January/February 2010

GEAR TECHNOLOGY®

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The Journal of Gear Manufacturing

Big Gears

Feature Articles

- Big Gears and Bigger Challenges
- Wind Yaw/Pitch Drives Market: A Global Report
- Wind Gearbox Issues in Full Supply

Technical Articles

- New, High-Performing Steels Debut Grinding Away at Profile, Lead Modifications
- Areas of Existence of External and Internal Gears Defined
- Profile, Lead Modification via Threaded Wheel and Profile Grinding

Plus

- Addendum: The First GPS?

THE GEAR INDUSTRY'S INFORMATION SOURCE

Star SU

grinding in one

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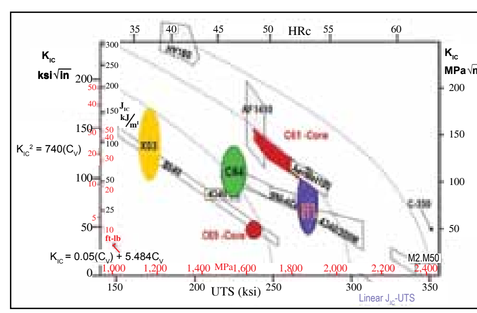

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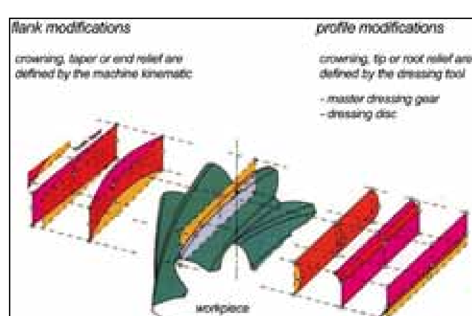


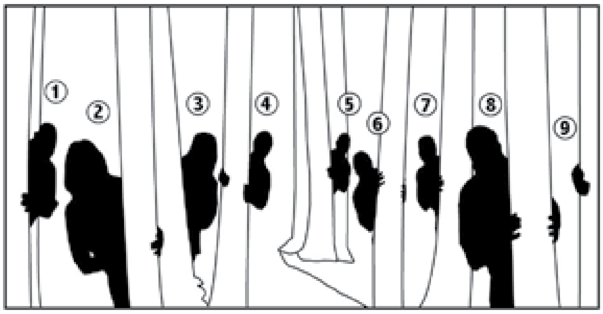
Vol. 27, No. 1 GEAR TECHNOLOGY, The Journal of Gear Manufacturing (ISSN 0743-6858) is published monthly, except in February, April, October and December by Randall Publications LLC, P.O. Box 1426, Elk Grove Village, IL 60007, (847) 437-6604. Cover price $7.00 U.S. Periodical postage paid at Arlington Heights, IL, and at additional mailing office (USPS No. 749-290). Randall Publications makes every effort to ensure that the processes described in GEAR TECHNOLOGY conform to sound engineering practice. Neither the authors nor the publisher can be held responsible for injuries sustained while following the procedures described. Postmaster: Send address changes to GEAR TECHNOLOGY, The Journal of Gear Manufacturing, P.O. Box 1426, Elk Grove Village, IL, 60007.

Who Says You Can't See The Forest (City) For The Trees?

Forest City Gear has a very "easy to see" way of doing business. We look at your product, the purpose of the gears in the overall mechanical motion process, your manufacturing requirements and many other factors. Then, our Forest City Gear engineers help devise the best solution for your needs.

Using the industry's most advanced technologies for gearmaking and gear finishing, the next step is the production of prototypes for your approval. Often times, we see a better solution and suggest it immediately, because we have no "one size fits all" mentality in the mind's eye at our company. It's precisely this flexible approach to gearmaking and our innovative thinking that's made us a longtime leader in the industry. That fact is borne out nowhere better than at the many other gear companies for which we work, helping them solve problems and performing machine operations that are recognized worldwide for their accuracy, repeatability and part verification protocol.

Forest City Gear people have a passion for what we do and that's also very easy to see, in the many gear industry awards and high standard recognitions we've achieved. Get the picture? Then, we invite you to look to Forest City Gear for your next "picture perfect" product. Go to **www.forestcitygear.com** and have a "look" for yourself. Seeing is believing.



(1) Pat Keeley, (2) Wendy Young, (3) Kika Young, (4) Rustin Mikel, (5) Jared Lyford, (6) Gene Fann, (7) Tom Christenson, (8) Fred Young and the shy guy, (9) Everett Hawkins.

FOREST CITY GEAR

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GEAR TECHNOLOGY

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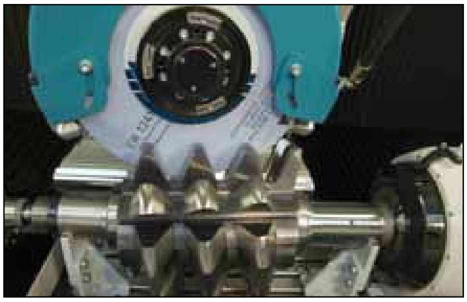

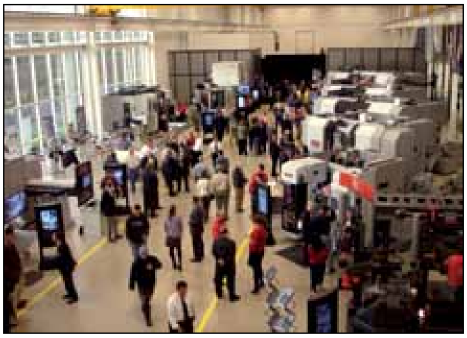

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GEAR TECHNOLOGY

VOL. 27, NO. 1

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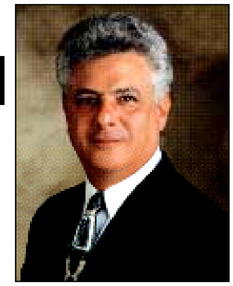
BPA WORLDWIDE


GEARS-TO-GO.
PRECISION
STOCK GEARS



WHERE ARE WE NOW?

The struggles of the manufacturing economy in 2009 are well documented. Even among those of us with long careers, most of us have never seen activity come to a screeching halt the way it did last year.

2009 was tough on all of us.

So, what should we expect in 2010?

Technically, the experts tell us, the U.S. recession ended in the summer of 2009. According to the Bureau of Economic Analysis, the real GDP growth rate was 2.2% in the third quarter of 2009. That's a positive sign, but there's still a long way to go, particularly with unemployment at 10%.

Many gear manufacturers I've talked to were able to weather 2009 due to enormous order backlogs. One gear manufacturer told me his backlog in 2009 was the largest it had ever been, and they were shipping gears throughout the year based on 2008's orders. But now, those backlogs have dwindled down to just a few months' activity, and the manufacturer is looking at 2010 with apprehension. If they don't begin taking new orders, 2010 could be a far worse year for them than 2009.

That gear manufacturer was one of the lucky ones. He still has a backlog. A lot of companies' business disappeared much more quickly. It didn't help that the auto industry for all intents and purposes shut down last year. Thanks to Cash for Clunkers and similar programs overseas, the auto makers are manufacturing cars again, but their production is nowhere near the levels it has been at in recent years.

Most other industries have been quiet as well (see our article on big gears, p. 71). Even the wind power industry is hard to predict, between government wishy-washiness and financing issues.

After Gear Expo, we reported seeing signs of quoting activity among suppliers to gear manufacturers. Quoting for cutting tools, workholding and fixturing was robust. One cutting tool supplier I spoke with has a customer who recently implemented a third shift to keep up with the demand coming from—believe it or not—the auto industry.

According to the U.S. Machine Tool Consumption report, sponsored by AMT and AMTDA, machine tool orders were up 16% in November 2009 (their most recent report, as of this writing). Although that was a big jump over September, the activity level is still well below that of 2008.

In addition, lately, I've been hearing that a number of gear machine tool manufacturers have begun seeing increased orders. One gear machine supplier sold three machines in the last quarter of 2009. Another I spoke to sold 10 from stock.

So there is activity in the gear industry, although much of the evidence is anecdotal and not yet widespread. As with any recovery, certain industry segments will pick up first, and others will lag behind.

But no matter where you are in the recovery process, it's important to talk to your customers about what you do best. Make sure you're communicating your core competencies, so when they come looking for suppliers, your strengths come to mind. Advertisers and agencies are again taking a strong look at their marketing and advertising—seeing if their message needs focus, clarity and greater exposure.

But I'm not just talking about advertising. You need to have effective communications with your customers throughout your organization. That includes your receptionist, your CEO and your sales engineers out in the field. It includes your website, your e-mail and your telephone answering system. Are you taking advantage of every opportunity to tell your story?

It's also a great time to examine those other aspects of your business that could or should be improved. What can you work on now that you'll be too busy to do when the order books fill up? What are the things you neglected during the busy times? Maintenance? Employee training? Research and development? Your company website?

Things appear to be picking up in some areas of the gear industry. But chances are, you've still got some time before things get really hectic. Make the most of it.

Michael Goldstein,
Publisher & Editor-in-Chief

All-in-One Broaching Capability

FASTER, MORE EFFICIENT MANUFACTURING OFFERED WITH TABLE TOP DESIGN

The Table Top Broaching Machine combines new concepts with traditional broaching methods in a smaller unit (courtesy of American Broach).

The table top design features crossing T-slots for faster and more accurate setups (courtesy of American Broach).

American Broach & Machine Company, located in Ypsilanti, MI, has developed a new concept to address customer complaints regarding traditional broaching machines. The Table Top Broaching Machine is a plug-and-play device designed for fast operator setup and simple changeover that requires no special foundation, pit or operator stand and is not model dependant.

"Our customers want faster, simpler, and cheaper, and they want it in a small, convenient package," says Ken Nemec, president at American Broach. "Our Table Top design is a clever merging of technology and physics where a broach cutting tool is pulled down through the broaching table. Our design melds known and new concepts together to effect the solutions our customers have been requesting while occupying very little floor space."

While many of these concepts are not new to broaching, it is uncommon to see so many features and functions in such a small, compact machine design, Nemec says.

"No one has ever put the drive system completely under a table in such a compact manner, giving the user access to a flat locating surface with no obstructions, to produce small, light, table top broaching," Nemec says. "These machines are quickly adaptable to many different applications."

The new improvements made in this vertical, pull down broaching technology consist of a "teach function" for

continued

adjusting stroke, and the elimination of the machine frame as the support for force resistance thru bulk, girth and guideways.

"It is our contention that these features used together or separately will achieve the desired results within the scope of our patent," Nemec adds. "The Table Top Broaching Machine was designed to minimize space and capital equipment cost, while providing speed and performance for manufacturers with smaller lot sizes, constrained space, and a need for an efficient, quick change broaching machine."

