roll) can be easily realized on free-form machines and is well suited to make profile crowning corrections during the practical development of a gearset.

Coniflex gears are applied as differential bevel gears in trucks, construction equipment, rail road transmissions and marine applications. They are also used as axle drives in farm tractors, construction machines, auxiliary transmissions for agriculture as well as industrial applications and power tools. Straight bevel gears usually do not undergo any hard finishing operations after the heat treatment process.

The Coniface method. Face gears can be manufactured on the same standard Phoenix free-form machines that are used for the manufacture of spiral bevel gears. The cutting edges of the stick blades in the peripheral cutter head (Fig. 12**,** right) have an involute shape that represents one side of the generating tooth. A view into the work area of a Phoenix free-form machine during the cutting of the face gear is shown (Fig. 12, left). Face gears are manufactured similar to Coniflex straight bevel gears by rolling or a combination of plunging and rolling.

The machine motions required to form face gear teeth are quite different from the motions used in the Coniflex method. The cutting tools are Coniflex Plus peripheral stick blade cutters, as the one shown (Fig. 12, left). Only the form of the cutting edges is not like, in the case of Coniflex, straight lines, but involutes that represent a flank of the mating pinion (Ref. 11).

The desired length crowning is achieved by cutter head tilt and cutting edges that generate an internal cone element while the cutter rotates. Profile crowning is realized by circular modifications of the involute blade profile. Machine freedoms like modified roll and a second order tilt-swivel motion can be applied during face gear development. However, it must be realized that all modifications that are known from spiral bevel and straight bevel gears will deliver exotic Ease-Off shapes that are difficult to convert to a decent looking Ease-Off (*see also text chapter 18.4.5 — Not optimized "butterfly Ease-Off"*). A special correction software has been developed and is offered as an option with the Gleason *GAGE* software.

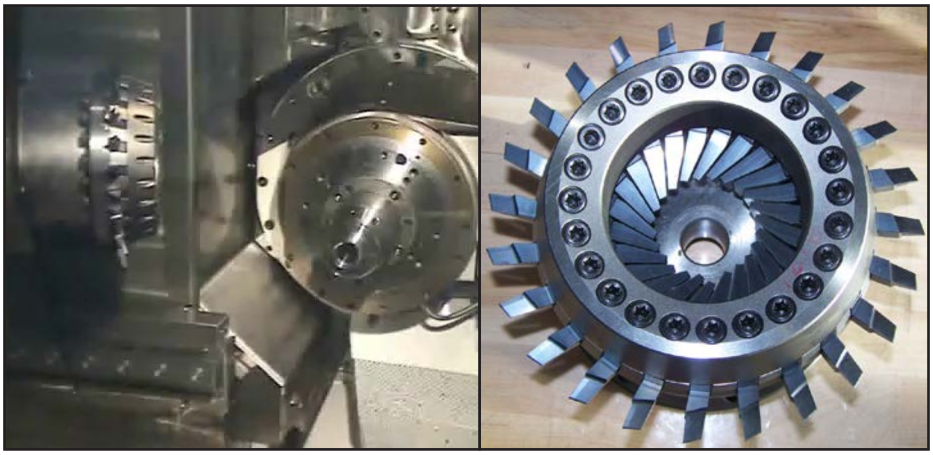

Figure 11 Coniflex Plus cutting (left), Coniflex Plus cutter head (right).