The machine will initially be offered in 24 inch and 36 inch stroke lengths, from 2–6 tons in power, with electromechanical dual-screw drive systems that eliminate the cadence (pounding) associated with hydraulic broaching machines. The twin-screw design provides smooth and steady power, increased tool life and part quality, while reducing the perishable tooling cost per part.

American Broach's design features a simple flat table top broaching area with crossing T- slots to accommodate fast, accurate setup. This one-piece solid table top has been designed to attach to a fabricated main box assembly, which is mounted on top of a coolant sump box base.

The modular design keeps the cost of build and maintenance service low, while maintaining structurally robust physical attributes by design, without the traditional girth used by broaching machines.

"In our design, the load distribution is transferred to the table top directly through the twin roller screw assembly without traditional machine ram, box way, rails, carriage, guide rods, or bearing cars. This eliminates the need for a heavy machine frame, and allows for a modular box design that meets our customers' needs," Nemec says.

The Table Top Broaching Machine also features an unguided pull bridge powered by two spindles (roller or planetary); they are mounted under the table in a compact design to eliminate the need for guide rods or bearing ways that will not tolerate being mounted in areas with chips and coolant under the table. These spindles are fully enclosed by slide covers to prevent chip interference and coolant damage.

The spindles are powered by a tooth belt by way of over sized tooth drive pulleys; this over sizing allows a single motor to drive both spindles simultaneously and with extreme accuracy without positioning the drive belt in line in the space where the cutting tool travels. Tool location is monitored by motor rotation position tracking by a simple encoder, and the drive system is enclosed and sealed into the hollow bottom under the broaching table.

"Quick changeover between parts to accommodate small production lots is an important concept behind our machine design," Nemec says. "We developed a quick teach button feature that adjusts the stroke for the length of the tool automatically in seconds, rather than using stops and switches, which do not hold up well in an 'under table' environment."

Additionally, it takes several minutes of trial and error to set traditional stops. Now with a simple visual setting, the stroke length is set and no data entry or measurement is required. The operator simply lowers the broach tool in the teach setup slow movement mode, and when the tool is just below the part nest, the teach button is pushed. Each stroke will now stop at the exact spot.

Standard features in the machine design include coolant and air ports designed into the table top (plenum) for ease of distribution in various applications. A removable ring type splash guard accommodates large or irregular shaped parts that cannot easily be broached on conventional broaching machines.

As an add-on option, the Table Top Machine is offered with a simple retriever attachment that will allow for complete auto cycle without requiring the operator to handle the broaching tool. This modular retrieve unit can easily be attached via a precision prepared surface that is part of the Table Top. The retriever is quickly and accurately located with keys and standard T-slots to assure it is on centerline with the pull head. The unit is electric motor and belt driven; once the retriever is mounted and bolted down, it is just plugged in and is ready for use.

American Broach plans to officially debut the Table Top Broaching Machine at IMTS 2010, although three machines have been sold to broaching customers to date.

"What sets American Broach's Table Top electromechanical broaching machine apart is that we have combined all of these recognized best broaching concepts and developed solutions together under the table, with a small compact footprint and simple design with a low price tag," Nemec says.

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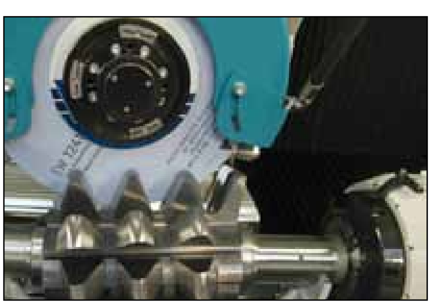
www.americanbroach.com

Cutting Tool Sharpener

HANDLES LARGE DIAMETER HOBS

In response to market demand for a machine capable of sharpening large, heavy hobs, J. Schneeberger has developed the Corvus C500 Coarse Pitch Hob Grinding Machine, which is capable of handling hobs up to 20 inches in diameter using wheels with equally large capacity.



"The need for larger hobs is created by wind generation. Larger gears demand larger hobs," explains Rolf Herrmann, general manager for J. Schneeberger. "Mining, large machinery, drilling (and) coal are other fields and industries where large hobs are required. Of course the tooling has been around for a long time but machine manufactures making machines for that market have diminished.

"In the tool grinding market, there are maybe three manufacturers left that will build machines up to three meters in travel length, machines to accept long tools such as broaches, long hobs, any long tool needed to be thread ground. In the last 10 years, Schneeberger has supplied that specialty market with the most sophisticated

continued

machine in design and technology."

The Corvus tool grinding machine is available in five- and six-axis versions and in different machine lengths to accommodate longer or heavier parts. The hob grinder relies on high horsepower to meet the substantial contact area sharpening that large hobs require. A 52 horsepower (78 horsepower duty cycle) direct drive motor is responsible for high stock removal and productive cycle times.

The machine is designed with a traveling column and stationary tool table, so extremely heavy tools can be set up on the table. The 1,200 Nm torque drive positions any tool quickly and accurately to meet quality requirements for indexing. Fanuc 310i technology is employed; linear drive motors provide accurate positioning. Other features include high rates of linear axis acceleration and deceleration and high positioning accuracy, cycle times and part quality.

The machine's base is constructed of polymer concrete to increase thermal stability and reduce vibration. The Schneeberger *Quinto5* software was developed to support operators preparing a tool. The software features a large tool and wheel database, a graphical and interactive touch screen interface for quick tool programming. The tools are simulated instantly in 3-D format and can be edited as needed by clicking on a desired geometry. "The ability to develop the software in the same location as the machine enables the software, mechanical and application engineers to fine tune the final product, our software, in the shortest period of time," Herrmann says.

"Other machine manufacturers are not equipped to develop software in house and rely on outside sources, which makes the R&D very time consuming and difficult."

For more information:
J. Schneeberger Corp.
1380 Gateway Drive
Elgin, IL 60124
Phone: (847) 888-3498
www.schneeberger-us.com

Gleason Grinding Process

CUTS FINISH TIMES IN HALF

Gleason's new line of Titan Grinding Machines was designed to reduce finish grinding times by up to 50 percent on cylindrical gears up to 1,500 mm in diameter.

On a single platform, the Titan machines offer users both pure profile grinding for the maximum flexibility producing single parts and threaded wheel grinding and profile grinding working together for faster, fully-automated large-scale production.

Power Grind is the new process introduced. It allows users to reduce grinding production time significantly by first using threaded wheel grinding to "rough" gears faster and then profile grinding for optimum gear quality, surface finish and complex gear modifications in the finishing operation.

As an optional feature, the Power Grind process can include an external set-up table, so the workpiece and workholding package can be set up parallel to primary production, instead of sequentially. This allows workpieces to load automatically through an optional workpiece changer. This, along with a new high-speed tool changer that automates the exchange of threaded wheel for profile grinding wheel, reduces non-productive time significantly.

The Titan 1200G and 1500G machines— for 1,200 mm and 1,500 mm workpiece diameters—also feature a patent pending universal dresser. Users can dress threaded grinding

continued

wheels and profile grinding wheels on the machine with a single dressing tool. This eliminates the changeover time and expense of multiple dressing tools.

Another optional feature is a patented dual-flank, twist-free grinding option that is capable of creating asymmetrical tooth trace modifications in half the time of conventional single-flank grinding.

The Titan machines are equipped with Siemens 840D CNC and Gleason's Windows-based Intelligent Dialogue software. One feature of this is a grinding technology database that recommends a production methodology for the Power Grind process before machining starts; this is useful for less experienced operators.

According to Antoine Tüerich, Gleason director of product management, the Power Grind process is an answer to the market's need for faster production of larger cylindrical gears, flexibly and with high quality. "Due to high market demand, manufacturers, particularly those that produce higher volumes of cylindrical gears, are under increasing pressure to greatly increase productivity while maintaining the highest levels of precision," Tüerich says. "Titan is the only machine that does both, with Power Grind. Roughing with highly productive threaded wheel grinding is followed by a fully automatic tool change to use profile grinding for the finishing operation, with all its well-known advantages and features.

"Users of course get all the proven functions, such as automatic centering, dressable grinding and final gear measurement that comprise the fundamental elements of this process. But when roughing large numbers of teeth up to module 14, threaded wheel grinding can be employed to reduce grinding time significantly, especially for large volumes. Optimal gear quality, surface finish and complex gear modifications are then achieved by profile grinding in the finishing operation. In, for example, the case of a workpiece with module 14 and a tip diameter of approximately 1,500 mm, the high gear quality achieved by the profile grinding process can be realized with a 55 percent increase in productivity."

For more information:

Gleason Corporation
1000 University Avenue
P.O. Box 22970
Rochester, NY 14692
www.gleason.com

Double-, Triple-Cut Hobs

ROUGH OR FINISH LARGE GEARS

The PWS large coarse pitch hobs available from Star SU are ideal for hobbing wind turbine gears. They come in a range of materials and coatings as well as ground forms up to DIN AAA quality. The hob sizes range from 20 (1.25 DP) to 40 (0.635 DP) module and lengths up to 430 mm (16.9 inches). CNC inspection reports as well as resharpening and recoating services are available.

For more information:
Star SU LLC
5200 Prairie Stone Parkway,
Suite 100
Hoffman Estates, IL 60192
Phone: (847) 649-1450
Fax: (847) 649-0112
www.star-su.com

Wireless Bore Gauge

CUTS OUT CABLES

The Wigigauge wireless bore gauge (WBG) from Solartron Metrology is the first in a new line of Bluetooth-enabled linear measurement and gauging systems.

The high-precision IP65-rated gauge functions without cables to download measurement data. Manufacturers can design and place workstations with respect to this freedom of limitation.

Previous hand-held electronic gauges connected tools to the receiving SPC system, printer or data logger. Cable

continued

damage and tangles were common and lead to downtime, and cable length and routing often dictated the design and placement of gauging stations.

"Industry has been asking for this type of wireless gauge for quite some time," says Neil Curtis, sales and marketing director for Solartron Metrology. "We are delighted to offer the solution. Applications for the Wigigauge WBG include any manufacturing plant producing precision bored holes, such as automotive components."

The Wigigauge is compatible with industry standard M6 and M10 gauge

head threads. The transducer is linear along its full measuring range, making it easy to set up and adaptable for applications other than bore gauging. Users choose resolution up to 0.1 µm. A NiMH battery pack provides up to 10 hours of continuous data transmission and is removable for off-line charging.

For more information:
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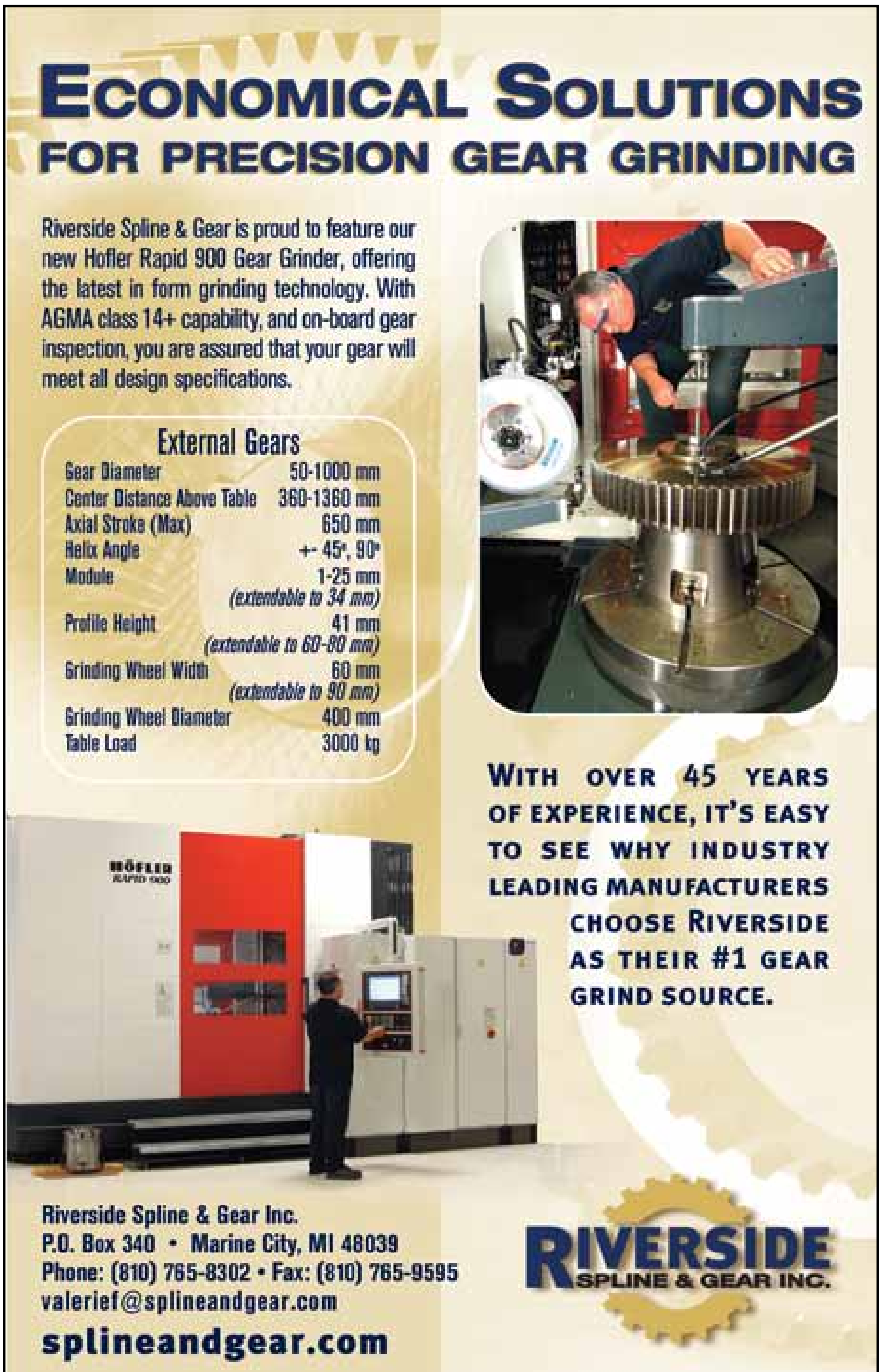
Gastonia, NC 28054
Phone: (800) 873-5838
usasales@solartronmetrology.com
www.solartronmetrology.com



Supertec Machinery

DEBUTS GEAR GRINDING MACHINES

Two CNC worm and thread grinding machines and a CNC gear profile grinding machine are the latest product additions from Supertec Machinery, Inc.

The WT200 has a 7.9-inch diameter capacity and the WT300 has an

11.9-inch grinding capacity. These two CNC worm gear and thread grinding machines feature a combined control, PC-based computer with Smart Grinding software, a direct drive motor and a linear motor ensures the machines' high precision.

The control's specially developed software is flexible and provides an almost infinite number of profiles, management of grinding cycles, dressing cycles and storage of machine processes and profile data. The flexible dressing software allows profile of grinding wheels for standardized worm profiles and multi-ribbed grinding wheels for thread grinding, including tip root modifications and profiles of pump rotors.

The WT200 and WT300 are designed for double lead grinding, taper thread grinding, single flank grinding, dual pressure angle grinding, plug thread gage, rolling die and crusher roller grinding.

The PG-400 achieves class AGMA 12 (DIN 4 grade) on profile and lead gears for tens of thousands of dollars less than other CNC gear profile grinders. Features include direct drive and linear motors and a Fanuc 2li-MB PC-based control with shop floor language. Other features include simple tooth tip modification, tooth flank (crowning) and reference root.

Thermal growth is minimized by the linear motor and grinding wheel spindle cooler, cutting oil chiller and an electric cabinet air conditioner. The PG-400 has a 5.1 inch thru hole

continued

bore on the workhead and 15.7 inches between centers for large part capability. The machine can grind very small teeth. The PG-400 is capable of grinding spline gears, modifying profiles and leading edges and grinding profile shifted gears.

For more information:
Supertec Machinery, Inc.
Phone: (562) 220-1675
www.supertecusa.com

Versatile Reishauer Grinder

ADAPTED FOR LARGER GEARS

The RZ 260 gear grinding machine from Reishauer is based on the successful RZ 150 series, but not only has size been increased, but all components have been adapted to handle higher loads and forces that occur when grinding larger gears. The machine is capable of grinding gears with an outside diameter of 260 mm and modules up to 4 mm.

One focus of Reishauer's in designing the RZ 260 was having the ability to achieve different production requirements for a range of customers. The machine can be fitted with one or two work spindles. The two-spindle version minimizes loading times. The single work spindle option is appropriate for when investment and tooling costs must be reduced and/or the workpiece handling times are less important.

Both versions of the RZ 260 can be equipped with a fixed or CNC-controlled axis for swiveling the dressing tool. With this option, dressing tool flexibility can be increased, so they can be used for a range of gears, compared to a fixed dresser, where tools are typically workpiece specific.

Other Reishauer design characteristics incorporated in the RZ 260 include the Reishauer generating module for highest gear quality, low noise shifting technology for low gear noise emissions, twist control grinding technology to create defined values for flank twist and the Reishauer HMI for fast change-over and set-up times.

For more information:
Reishauer
1525 Holmes Road
Elgin, IL 60123
Phone: (847) 888-3828
www.reishauer.com

High-Speed Tool Resharpener

PRICED COMPETITIVELY

The small-footprint ANCA FastGrind CNC tool and cutter grinder for high-speed tool resharpening is appropriate for tools 0.35 mm to 12 mm in diameter. The concept behind the FastGrind is to provide grinding quality and reliability of the ANCA range at an economical cost, according to the company in a press release.

The FastGrind provides high positioning accuracies in all five mechanical axes with an additional four software axes. Linear axes are ball screw-driven, and the two rotary axes are direct-driven. The FastGrind sharpens drills, step drills, end mills, burrs, profile tools, routers and special tools.

continued

The machine features a double-ended HSK40 wheel spindle for flexibility and minimizing set-up time. Maximum wheel diameter is eight inches. A part probing system comes standard.

The FastGrind features the ANCA *iGrind* software and is priced at $120,000.

The ANCA *Iview* tool inspection software package is optional. The software works smoothly along with the machine operating software and a camera, which mounts inside the grinder. *iView* has a standard magnification of 300:1, and other magnifications can be supplied. The system accuracy is two microns. The software generates

the ideal shape for standard tool geometries and protracts it over the actual tool image.

The machine axis saddles are constructed from a single-piece casting, so they feature extreme rigidity and reduced vibration during machining. The grinding spindle is mounted on a single piece casting as well for robustness. Optional features include a fire suppression system, manual steady and manual hydraulic Schunk chuck.

According to Russell Riddiford, ANCA, Inc. president, "With the FastGrind, we created a way for the tool-making shops to access ANCA technology affordably, without compromising ANCA quality."

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www.anca.com

25 Bar Furnace

A VIABLE ALTERNATIVE TO OIL QUENCH

Seco/Warwick introduced a 25 Bar Single Chamber Vacuum Furnace as a process alternative to vacuum furnaces using an oil quench. The 25 Bar HPQ provides the same hardness properties as an oil quench, and when it is equipped with optional PreNit and FineCarb advanced LPC vacuum carburizing technology, the furnace can reduce cycle time by up to 50 percent in certain applications.

Using helium as a quench medium, the 25 Bar furnace lowers distortion and renders parts washing unnecessary. Loads are both heated and quenched in the same chamber with the single chamber furnace. Many of the problems associated with oil quenching are minimized with the 25 Bar HPQ including the disposal of spent quench fluids, the requirement for a washer to clean parts and post heat treating machining needed to compensate for part distortion in oil.

Helium is used as a process atmosphere to maximize cooling. Recycling systems are available to recover and reuse the helium, which tends to be higher cost than other process gases; however, there are many choices for supply systems, and helium follows the same installation guidelines as nitrogen.

Seco/Warwick is offering free trials for a limited time at their R&D facility, so companies interested in the process can obtain a full metallurgical report for their samples without any risk. Customers that decide to invest in the new technology will receive extra field support to assure proper installation and efficient operation.

For more information:
Seco/Warwick
P.O. Box 908
Meadville, PA 16335
www.secowarwick.com

Grinding Wheel

IMPROVES SURFACE FINISH

The SK23w ceramic grinding wheel specification from Burka-Kosmos drastically increases the Q'w and V'w rates. This type of grinding wheel is more reliable in respect to burning/cracking while improving surface finish and lowering grinding times. Since grinding wheel wear is reduced and there is the capa-

bility to self-sharpen during the grinding process, form is maintained, which results in reduced dressing cycle. The SK23w provides for longer wheel life and lower cycle times.

For more information:
JRM International, Inc.
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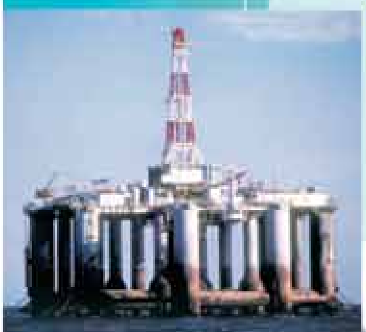

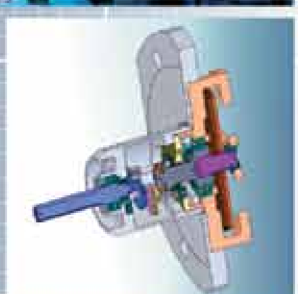

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Wind Turbine Pitch and Yaw Drive Manufacturers

DRAW BREATH AS MARKET SLOWS

Colin Marson, Lisergy Consulting

(This article has been prepared by UK-based Lisergy Consulting, an independent market research consultancy working within the wind energy sector.)