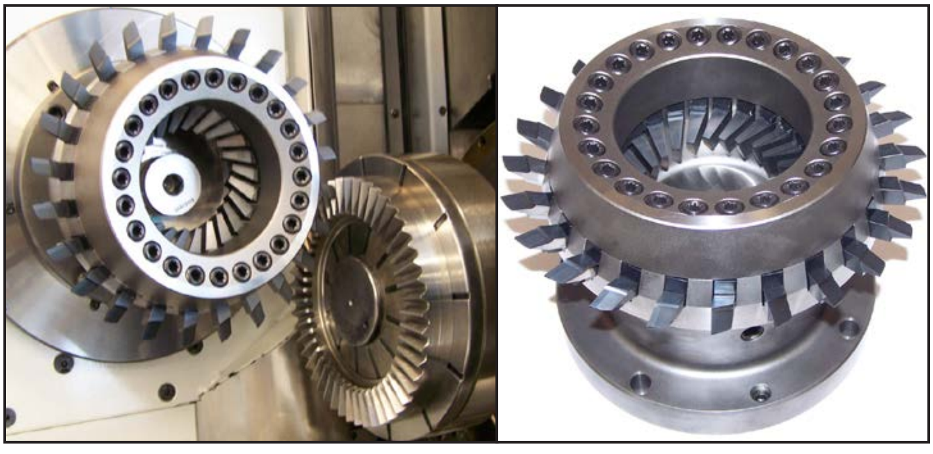

Figure 12 Coniface cutting (left), carbide stick blade cutter (right).

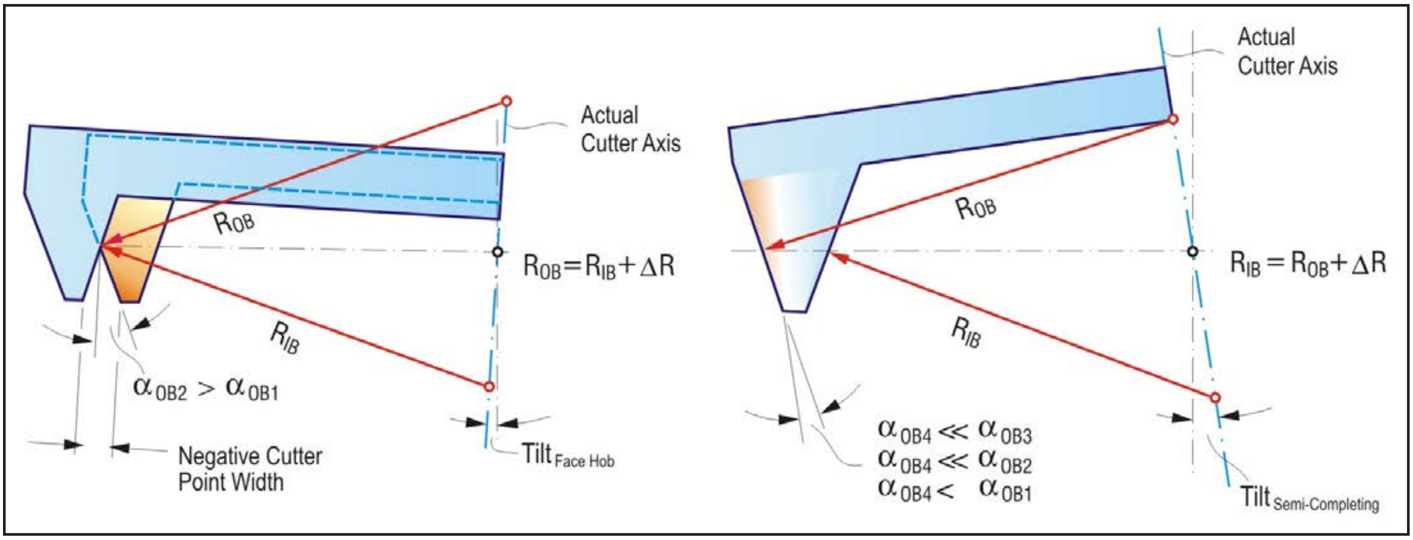

Figure 13 Continuous working cutter head (left) and semi-completing grinding wheel profile (right).

Table 1 Geometrical and kinematical classification of Gleason bevel gear cutting methods.