The global wind energy market has seen average growth rates of 28 percent over the last 10 years, according to the Global Wind Energy Council (GWEC), creating major challenges for the component supply industry. GWEC also forecasts an average growth rate of 22 percent for the next five years, which if realized, will continue to put pressure on suppliers of turbine components.

While the current financial crisis is dampening demand temporarily, the market is expected to rebound, potentially

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resulting in future bottlenecks in supply of key components.

Some of the least-discussed but critical components are the yaw and pitch drives used to orient the turbine and blades in relation to the wind. These drives ensure the turbine optimizes its position to generate energy efficiently and safely.

To understand the dynamics of this vital but little-researched part of the market, Lisergy Consulting has interviewed the major players and some new entrants to create a view of the market and its future challenges.

Four key global players were interviewed: Bonfiglioli Riduttori, Comer Industries, Brevini Power Transmission and Nanjing High Speed Gearbox, plus other players, to gain their perspective on this fast-changing market.

Market Structure

One of the first areas to investigate was to identify the size of this market. Based on industry estimates, the combined global volume for yaw and pitch drives in 2008 was around 118,000 units.

The market value is now estimated to be over 420 million euros per year. This has created opportunities for existing players to grow rapidly and has attracted the attention of new entrants who seek to gain a position in the fast-growing wind energy market.

The wind turbine pitch and yaw drive market is currently dominated by Italian suppliers, particularly Bonfiglioli, Comer and Brevini, but more recently, Chinese supplier Nanjing High-Speed & Accurate Gear Group Co., Ltd. (NGC) has also become significant. All of these companies have largely come from traditional drive and gearbox markets for use in cranes, industrial machinery and agriculture.

By diversifying into wind energy, each has grown its business dramatically and gained a significant market share. This success is in some part making up for the current downturn in building construction machinery and vehicle manufacturing, markets in which several wind industry players are also involved.

Of the top eight global players, three are Italian, three are German, one is Chinese and one Japanese. Unlike other global sectors, no major U.S. manufacturer holds a significant position in the wind turbine pitch and yaw drives market, but today this is perhaps set to change.

Key Players Dominate

The top six players represent more than 87 percent of the global production.

Bonfiglioli, based in Lippo di Calderara (near Bologna), Italy is a family owned company and is the key yaw and pitch drive supplier globally, with a market share of 29 percent. It has doubled its production capacity in two years in Italy and opened a new factory in India to service the Asian market.

Comer Industries, also based in Italy with a head office in Reggiolo, is the second-largest supplier and has expanded its manufacturing recently, investing in additional capacity in three plants, including one in China. It is 100 percent-owned by the Storchi family and has a 20 percent market share.

Brevini is also family owned. While the smallest of the three main Italian producers of drives, it has invested significantly in manufacturing in China and more recently released plans for a large wind drive production plant in the United States scheduled to start production in 2011.

China-based NGC is the only non-European company to be producing more than 10,000 units a year. Their market share is around 10 percent, but increasing rapidly based on the fast growth in the Chinese wind energy market. Most of the drives are for Chinese consumption, but NGC has a supply arrangement with GE Energy resulting in some global sales. Nanjing, like Zollern, is a major producer of main drive gearboxes for wind turbines.

The Liebherr Group is one of the largest construction equipment manufacturers in the world. For the wind energy market, it produces gear cutting machines and mobile cranes for mounting wind turbines. The manufacture of drive technology is based in Biberach, Germany. Liebherr-Werk Biberach GmbH has almost 60 years of experience as an internal supplier for drive technology for many applications within the group, which has been applied to the wind energy market since the mid-1990s. The company is the only manufacturer worldwide that offers not only individual components but also produces complete drive systems consisting of gearboxes, electric motors, bearings and control units.

Zollern is a long-established German manufacturing group, partly owned by the Hohenzollern and Merckle families. Pitch and azimuth gears are produced in Germany and also in its assembling facility in China. Zollern also produces wind turbine gearboxes, and thus has a wider offer to the wind energy market than pitch and yaw drives.

Nabtesco is known globally for motion control technology, particularly in the robotics reduction gear market, where it holds over 60 percent global market share. Nabtesco manufactures yaw and pitch drives that use a unique gear technology, making them significantly lighter and smaller than conventional drives.

Other players in the market include Bosch-Rexroth, the large German industrial machinery manufacturer that also produces wind turbine gearboxes.

Has the Financial Crisis Impacted the Market?

The major drive producers over the last few years have seen growth rates of 20–30 percent in sales, reflecting the increases in wind turbine production. This rate of growth has brought with it major challenges for the component supply industry.

As wind power sales manager at Bonfiglioli, Fabio

Campana states, "The last three years saw an amazing growth of the demand. We had to double the production capacity in three years in Italy and open a new factory in India."

However, the global financial crisis has now affected planned wind turbine projects in most countries, resulting in a reduced forecast growth rate for 2009 of around 10–15 percent globally. Only within China have growth rates remained well above this global average, as the Chinese government funds internal infrastructure projects such as wind energy. NGC has indicated annual growth rates in the last three years have been 100 percent in China, with 2009 forecast to be again at this level. So indigenous suppliers such as NGC and those supplying imported drives or components (bearings), will continue to see rapid growth due to Chinese demand.

This reduction in growth globally may actually provide opportunities for the drives suppliers to consolidate and restructure their supply chain, providing a more consistent and resilient supply of drives to wind turbine companies.

Are the Long Lead Times for Drives Likely to Reduce?

One of the key challenges for wind turbine companies in the last five years has been the growth in demand and the inability of component suppliers to match this requirement. In recent years, lead times have been well in excess of six months for wind drives, causing some problems for wind turbine producers.

As Campana of Bonfiglioli states, "The demand has grown too quickly. Clients were asking for more products immediately, but we could not fulfill such growing demand, so we could just speed up the existing plants (expansions) and the opening of new plants. During that time we were running behind the demand. We are not experiencing problems anymore, but we did for the past three years."

Much of this long lead time was actually not entirely due to drive manufacturers themselves, but to bottlenecks of bought-in drive component supplies such as notch gears and bearings. This has resulted in several drive producers looking to internalize manufacturing of strategic components.

Massimiliano Colombo, marketing manager at Brevini, confirms this. "Like our competitors, we also decided to internalize the production of pinion gears. We now produce them internally. We want to be fully independent within three or four years."

Matteo Storchi, sales director at Comer Industries, reports a similar situation. "There has been a big problem in sourcing the components to manufacture our products. This is because such growth in demand was unexpected. The supply chain was not ready for it. Most manufacturers could not fulfill the demand; they just did not expect the high demand and were not prepared for it."

Key drive suppliers such as Comer and Bonfiglioli have

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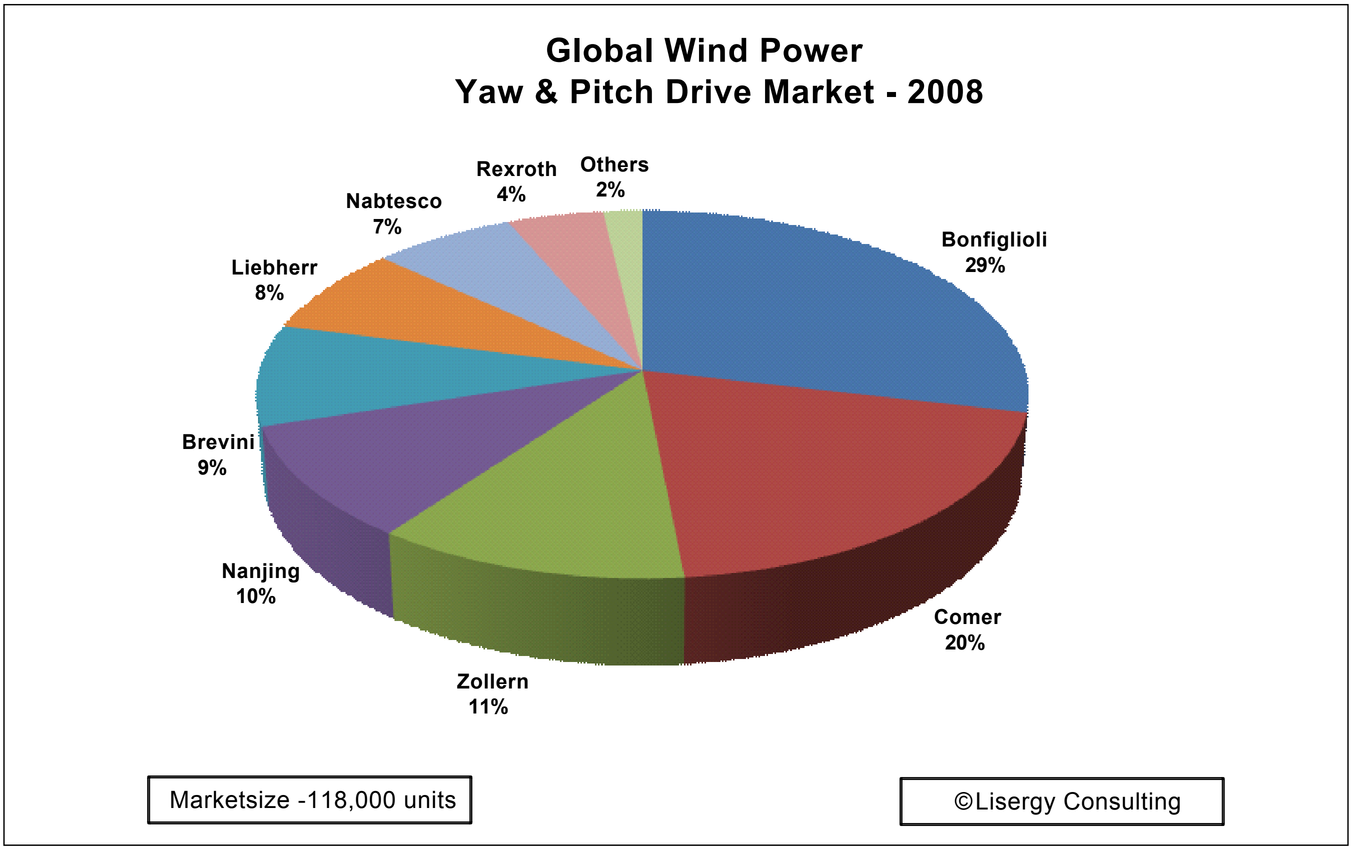

expanded capacity to reduce lead times and brought in-house some outsourced manufacturing to reduce bottlenecks from suppliers.

"The supply problems were a critical factor until the end of the first half of 2008. We have made additional investments in order to be more flexible and avoid these bottlenecks. They mainly involved a vertical integration," says Storchi.

As result of the slowdown in demand, due to the financial crisis and increased capacity by Bonfiglioli, Comer and others, lead times have now reduced to four to six weeks for standard items. However, specialist drive configurations can still see drive suppliers quoting lead times more than 24 weeks from order placement.

Once the market improves, and if growth rates get back to 25 percent a year, we may see these lead times increase again, although the additional capacity from existing and new entrants, plus in-house manufacturing of some components, should help protect against this.

Different Strategies are Evolving

The market offerings of the suppliers of yaw and pitch drives are also changing over time, as the market develops, becoming more competitive and sophisticated.

Liebherr-Werk Biberach GmbH, the German component supplier, sees its main advantage in being an "expert partner" for its clients. Solutions for wind turbines include complete pitch and yaw systems consisting of gearboxes, bearings, electric motors and, on demand, electronic control units. Its high degree of vertical integration enables the Liebherr Group to offer hydraulic pitch systems as well.

At Comer Industries the approach is somewhat different, with Storchi stating reliability as the main feature. "The technology is not as important as the reliability of the product. The intervention costs are very high, so it is important to deliver a product that works and lasts."

Bonfiglioli again has an inclusive strategy, similar to that of Liebherr, as explained by Campana. "Our advantage is to be a wind solution provider that means to offer a complete set of products needed for a wind generator—a complete package. Drives (for yaw and pitch) remain our core business, but we tend to promote sales of complementary products." At Bonfiglioli, the emphasis is towards the control systems, with the electronics becoming part of its wind drive system sell.

Brevini has made great efforts to grow its business in the wind sector, seeing quality and availability as key factors. "Luckily we don't see emerging new technology, so our demand will remain steady," says Colombo.

Nabtesco, the Japanese manufacturer, has created a significant market position based on its novel gear technology, which has led to lighter and smaller drives over conventional units.

Investment and Growth

The investment in drive production capacity has been significant, to close the gap with demand. All of the major drive manufacturers have increased capacity and have plans to increase it further.

Says Campana, "We invested 50 million euros in increasing the capacity. Over 7 percent of turnover was spent on new machinery."

For Comer Industries, the plans for capacity expansion have been aggressive. "We planned to produce three times more gearboxes, expanding the production of the components that created supplying problems to three plants, one of them in China," says Storchi. "I expect a capacity growth between 40 and 50 percent per year. To reach a total of 55,000 or 60,000 units in three years."

At Brevini, the position is equally ambitious, according to Colombo. "Our strategy will be to expand in China, Japan and the U.S.A, opening new facilities and doubling our production capacity."

Even with the current, challenging global conditions, drive manufacturers are taking a longer-term view, such as that from Storchi at Comer. "There is a high demand. I read the growth is estimated at 15 to 20 percent per year until 2020."

Meanwhile, NGC has also increased its capacity of drives dramatically in the last three years by tripling yaw production and doubling pitch production.

New Entrants

The dominant positions of the current global players may well begin to come under threat in the near future, as new companies begin to enter the market and others begin to review their wind energy strategies.

Sumitomo, the major Japanese industrial giant, is already

present in the market supplying gearboxes for wind turbines, but it launched a new yaw drive for wind power use at Hannover Messe 2009.

ABM Greiffenberger, a specialist German supplier better known for its gearboxes and electric motors, also entered the market in 2009 at Hannover Messe. ABM's range includes yaw and pitch drives as well as its own purpose-built electric motor.

Oerlikon Fairfield, with global headquarters in the United States, has been involved in the North American wind power

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market for almost three decades, providing customized main turbine and yaw drive assemblies as well as large precision gearing components. “We have numerous new opportunities under review that will increase our share in the wind market segment,” says John Strickland, Fairfield’s vice president of marketing and strategic planning.

The drives market is becoming an increasingly competitive marketplace. In view of the small number of global wind turbine producers and the dominance of the existing drive producers, it remains to be seen if these new suppliers can find a long-term position in the market.

Will there be Winners and Losers?

The recent increase in the number of new entrants and the rapid expansion of capacity raise the question of who will survive in the long term and whether the market can sustain all these new companies.

At Bonfiglioli, the view is clear. “Our goals were and still are to be the market leader in the yaw and pitch segments, and this can only be achieved by offering complementary products in order to offer a complete package and pursuing the quality excellence for the most reliable products,” says Campana.

Only time will tell, but perhaps those companies that can sustain consistent availability and quality, and can provide a “systems solution,” are perhaps best placed in the longer term.

As Storchi of Comer Industries stated, “There will be proof of Darwin’s law of natural selection. Only the large and solid manufacturers will remain on the market. It will be tough, but the strong companies will survive.”

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Lisergy Consulting is a specialist market research consultancy with over 20 years experience in business-to-business markets. The consultancy specializes in technical and engineering, including global gear and drive markets. Their experience extends to renewable energy applications such as solar and wind energy, as well as a range of specialist applications in robotics, valves, lathes, x-ray and radar.

Colin Marson

Colin Marson has held senior commercial positions with several global organizations, with responsibility for marketing, competitor intelligence, strategic planning and business development. He initially worked for Shell in a marketing capacity, before moving to GlaxoSmithKline as a UK business manager. Colin has also worked for Reckitt & Benckiser and Akzo Nobel in senior international roles, responsible for industrial products. Prior to establishing Lisergy Consulting, Colin was a senior consultant with Frost & Sullivan, a global market research consultancy, operating within major industrial and engineering markets.

Colin has over 20 years’ experience in industry, with 10 of these involved in market or competitor research services and consultancy. He provides corporate clients with a range of market research capabilities, from primary field research, strategic analysis, through to distributor identification and corporate profiling.


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Wind market forecasts and statistics paint a positive picture for the future, but there are issues and challenges for U.S.-based manufacturers seeking entry to the gearbox supply chain (courtesy of Vestas).

Tapping into the Wind Gearbox Supply Chain

BIG GEARS, BIG OPPORTUNITIES, BIG RISKS AND BARRIERS

Lindsey Snyder, Assistant Editor

Although typically considered a late bloomer in the call to wind energy arms, the United States is now the number one wind power producer in the world with over 25,000 MW installed by the end of 2008, according to the Global Wind Energy Council in January 2009.

President Obama has called for the country to double its production of renewable energy in three years, and as stated in the American Recovery and Reinvestment Act, wind has the potential to provide low carbon energy and a boost to the beleaguered U.S. manufacturing industry. The domestic gear market has started to itch for a piece of the pie.

At Gear Expo this year in Indianapolis, AGMA brought the subject front and center at a special seminar dedicated to informing U.S. gear manufacturers about the opportunities and challenges to entering the wind energy supply chain. Coordinated by wind engineering consultancy Romax Technology with support from consultants Garrad Hassan, bearing supplier Timken and the American Wind Energy Association (AWEA), the seminar covered a range of topics, including market dynamics and forecasts, technical trends, supply chain issues and company case studies. Limited places for the seminar sold out as a clear expression of the industry's desire to explore the potential of wind energy as a new revenue stream.

In regards to the seminar, Joe Franklin, AGMA president, commented to Romax, "There are clear opportunities within wind energy for our members to leverage. However, as frequently happens with new market opportunities or new technologies, there is a distinct lack of good quality information and support for gear manufacturers who recognize wind energy's potential. This seminar is another step in AGMA's aim to help address this knowledge gap and ensure that the AGMA members and others in the industry are well informed and

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placed to make crucial decisions about its future role in supplying key components to this rapidly growing industry.”

Despite the 2009 financial situation, which is evident in stalled projects and financing bottlenecks, wind energy continues to grow. In the first half of 2009, over 4,000 MW of wind power was installed in the country, according to AWEA statistics.

“The wind market today is relatively stable and sane considering where it was 16–20 months ago,” says Matt Garran, supply chain manager for AWEA.

Vestas is one of a small number of European turbine manufacturers dominating the market that have strong relationships with trusted gearbox suppliers. This makes market entry more challenging for U.S. gear companies (courtesy of Vestas).

Garran believes healthy financial markets are imperative for wind industry growth, and the markets are returning to a healthy state in his view. “With stimulus funding, we are seeing new farms being planned and developed. The money is flowing,” he says. “It has not flowed fast enough to keep the industry at the level it was, but having said that, what we’re seeing now is here are a number of manufacturers starting to consume their inventory, and you’re starting to see new orders being tendered for late January.”

Garran is optimistic, but he is quick to point out that the industry is not where it was in 2008. “You will see that level of growth return, but not immediately.

“Work is ongoing, but is reduced and is more thought out,” he says of the current state of wind affairs.

As the U.S. Department of Energy reported in 2008, there is the capacity to achieve 20 percent of the country’s energy from wind resources. In this scenario, new wind power capacity would increase to over 16,000 MW per year by 2018, and continue at that rate through 2030.

Although there is a positive picture painted by market forecasts and statistics, there are issues and challenges for U.S.-based manufacturers seeking entry to the wind market. The current global market is dominated by a small number of European turbine manufacturers—Gamesa and Vestas are two of the largest. They have very strong relationships with trusted gearbox suppliers. “The Europeans have a different mindset about doing business,” Garran says. “They’re looking for long-term relationships with a few key strategic partners that will grow with them. In North America, we’re used to doing contract volume work, and that’s two different mindsets.”

If U.S. companies are going to compete, they must be knowledgeable in turbine manufacturer supply chain issues, turbine technology, advanced gearbox design and other industry nuances. But the opportunity is clearly there.

The tremendously variable stresses wind turbines operate under is the main source of technological challenge. With reliability issues and high costs for maintenance and repair, turbine gearboxes are highly engineered to strict, specific manufacturing standards set by IEC and AGMA in conjunction with AWEA. These standards force manufacturers looking to supply the industry to make significant investments in manufacturing equipment and design capabilities, so there is a great deal of cost and risk involved. “These gearboxes must be perfect,” says Roland Ramberg, chairman and CEO of the Gear Works—Seattle, which is a job shop involved in the repair and rebuild of wind gearboxes. “Defects can’t be tolerated. The costs of failure are so high.”

Cautious optimism is echoed throughout the industry. “Currently, there is huge pressure on the wind turbine supply chain and the industry is looking to potential manufacturers from other industries to help increase supply,” says Andy Poon, Romax Technology director of renewables. “But entering a new market, especially one as complex and unique as the wind energy industry, is a risk and, as such, needs qualifying through a sound understanding of industry demands. In our position as a leading wind energy technical solutions provider for gearboxes, we feel it is important to provide accurate information to gear manufacturers to aid their successful diversification and development of the industry.”

The biggest opportunities rest in the industry’s anticipated growth, design development and maintenance/repair to existing, aging turbines.

“The opportunity is as broad as the industry,” Garran says. “Your OEMs and tier ones, some try to do as much in-house and others like to sublet as much as possible.”

Barriers to market entry include the high level of design expertise necessary, high cost and size of new equipment, short supply of qualified and experienced technicians and liabilities for design and warranties.

The risks are well documented, but for those accepting the challenge, what is actually involved in joining the wind gearbox supply chain?