Method	Indexing Kinematic	Flank Line	Tooth Depth	Number of Cuts	Gear Formate	Length Crowning	Profile Crowning	Inventor
Five-Cut	single indexing	circular Arc	tapered	5	possible	cutter radii	machine	Böttcher, Wildhaber
Completing	single indexing	circular Arc	tapered	2	possible	cutter tilt	in blades	Wildhaber, Baxter
TRI-AC	continuous	epicycloid	parallel	2	possible	cutter tilt	in blades	Krenzer
Cyclocut	continuous	epicycloid	parallel	2	N/A	cutter tilt	in blades	Stadtfeld
Spiroform	continuous	epicycloid	parallel	2	possible	cutter tilt	in blades	Stadtfeld
HRH SRH	single/continuous	circlular arc/ epicycloid	parallel/ tapered	2	always	cutter tilt	in blades	Baxter, Stadtfeld
Hypoloid	single indexing	circlular arc	tapered	2	always	cutter tilt	in blades	Stadtfeld
Coniflex	single indexing	straight	tapered	4	possible	in the tool	machine	Carlsen
Coniflex Plus	single indexing	straight	tapered	4	possible	in the tool	machine	Carlsen, Stadtfeld
Coniface	single indexing	?	parallel	4	N/A	in the tool	in blades	Stadtfeld
Semi-Completing	single indexing	circlular arc	parallel	4	possible	cutter tilt	in blades	Brandner

Face gears are applied in special transmissions, e.g. — for actuation in aircraft, in transfer cases of four-wheel-drive vehicles, in special industrial applications and power tools. Depending on the field of application, face gears are either ground after heat treatment or used without any hard finishing.

The semi-completing method. Semi-completing is a single indexing method that machines both flanks of one slot in one chucking, yet applies two passes each with different machine basic settings. In case of the classical five-cut method (and continuous cutting methods), the problem is the fact that the radius of curvature of the inside blades must be larger than that of the outside radius. The curvature radius is the length of a line that is perpendicular to the blade enveloping cone and connects the blade reference point and the tool axis. This is shown (Fig. 13, left) for a continuous working Cyclocut cutter head (see R_{OB} and R_{IB}). The inside and outside cutting edges of a continuous working cutter head cross each other at the blade reference point with the slot width the result of the spacing between those blades and the continuous cutting motion.

It is also possible to achieve the resulting curvature relations between inside and outside blades in a single indexing cutter head by drawing the cutting edges of inside and outside blade with the a reduced point width (Fig. 13, right). Then the curvature radii from the left part of Figure 13 are drawn perpendicular to the respective cutting edges, beginning at the blade reference points. The connecting line of the two radii end points is the position of the new cutter axis. With knowledge of the cutter axis position, all cutter head and profile parameters of the newly designed tool can be determined (Ref. 12).

Semi-completing is applied for the grinding of bevel gears that are semi-finished in the soft with the continuous Cyclocut method. The epicyclic flank lines are replaced by circles that require a highly uneven stock removal between toe and heel. Semi-completing is used in certain applications, mostly for ring gear diameters between 400 mm and 800 mm, like industrial gear boxes as well as ship and railroad transmissions.

Geometrical and Kinematical Placement of the Different Methods

The eleven common Gleason bevel gear cutting methods are listed in Table 1 with regards to their geometrical and kinematical characteristics. The table provides an overview regarding indexing method; mathematical flank line function; tooth depth taper; number of manufacturing steps; kind of crowning generation; and the originator of the particular method. The table also mentions whether the ring gears can be manufactured in Formate, i.e. — if they are always manufactured in Formate.

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Dr. Hermann J. Stadtfeld

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

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McInnes Rolled Rings

COMPLETES HEAT TREAT EXPANSION

McInnes Rolled Rings has completed an $8 million, 25,000-square-foot expansion to its current manufacturing facility. The addition expands its present heat treat size capabilities by providing the ability to quench and temper forgings up to 144 inches in diameter. With separate high agitation water and polymer quench tanks, this new state-of-the-art bay will significantly expand the daily tonnage capacity to ensure the fastest delivery times available in the industry.

McInnes contracted with Can-Eng Furnaces Intl. Ltd. to design and install the most advanced technology to process large diameter products. The furnace and quench tank designs are augmented by a customized material handling system by Dango and Dienthal Hollerbach GmbH capable of processing loads up to 25 tons. The system's fast transfer from furnace to quench tank provides optimal and repeatable process controls.

"This new bay nearly doubles our quenched and tempered offerings to the power transmission industry and adds the ability to solution anneal large diameter stainless steel rings. Also, the addition of water quenching improves our ability to meet the high property demands of the custom flange markets," said Shawn O'Brien, vice president, sales and marketing. The expanded heat treat operation officially began service on March 1, 2016.

The Adams Company

INVESTS IN TURNING CAPABILITIES

The Adams Company, a custom gear and shaft manufacturing company located in Dubuque, IA., recently announced the delivery of a new Okuma LU4000 EX turning machine. This is a state-of-the-art shaft turning machine that will greatly increase both The Adams Company's capabilities and capacity in shaft manufacturing.

Features include: four-axis movement, upper and lower turrets, a retractable tailstock, two meter bed length, maximum 158.75 mm diameter turning capacity, live tooling and y-axis functionality, and capability of holding a ±.00025" tolerance. Additional unique features with this machine include a self-centering chuck and balanced cutting or "pinch turning." With "pinch turning" you not only get reduced cycle times, but "chatter" is eliminated during the machining process. The specialized workholding will allow The Adams Company to finish shafts complete without having to move them to multiple workcenters.

"The goal," said Steve Arthur, president & CEO, "was to find a machine that would enable us to make complete shafts with keyways, splines, holes, etc. in one operation. The machine had to produce shafts fast while holding some rather tight tolerances. It was a tough challenge, but Okuma hit a home run with the LU4000 EX."

"The Hartwig team has worked closely with The Adams Company for several years, and we knew that addressing their shaft manufacturing was a big priority. We sat down with the team at The Adams Company and together we created an entire process, not just a machine tool," said Jay Montgomery a sales engineer at Hartwig, Inc., the company representing Okuma. "With the LU4000 EX machine we proposed some unique features that allow them to take full advantage of their investment; The Adams Company will now have state of the art shaft turning capabilities that will make them globally competitive in shaft manufacturing. It's incredibly exciting to have truly world-class technology and manufacturing capabilities coming to Eastern Iowa. Their investment is a huge win for them and their customers."

"Not only will this machine enable us to increase productivity with our current customers," Arthur added, "but it also has opened the door for new opportunities. It will be an excellent addition to our current custom gear and shaft manufacturing capabilities."

Emuge

APPOINTS MILLING PROJECT MANAGER

Emuge Corp., a manufacturer of taps, thread mills, toolholders, clamping devices and other rotary cutting tools, has announced the appointment of **Dan Doiron** to the position of project manager, milling. In his new position Doiron will be responsible for end mills, tool holders, technical and CAD/CAM program support for milling products.

"I am pleased to welcome Dan to Emuge," said Bob Hellinger, president. "He brings with him valuable experience in milling applications and five-axis programming. This puts him in a unique position to help us as we expand our milling tool products and guide our customers on the challenges of modern milling."

"Emuge end mills were always my first choice in moldmaking and machining. I am thrilled to join Emuge and apply my industry expertise to the milling product lines," commented Doiron.