For Clipper Windpower, the process begins by registering interest as a potential supplier via the company's web form. Clipper has a detailed supplier page on its website, complete with general information on what Clipper looks for in a supplier and FAQs (*www.clipperwind.com/suppliers*). "The supplier and approval process can take over a year," says Ian Cluderay, vice president of supply chain for Clipper Windpower.

"Time needed can be impacted on whether or not new equipment is necessary and purchased to support the project.

"Clipper looks for suppliers that are leaders in their respective industry with robust quality systems and mature manufacturing capabilities with the ability to increase capacity as demand requires it," Cluderay says.

Naturally, Clipper has received interest from many gear manufacturers, and multiple domestic and international companies currently belong to its supply chain. And while acceptance of a new supplier may take over a year, the actual decision-making is another process unto itself, involving multiple parties within the company. "The supply chain management team is in charge of this process, but all sourcing decisions involve input from key stakeholders, such as quality, engineering and manufacturing teams."

Winergy Drive Systems also has a detailed, time-consuming procedure for selecting new suppliers. "Our supply chain has been built over the last four years," says Parthiv Amin, president of Winergy. "It is a long process to qualify a supplier. It takes a year to a year and a half. We have a 12-step process."

And, as trends in the European business market indicate, "The idea is to partner for long-term opportunity," Amin says.

In June 2009, Winergy began production from a newly built, state-of-the-art, 130,000-square-foot gearbox facility, about five miles from its existing plant in Elgin, IL. "We have converted the old facility into a parts manufacturing facility," Amin says.

The new site enables Winergy to import fewer of its gears from Europe; although, "Some of the gears do come from Europe." Amin estimates, "Less than 20 percent. The balance of the gears is bought from our supply chain locally. Of the 80 percent that is producing [gears] in the U.S., a percent comes from our facility, but we are still dependent on our supply chain."

Winergy currently has four gear manufacturers in the U.S. supplying it with gears. Amin describes them generally as "mid-sized companies." The majority of them have previous experience in large automotive applications, like heavy trucks and off-road vehicle type applications. These categories of production have transitioned well into the wind industry, he says.

continued

The run-of-the-mill, high-volume small component auto suppliers are not ideally equipped for a simple transfer of skills into the wind industry. "The quality requirements are much tougher than what the automotive guys are used to," Amin says. "They have good quality procedures in place, but the precision and volume is a challenge for them."

Another way Winergy's new facility is improving the prospects for domestic gear suppliers is that it has the capabilities of a shop floor classroom with brand new machinery and quality control. This enables Winergy to teach new employees and prospective suppliers the skills they need to transfer to wind without having to send them to Germany, as was the case in the past. "These guys know how to make gears; they know how to make good gears. The question is how to do it for wind. What machines, tools and techniques to use," Amin says.

One less obvious segment of the wind market Winergy is involved with and was also a subject of the AGMA seminar at Gear Expo is the repair and remanufacture of existing turbine gearboxes. Wind gearboxes are expected to be perfect, but they are nevertheless subject to failures on top of normal wear as they withstand dramatically variable loads.

About 10 percent of Winergy's total business is in repair/rebuild jobs. Another player in this field is the Gear Works—Seattle, as mentioned earlier.

The Gear Works is a family-run job shop specializing in small lot production of larger precision gearing—from 12 inch diameters to four meters—and gearbox repair service for all industries. The business from wind applications has grown in light of the recent industry growth. This includes a significant physical growth in the gearboxes. "In the last 10 years, it has become a bigger segment of our business, and the units have grown larger," Ramberg says. "Ten years ago we were fixing gearboxes of about 100 kw; now we're replacing gearboxes of 1.5 MW."

The Gear Works opened a new repair and test facility about four years ago. It is capable of repairing gearboxes up to 20 tons. Material handling and logistics of the wind industry are just as complex as the engineering.

Experience is a major factor in successfully catering to the wind industry, and the Gear Works stands apart from others by its history in the large precision gear industry. "I believe we are one of the few, if any, that has the ability to do the teardown, forensics, engineering and manufacturing of the components," Ramberg says. "I call it a fully integrated facility."

The initial investment involved to cater to such a high-end market is daunting. For the Gear Works, the focus was not on a single market, like wind, but the other large-sized gear markets that exist, like mining and off-road vehicles. "We made huge investments in our business in the last 10 years. I would say it wasn't only focused on wind. It was focused on real high-end gear and engineering capabilities and quality control. We invested heavily in gear inspection equipment and in our inspection department, and in metallurgical testing and nondestructive testing."

With the large-scale means in place, "the [wind] industry lends itself to our existing capabilities."

And the quality standards are equally as important in repairing gearboxes. "We were always into large precision gearing," Ramberg says. "To be prominent in the wind repair niche, it's paramount that you are able to replace the existing gears to the same quality or better than they were originally produced. The gears being produced for the wind industry now are some of the best in the world. To fix them, you need to have the same quality as the original manufacturers."

In addition to appropriately scaled equipment that includes cutters, grinders, heat treating and testing, Ramberg points to the importance of investing in the work force as much as the machinery. "You need a good engineering team to do failure analysis and forensics to figure out why they're failing.

"The talent—you don't just pull off the street to perform this kind of work. It is as much an investment in people as it is in the tools themselves."

So what about those skilled workers?

The Society of Manufacturing Engineers (SME) announced in December a new collaboration with AWEA and its Canadian counterpart, CanWEA, to not only help equip the industry with a well-educated, skilled work force, but to help connect suppliers with turbine manufacturers.

"SME's partnerships with two of the strongest industry voices for wind energy—the American Wind Energy Association and the Canadian Wind Energy Association—will help build capacity and provide support for the wind energy manufacturing supply chain," says Pam Hurt, SME strategic alliances manager, in a press release.

"These working relationships enable SME to connect manufacturers to a growth industry that is fairly young but still complex. By sharing technical information and programming, our associations support advanced manufacturing and its work force.

"SME will provide the platform for a technical community network to share manufacturing knowledge, expertise and opportunities for the North American wind energy industry," Hurt says.

AWEA is doing its part to help by organizing various industry events nationwide, including regionally based supply chain workshops, which have proven very popular. "In every program we've done, the number of attendees has well exceeded the expectations," Garran says.

As far as getting involved in the wind industry supply chain at this highly competitive stage, "I'd say if you don't get involved in the next year or two, you'll be outside looking in,"

continued

Winergy's Amin says. "Two years ago was even better. If you're not getting involved now, the train is leaving the station. If you're going to do it, now or over the next 14–18 months is the time. But after that, it is going to get more difficult. Not anyone from automotive can jump in."

He estimates it will take 12–18 months for manufacturers starting the investment now to begin getting wind business; although, "If you asked me this question a year ago, I would have said 2–3 years."

While expressing as much caution in his forecasts as others, Amin was equally as expressive in his enthusiasm for the opportunities that exist for gear manufacturers. "It is once in a lifetime the opportunity comes to be in a new industry."

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Design, Development and Application of New, High–Performance Gear Steels

J.A. Wright, J.T. Sebastian, C. P. Kern and R. J. Kooy

Management Summary

QuesTek Innovations LLC is applying its *Materials by Design* computational design technology to develop a new class of high-strength, secondary hardening gear steels that are optimized for high-temperature, low-pressure (i.e., vacuum) carburization. The new alloys offer three different levels of case hardness (with the ability to "dial-in" hardness profiles, including exceptionally high case hardness), and their high core strength, toughness and other properties offer the potential to reduce drivetrain weight or increase power density relative to incumbent alloys such as AISI 9310 or Pyrowear Alloy 53. This new class of alloys utilizes an efficient nanoscale M_2C carbide strengthening dispersion; their key benefits include: high fatigue resistance (in contact, bending and scoring); high hardenability achieved via low-pressure carburization (thus reducing quench distortion and associated manufacturing steps); a tempering temperature of 900°F or higher (providing up to a 500°F increase in thermal stability relative to incumbent alloys); and core tensile strengths in excess of 225 ksi. Ferrium C61 is one alloy in this family and is currently used in transaxle ring and pinions for SCORE 1600 class off-road racing cars as well as process equipment applications. C61 is also being examined in an Army SBIR (Small Business Innovation Research) program as a potential replacement for 9310 in CH-47 Chinook helicopter main rotor mast applications, yielding a projected potential weight savings of 15–25%. Secondly, Ferrium C64 is being developed under a Navy STTR (Small Business Technology Transfer) program aimed at rotorcraft gear transmission applications in order to reduce weight, improve fatigue performance and improve high-temperature operating capability relative to the incumbent alloy Pyrowear Alloy 53. Lastly, Ferrium C69 can achieve a carburized surface hardness of HRC 67 (with a microstructure substantially free of primary carbides) and has exceptionally high contact fatigue resistance, which makes it a candidate for applications such as camshafts and bearings, as well as gear sets.

Introduction

Carburized steel gears are widely used for power transmission in rotorcraft, transportation vehicles, agricultural and off-road equipment, industrial rotating equipment and thousands of other applications. Commonly used alloys such as AISI 9310 (AMS 6265) and Pyrowear Alloy 53 ("X53") (AMS 6308; UNS K71040) have functional limitations that may not meet all of the performance requirements arising in next-generation equipment. Increasing demands to reduce energy consumption, material use and environmental impact are driving the need for dramatic improvements in gear steel manufacturing and performance. For example, the *Gear Industry Vision: A Vision of the Gear Industry in 2025* (published in 2004 by AGMA, ASME and other leading governmental, professional and commercial interests), identified strategic goals such as "Increase power density by 25% every five years (Ref. 1)." Or, as another example, the U.S. Navy estimates that a 20% increase in gear endurance could provide $17 million per year in cost savings to the Defense Logistics Agency alone (Ref. 2).

Past efforts to increase the power density, reliability or endurance performance of gears have included studies of hard tribological coatings; however, many potential coatings do not work well due to processing constraints or poor adhesion to the underlying alloy (Refs. 3–5). Powder alloy approaches have also been studied, but are often inadequate for fatigue-limited applications due to the higher fraction of oxide inclusions and porosity, which can act as fatigue initiation sites. Many improvements in the fatigue performance of commonly used alloys have been made using surface processing technology advancements such as superfinishing, shot peening, laser shock peening or cavitation peening. But these do not improve the intrinsic characteristics of the base alloys. This paper summarizes a first-principles-based, integrated computational materials design approach that is being used to create next-generation, high-performance base alloys with improved performance and reduced manufacturing complexity and variability.

Overview of Computational Materials Design Technology

New materials have historically been discovered either by chance or by intricate and costly cycles of trial and error, yielding a limited understanding of optimization and design. The limitations of the past approach are widely known, and numerous national studies over the past decade have consistently emphasized that traditional, empirical material development methods have not kept pace with modern, design-based product development efforts. One result is that a number of renowned materials companies have all but dropped their labor-intensive internal research and development programs due to their prohibitive cost, and have instead refocused their efforts on reducing costs to manufacture and process generic materials.