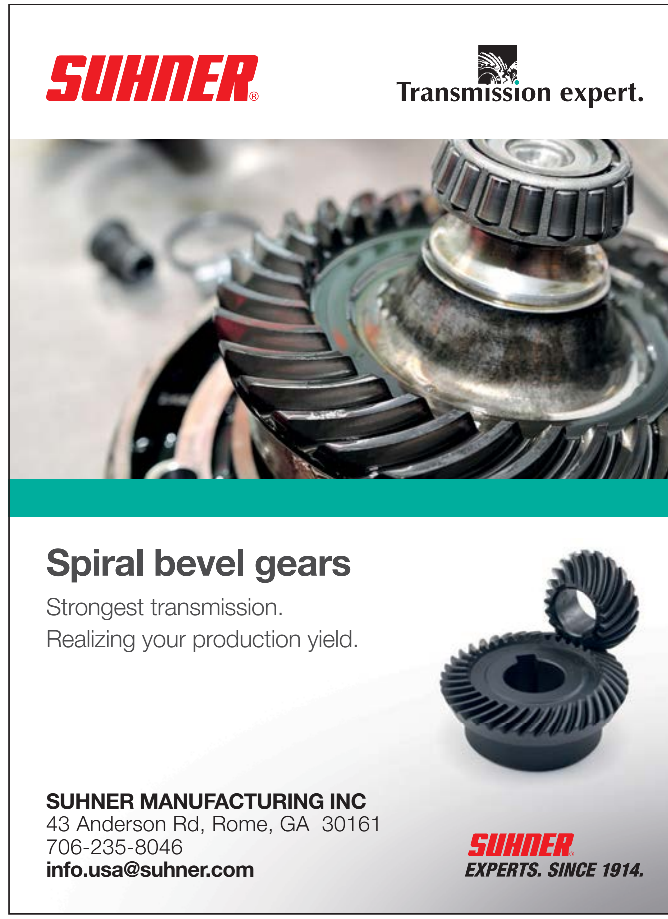
Prior to joining Emuge, Doiron worked for eight years at Micron (Fitchburg, MA), a medical manufacturer, where he most recently held the position of lead programmer, working with demanding materials in a variety of medical implant applications. Before that, Doiron spent 24 years at Doucette Tool & Die (Leominster, MA) where he acquired years of experience in moldmaking and CNC machining. He attended Leominster Trade School and is a Leominster resident.

Gleason and Rochester Institute of Technology

ANNOUNCE NEW DOCTORAL FELLOWSHIP PROGRAM

Gleason Corporation and the Kate Gleason College of Engineering at Rochester Institute of Technology (RIT) have announced the establishment of a Doctoral Fellowship program. The fellowships will be incorporated into RIT's Ph.D. Engineering Program. Gleason has donated $300,000 in support of these fellowships.

Brian M. Perry, vice president of Rochester operations at The Gleason Works, said, "Gleason and RIT have enjoyed a mutually beneficial and highly valued relationship for over 100 years. As Gleason celebrated its 150th anniversary in 2015, we felt it

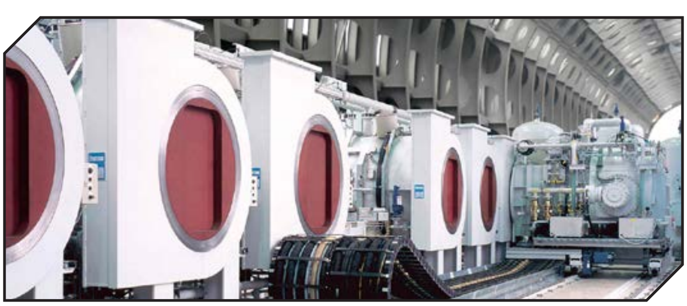


important to build on our success with RIT and establish these Doctoral Fellowships. As a leader in the gear industry, Gleason relies on the strong engineering talent that RIT develops here in Rochester. We are proud that Gleason employs almost 100 RIT alumni in our Rochester plant. This fellowship program sponsors valuable research into advanced gear design and systems engineering that will benefit gear producers globally. Gears are used in a wide variety of products across hundreds of different applications. The needs for greater energy efficiency, improved noise characteristics, greater duty cycles and lower costs are key objectives within the research plans."

ALD Vacuum Technologies

ACQUIRES ALD-HOLCROFT

AMG Advanced Metallurgical Group N.V. has announced that ALD Vacuum Technologies has acquired the remaining 50 percent share of their joint venture company, ALD-Holcroft Co. Inc. from AFC-Holcroft LLC. ALD-Holcroft, formed in 2005, acts as the exclusive sales agent for ALD's heat treatment product lines in the NAFTA region. The acquisition will enable AMG to streamline its heat treatment and metallurgy furnace marketing operations in America, Canada and Mexico.



Industrial Heating Equipment Association

ANNOUNCES NEW INDUCTION DIVISION

The Industrial Heating Equipment Association (IHEA) has launched its Induction Division which represents a very important segment of the heat processing industry. This division will focus on educating both the induction OEM's and end users of thermal process technologies on best practices such as safety and operations, where the technology is best used and keeping the industry updated on the latest innovations related to induction.