The use of powerful computational tools, property databases and intellectual expertise to computationally design and create new materials is a rapidly emerging, alternative approach. These techniques can be used to quickly and economically design and develop unique materials as integrated systems in order to deliver optimal performance requirements for a given application. The Steel Research Group (SRG) at Northwestern University of Evanston, IL pioneered this technology beginning in the mid-1980s. The strategic importance of computational materials design to the national mission was set forth in 2000 when the U.S. President's Office of Science and Technology identified computational design of materials as one of five critical technologies for the coming decade (Ref. 6).

Evanston, IL-based QuesTek is building on the SRG's initial efforts by using its proprietary *Materials by Design* technology to computationally design many new materials, including: iron-, copper-, aluminum-, nickel-, niobium- and titanium-based materials. Dr. Gregory B. Olson, the Wilson-Cook chaired professor in engineering design at Northwestern University's Department of Materials Science and Engineering, is QuesTek's chief science officer and a founder of the company. QuesTek was one of only a few commercial firms highlighted in 2008 by the U.S. National Research Council as examples of firms utilizing Integrated Computational Materials Engineering (ICME) for integrated manufacturing, materials and component design (Ref. 7).

The computational materials design approach considers material design goals and desired performance in the context of a material system. This approach integrates materials process-structure and structure-property models in a systems-based framework in order to meet specific, defined engineering needs, and to also address manufacturing processes and material qualification hurdles (including prediction of manufacturing variation). Like any other design effort, judicious decisions regarding key trade-offs among many competing requirements are often needed. Combinations of properties must be considered within specified process, cost, environmental and life-cycle constraints. Advanced computational modeling tools provide valuable scientific understanding in order to optimize such trade-offs in an efficient and knowledgeable manner, and typically provide enough fidelity to not only determine the favorability of one design solution over another, but to also search for design optima in previously unexplored terrain.

Some of SRG's and QuesTek's work has focused on computationally designing next-generation, high-performance gear steels in order to significantly improve performance properties such as strength, corrosion resistance, wear resistance and fatigue resistance while designing for robust, efficient and flexible processing paths. The new resulting alloys are in a class of QuesTek alloys termed Ferrium alloys.

Design and Overview of Ferrium Gear Steel Alloys

Ferrium C61, C64 and C69 are three new alloys being used or considered for power transmission applications. All of these alloys utilize an efficient nanoscale

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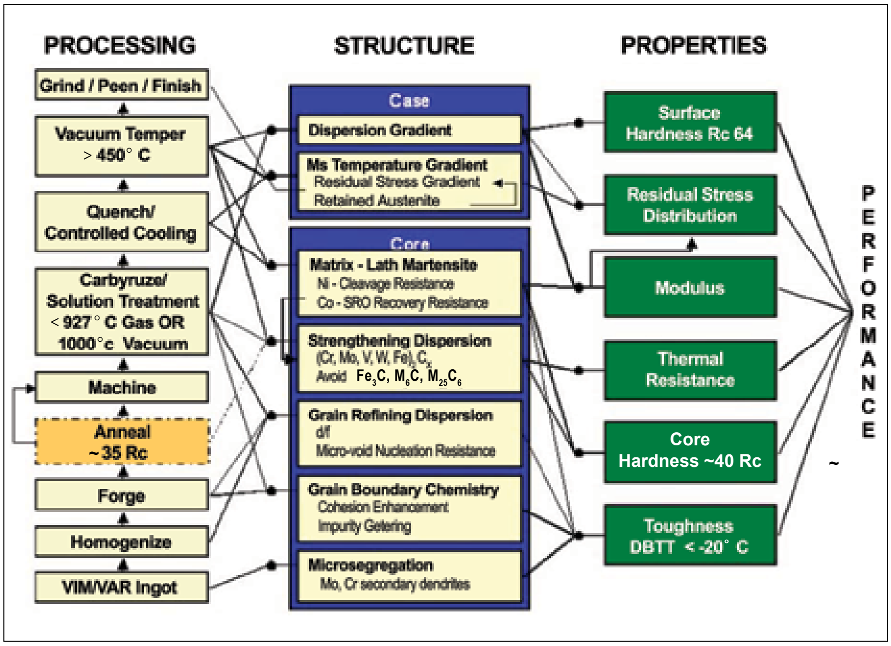

Figure 1—The "Design Chart" used by QuesTek to design the Ferrium C64 alloy. The hierarchical relationships between processing, structure, properties and performance are summarized graphically and serve as the template for alloy design.

M_2C carbide strengthening dispersion within a Ni-Co lath martensitic matrix. Utilizing their suite of computational models, QuesTek designed these alloys considering the complex interplay of critical design factors including: martensitic matrix stability (M_s temperature); M_2C carbide thermodynamic stability and formation kinetics; matrix cleavage resistance; and embrittling phase thermodynamic stability.

The hierarchical relationships between processing, structure, properties, and performance are summarized by QuesTek in the form of a "Design Chart," which serves as the template for alloy design (Fig. 1). The performance of the alloy is embodied in the combination of properties outlined in the column on the right. The design process determines suitable microstructural concepts to meet these property goals, as indicated by the middle column. Available processing paths to access the microstructural objectives are quantified in the left column. The links between the subsystem blocks in the flow-block diagram represent process-structure and structure-property models required to quantitatively design an alloy to meet the desired material performance objectives.

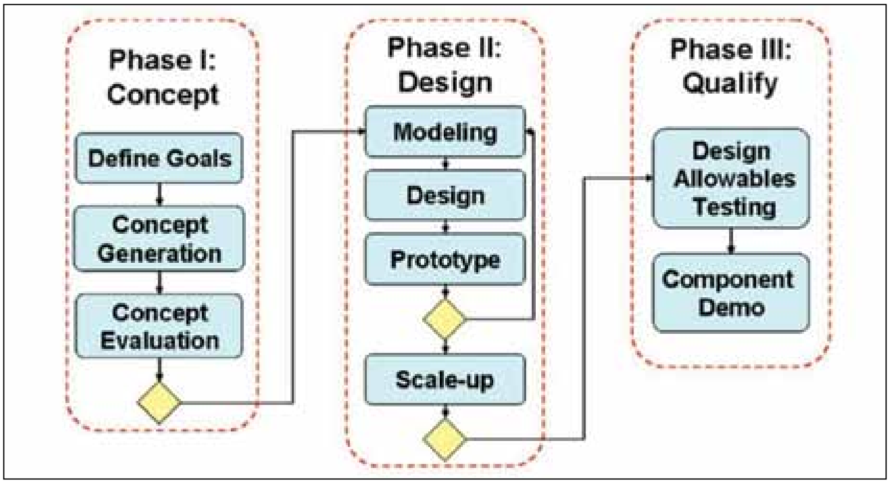

Figure 2—Overview of QuesTek's custom stage-gate process showing the development of a new material from identification of the customer-defined needs through qualification and component demonstration.

Alloy	YS (ksi)	UTS (ksi)	Core Hardness (HRC)	El (%)	RA %	Fracture Toughness (ksi √in)	Achievable Surface Hardness (HRC)	Tempering Temperature (°F)
AISI 9310	155	175	34-42	16	53	85	58-62	300
Pyrowear Alloy 53	140	170	36-44	16	67	115	59-63	400
Ferrium C61	225	240	48-50	16	70	130	60-62	900
Ferrium C64	199	229	48-50	18	75	85	62-64	925
Ferrium C69	195	235	48-50	19	65	40	65-67	925

Figure 3—Tabular comparison of core properties (typical).

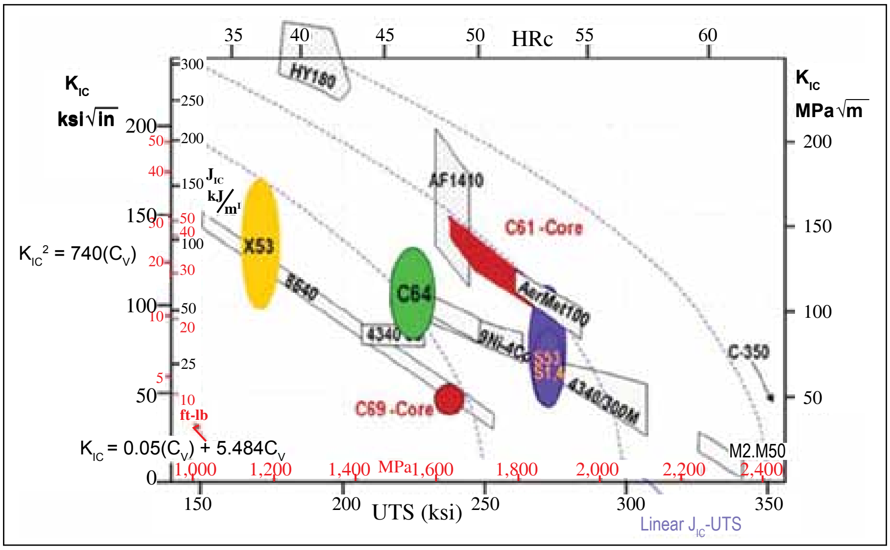

Figure 4—Graphical comparison of core properties and design targets.

As it has done in its other development programs (Ref. 8), QuesTek and its partners utilized its custom stage-gate process, as illustrated in Figure 2, to design and develop the Ferrium alloys in a rapid manner while minimizing development costs. The process begins by working with the key stakeholders, such as gear designers and manufacturers, to establish specific system property goals and processing constraints. Within these customer-defined objectives, QuesTek applied its computational models to explore viable microstructural concepts. With the most promising concept selected, the alloy design plan is reviewed for its viability prior to proceeding to the design phase.

QuesTek's *Materials by Design* process is iterative, with review meetings at critical decision points throughout the modeling, design and prototyping tasks. After completing the initial modeling and prototype designs, QuesTek procures sub-scale ingots to validate the proof-of-concept with material testing and microstructural characterization.

Having achieved the design goals with sub-scale material, QuesTek proceeds to full-scale commercial production. For example, QuesTek prototyped Ferrium C64 with one round each of sub-scale and intermediate-scale prototypes prior to the finalized commercial-scale production.

The objective of the final phase of QuesTek's alloy development process is to develop materials design allowables of the alloy and to manufacture full-scale components. These two tasks may be executed in parallel, depending upon the specific situation at the time. Multiple heats of the alloy may be required for statistical development of materials design allowables. In the case of the gear steels, this includes rotating gear and rig testing to provide statistically validated fatigue design data. The majority of the work in the qualification phase of development is performed by (QuesTek) manufacturing partners and leading adopters of the material. QuesTek's design methodology yielded a number of attractive material properties for C61, C64 and C69 alloys. A tabular and graphical summary of key properties versus common, incumbent materials is shown in Figures 3 and 4.