IHEA president B.J. Bernard states, "IHEA strives to be the authoritative voice for the entire thermal processing industry. Of course, there are many different ways to apply heat. The Induction Division will focus on the specific issues facing induction suppliers and end-users. IHEA welcomes the new Induction Division and looks forward to working with them to improve the thermal processing industry as a whole."

The three charter induction OEM's are Ajax Tocco Magnethermic, Ambrell, and SMS Elotherm, with Taylor-Winfield joining in 2016. The utility members involved are Duke Energy, Georgia Power and Alabama Power along with the Electric Power Research Institute (EPRI). The Induction Division allows IHEA to expand its reach in the heat processing industry to provide critical information and education on induction technology. The addition of induction companies will also benefit all IHEA members by providing great resources and knowledge of numerous innovative areas for members.

The Induction Division is in the process of developing content for IHEA's 2016 Induction Seminar, which will take place this Fall. They are also developing induction content for IHEA's website. Division Chair Michael Stowe of Advanced Energy remarks, "This new Induction Division will focus on induction technology and its technical applications. We have had two division meetings thus far with the participation of active induction OEM's and electrical utilities." Along with the 2016 Induction Seminar, there will be regular division meetings at IHEA Annual Meeting from April 20–23 in Colorado Springs and later this year at IHEA's Fall Business Conference.

PTG

WINS GREATER CHINA BUSINESS AWARD

Precision Technologies Group (PTG) was the proud winner of the Business Award category at the 11th Annual NW England Greater China Awards in February. Organized by U.K. Trade & Investment (UKTI), the 2016 event was held at The Lowry Theatre, Salford. The award given to PTG was in recognition of the organization's continued successes in developing business and network links across Greater China, including bilateral trade and investment. "We were surprised and honored to secure the 2016 Business Award," comments PTG's Chief Executive Officer, Dr. Tony Bannan, "This further recognition by UKTI of our achievements is clear proof of our ongoing drive to build solid business relationships with organizations that could benefit from our ultra-precise rotor milling and grinding technologies."

Precision Technologies Group has been developing strong business connections with China and Taiwan since the 1980s. The business established a Chinese office in 2007 and has enjoyed increased sales into China year-on-year. In 2010 PTG was acquired by Chinese industrial corporation, Chongqing Machinery & Electric Co. Ltd. (CQME), which has made significant investment in the Rochdale business since acquisition. Typically, 98 percent of PTG's products are exported, with 71 percent destined for Greater China.

The NW England Greater China Awards are sponsored by Cathay Pacific, CIMA, Koehler Group and Orangefield Group and recognize success through the following categories: the Recognition Award, the Education Links Award, the Rising Star Award, and the Business Award. By coincidence, the 2016 Education Links Award was won by Alliance Manchester Business School – an institution that PTG company, Holroyd Precision, has established solid ties with, by helping students gain 'real-world' international business skills.

April 11–15—MACH 2016 Birmingham, England. The Manufacturing Technologies Association (MTA) organizes this biennial exhibition that showcases live working machinery and brings together the industry's finest manufacturers across a range of technologies including milling, turning, metrology, additive manufacturing and tooling. The seminar program involves organizations like Airbus, McLaren and Cranfield University with topics on Industry 4.0 and additive manufacturing. MACH 2016 will also be welcoming the next generation of talent to the exhibition. A dedicated Learning and Development Zone will act as a base for student visitors as well as housing some key exhibits and a showcase of MTA Members' apprentices and graduates at work. The MTA is delighted to announce that Sandvik Coromant will once again be sponsoring the Zone, demonstrating their support for bringing young people into the industry. Featured organizations within the Learning and Development Zone include the AMRC, the Bloodhound SuperSonic Car, the Ministry of Defense as well as a chance to see the next generation of engineers in action with Apprentices at Work demonstrations. For more information, visit *www.machexhibition.com*.

April 12–14—American Coatings Show 2016 Indianapolis, Indiana. Exhibitors and visitors alike see the American Coatings Show offers innovative features to provide immediate business opportunities, a complete portfolio for the production of high-grade, competitive coatings, paints, sealants, construction chemicals and adhesives. In 2014, more than 8,700 industry attendees from 69 countries visited the American Coatings Show to source information about state-of-the-art developments in raw materials, laboratory and production equipment, testing and measuring equipment and services for the coatings industry. Once again, the 2016 American Coatings Show will set the trend for future developments in the paint and coatings industry. For more information, visit *www.american-coatings-show.com*.

April 14–15—AGMA Spring Marketing & Forecasting Conference 2016 Crowne Plaza O'Hare, Rosemont, Illinois. Growing automotive production, housing construction and capital spending are positive indicators for gearing in the near term. But the gear industry faces risks from uncertain government policies, a slowing energy sector and weak markets in Europe and Asia. Speakers include Randy Disharoon, vice president, strategic accounts at Rexnord and Tom Runiewicz, senior principal economist, IHS Economics, US and World Industry Service. Pricing is $425 first registrant and $375 for each additional registrant from the same company. It is only open to employees of AGMA member companies. For more information, visit *www.agma.org*.

April 15—International Conference of Transportation Engineering 2016 Washington D.C. The International Conference of Transportation Engineering (TEC) promotes innovation and progress in transportation engineering through research. This conference intends to facilitate this goal through an objective and interdisciplinary setting. The one-day schedule includes short courses, panel discussions, workshops, training lectures, papers and plenary lectures. For more information, visit *www.gtconf.com*.

April 19–21—Discover More Mazak Midwest 2016 Midwest Technology Center, Schaumburg, Illinois. From models with simple, but innovative milling and turning capabilities to advanced manufacturing cell solutions, Mazak will run part cutting demonstrations on more than 20 of the company's newest machine tools, many of which will feature the latest ancillary equipment. Several of the multi-axis machines on display will feature Smooth Technology, which comprises intuitive hardware, new high-speed servo systems, enhanced ergonomics and optimized programming via the latest Mazatrol SmoothX and SmoothG CNCs. Application engineers will also be available during the demonstrations to discuss how these machines can solve production challenges. For more information, visit *www.mazakusa.com*.

April 26–29—Sandvik Metal Cutting Technology 2016 Sandvik Coromant Center, Schaumburg, Illinois. Having the right tooling strategy has a huge impact on machining time and profitability. To develop the best strategy requires proper training in basic metal cutting principles. Sandvik's Metal Cutting Technology course builds a foundation in basic metal cutting theory and teaches participants how to apply it properly. Topics include: turning, milling, drilling, parting and grooving, boring and tool holding. Come to this training and leave with the ability to overcome critical process challenges and develop more efficient and profitable operations. This is a 3.5 day course. For more information, visit *www.sandvik.coromant.com*.

May 3–5—Gearbox System Design: The Rest of the Story Sheraton Sand Key Resort, Clearwater Beach, Florida. This course focuses on the supporting elements of a gearbox that allow gears and bearings to do their jobs most efficiently. Learn about seals, lubrication, lubricants, housings, breathers and other details that go into designing gearbox systems. Sponsored by AGMA, this course is taught by Raymond J. Drago, chief engineer, and Steve Cymbala, senior drives engineer, at Drive Systems Technology, Inc. This seminar will start with the basics and then focus on the pros and cons of types of housing construction, housing elements, bearing mounting, selection and role of gearbox accessories, appropriate lubricant selection and more. AGMA members ($1,895) and non-members ($2,395). For additional information, visit *www.agma.org*.

May 12–14—2016 AGMA & ABMA Annual Meeting Omni Amelia Island Plantation Resort, Amelia Island, Florida. Highlights for the 2016 AGMA & ABMA Annual Meeting include a diverse lineup of speakers and presenters, the return of the popular AGMA/ABMA golf tournament, (a scramble at the Amelia Island Omni Ocean Links Golf Course that winds along the coastal Atlantic Ocean), a formal Centennial Dinner, First Timer's Luncheon and special AGMA and ABMA dinners for its members. The whole meeting community will group together for a historic photo on Thursday afternoon. Additionally, retired members are welcome back to the meeting so please contact the AGMA or ABMA if you know any fully retired gear or bearing executives that need an invitation. Resort service fee includes complimentary self-parking, unlimited deluxe internet access, on-property resort transportation services, unlimited use of health and fitness center and resort beach access. For more information, visit *www.agma.org*.

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

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

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Adding Up Gear Spheres

Math, Gears and 3D Printing Come Together to Make Art

Alex Cannella, News Editor

Paul Nylander is something between an entrepreneur and a Renaissance man. He has degrees in engineering and physics, but he's also a creative artist who's put together sketches and 3D renderings alike. His website, *bugman123.com*, features everything from an in-depth explanation of a Tesla coil to 3D renderings of physics equations to an extensive library of fractal-based artwork. At first glance, one might find Nylander's many pursuits to be somewhat scattershot, but at their core, his works are tied together by his love for all things mathematical.

As you've probably already guessed, one of Nylander's myriad interests is gears. Specifically, he makes gear spheres. They're exactly what they sound like: art pieces where gears are interlocked together so that they form a sphere. It is, however, a recent interest as far as Nylander's portfolio goes. He's been making gear art for four years now after a friend introduced him to the idea. As with many things, Nylander took it and ran with it.

"My friend was an engineer," Nylander said, "and he had a book on gears. And he showed me all these weird kind of gears in that book. And I'd already seen gear spheres and stuff online before, but after looking at my friend's book, I was like, 'This is kind of my thing.' I love math, I love engineering, and this is really something I should get into."

Nylander's designed spheres with 32, 92, 182 and 242 gears, and they all work. The crown jewel of the collection, however, is the "Bucky Brain Gear/Sphere Gear Combo" (pictured right). The piece combines Nylander's 32-gear sphere with what he's dubbed the Bucky Brain Gear, which, as Nylander describes on his website, is "a set of 60 interlocking double bevel gears arranged to rotate freely around the edges of a truncated icosahedron (Buckminsterfullerene), with the gear planes forming the edges of a rhombic triacontahedron."

With the Bucky Brain Gear, Nylander's love for math and science shines through, particularly in the piece's name, which is at once both descriptive and referential. Icosahedrons are 20-sided polyhedrons, but when you truncate one, or cut off its vertices, it becomes 32-sided. This shape, the same one Nylander used as a skeleton for his gear art, is also the same as a particular carbon molecule, Buckminsterfullerene, or as some call it for short, a buckyball, hence the Bucky Brain Gear's name.

"If you truncate an icosahedron, it's basically like a soccer ball," Nylander said. "And you can push that further and you can keep tessellating more and more hexagons and pentagons."

The shape is also the basis of the geodesic dome (made famous by Buckminster Fuller...see the rabbit hole of references here?), and thus a natural frame for many of Nylander's more traditional gear spheres. With both Nylander's normal and Bucky Brain spheres sharing the same framework, it may have been inevitable that they got mashed together into what you see here: a cornucopia of gears so tightly packed together that they can't even be made by hand. Because of the way the Bucky Brain Gear half of the piece interlocks with the rest, the Gear Combo can only be made via 3D Printing.

Surprisingly, somewhere in all those gears, Nylander also managed to fit a lightbulb. The Gear Combo also works as a lamp with different settings that could either illuminate your desk or just provide a cool carved pumpkin-esque look.

"I think the concept of a geared sphere is something that could actually be a real moneymaker in a variety of ways," Nylander said. "If it has utility and it has a use like a lamp, and it happens to be cool because it has moving gears on it, then I think it's gonna be much more interesting to a larger audience."

Moneymaker or not, the Gear Combo is still a work in progress for Nylander, though he did show off a prototype at the 2014 3D Printer World Expo. While it's clear that he intends to sell them eventually, it'll be a while before you can pick up a lamp of your own. While you're waiting, however, there's still plenty of math art to be dazzled by.

For more information:
Paul Nylander
http://bugman123.com/

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