These properties, and the material processing routes available with these materials, yield performance features such as the following:

Greater core strength. These alloys exhibit core steel tensile strengths (UTS) of 229 ksi or more, which is a + 35% increase versus conventional gear steels and allows significant reductions in part size and weight, particularly where structural components are integrated with gearing into single components.

Greater surface fatigue resistance. These alloys demonstrate high surface fatigue resistance, which leads to increased contact fatigue and bending fatigue performance. Generally speaking, increasing the surface hardness without creating embrittling features (such as interconnected primary carbides) increases surface fatigue resistance. Since surface fatigue resistance can often be a limiting factor in gear design, increased surface fatigue resistance can enable either smaller, lighter-power transmission units or higher power throughput in a given unit size.

High surface hardenability designed to use high-temperature, low-pressure (vacuum) carburization methods. These alloys were specifically designed to achieve high surface hardenability and to use high-temperature, low-pressure (vacuum) carburization and gas quenching processing methods, the combination of which can permit significant reductions in manufacturing costs and schedules due to:

- shorter processing times at higher carburizing temperatures
- elimination of the secondary hardening and oil quench process step, and the associated costs of custom press quench dies, liquid quenchants, rapid transfer mechanisms, hydraulic systems, etc.
- reduction of excess grinding labor, excess stock removal waste and part scrap waste; by reducing part quench distortion and avoiding the intergranular oxide (IGO) formation inherent in a pre-oxidation step, the slower gas quench process is far less severe and far more spatially uniform than a rapid liquid quench
- enhanced manufacturing flexibility and control, due to the ability to "dial in" the depth and profile of case carburization

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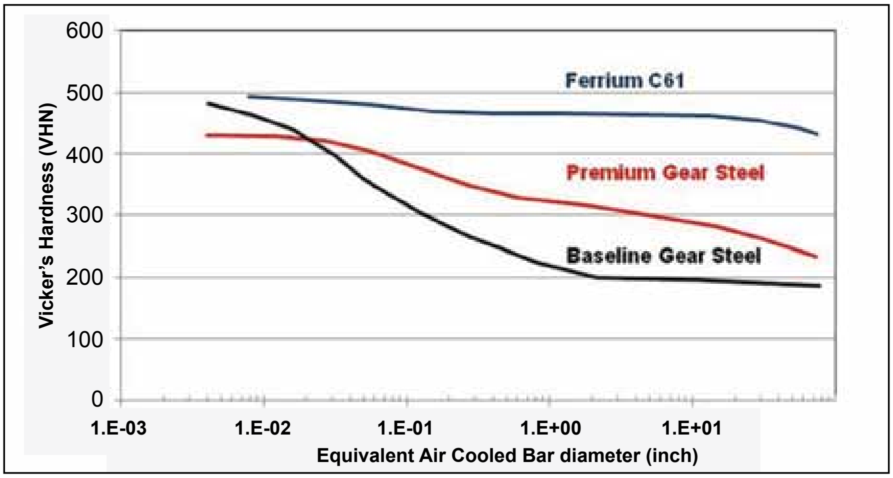

Figure 5—Hardenability comparison for center of an air-cooled bar between legacy baseline steel, current premium grade steel and Ferrium C61.

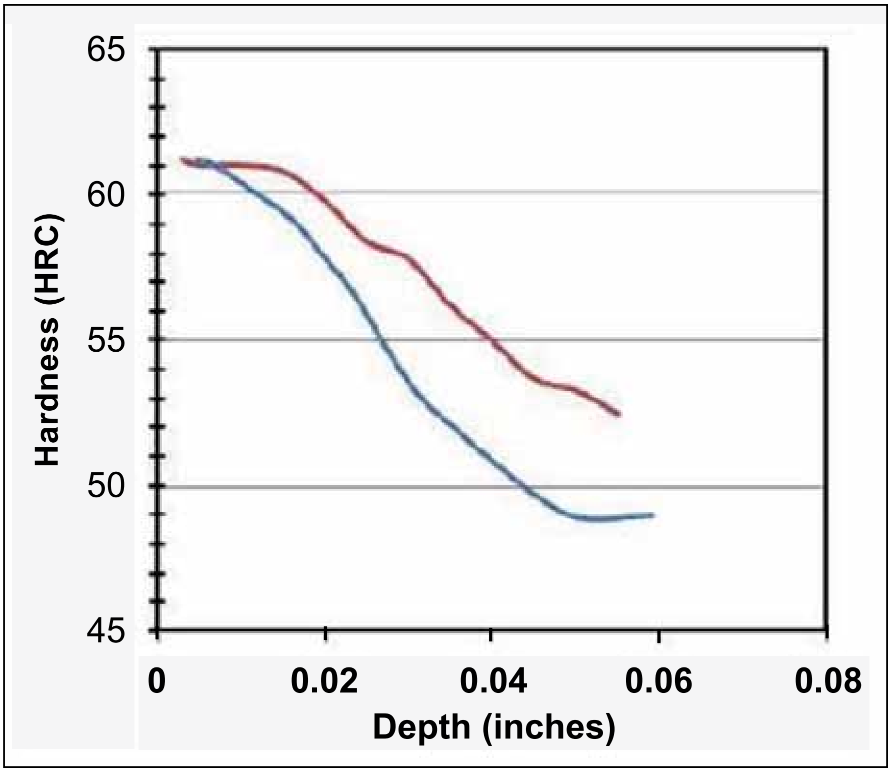

Figure 6—Two different hardness profiles developed in Ferrium C61 using two different carburization and heat treatments illustrate the ability to "dial in" the depth and carburization profile in Ferrium gear steel alloys, in order to allow for differing amounts of lapping or grinding stock removal.

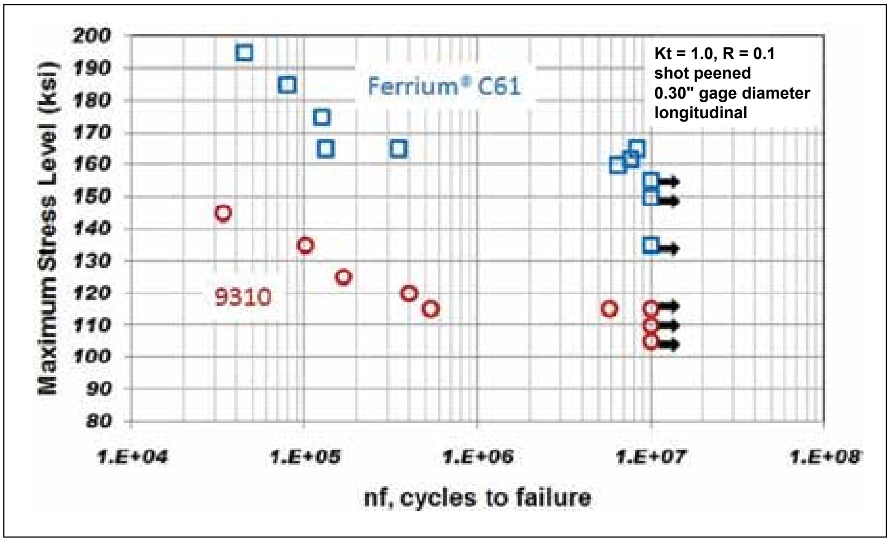

Figure 7—C61 exhibits improved axial fatigue performance relative to 9310, (smooth bar axial fatigue testing, shot peened specimens; arrows denote runouts) in this data developed under U.S. Army Contract #W911W6-09-C-0001.

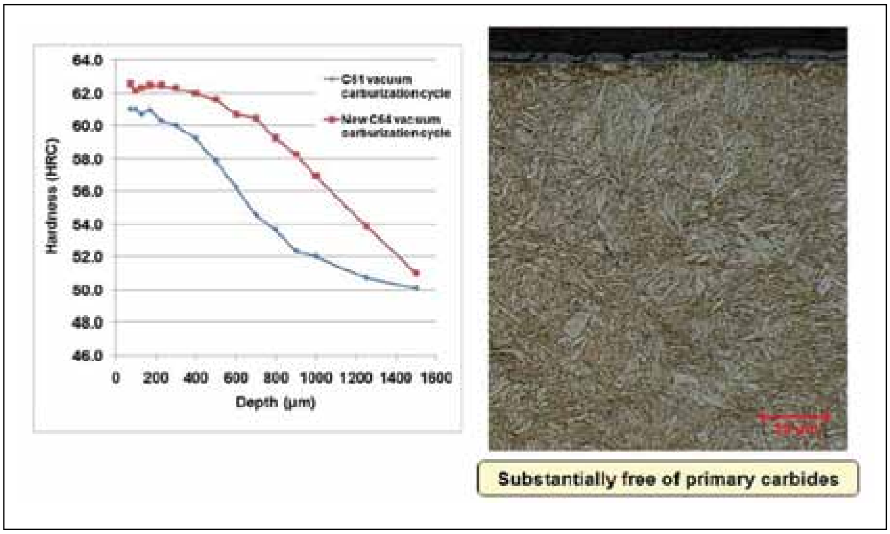

Figure 8—Comparison of C64 and C61 hardness profiles from typical carburization cycles (left), and photograph of C64 microstructure illustrating absence of primary carbides (right).

For example, the high hardenability of Ferrium C61 when compared to a conventional, baseline gear steel, as well as a premium gear steel, is illustrated in Figure 5.

Greater High-Temperature Survivability

These alloys exhibit increased thermal stability versus AISI 9310 or Pyrowear X53 because they were designed to be tempered at 900°F or 950°F, which is up to 500°F hotter than AISI 9310 or Pyrowear X53. Increased thermal stability is expected to result in a greater ability for a gearbox to survive "oil-out" or low-lubricant situations, and to endure other high-temperature operating conditions. Additional information about the properties and development status of each alloy is described separately below.

Ferrium C61. Ferrium C61 was designed to provide a carburized surface hardness of 60–62 Rockwell C Hardness (or HRC), which is similar to conventional gear steels such as X53 (59-64 HRC) and AISI 9310 (58-64 HRC), but delivers ultra-high core strength and excellent fracture toughness comparable to AerMet 100. C61 has surface-wear properties, toughness (~130 ksi√in), and case fatigue properties that are similar to those of current commercial alloys, but C61's typical core hardness of 49–50 HRC far exceeds X53's core hardness of 36–44 HRC. In addition to increasing the maximum allowable load, the increased core strength has been shown to increase fatigue strength. C61's good combination of strength and toughness can enable weight reductions in shafts and other integral structural components compared with alternative gear materials.

As summarized earlier, the ability of this class of alloys to use low-pressure (vacuum) carburization and gas quenching offers a number of benefits, including reduced part distortion during quenching (to reduce subsequent machining waste and scrap) as well as simpler part clean-up. The ability to "dial in" the depth and profile of carburization in this class of alloys is illustrated in Figure 6, which shows two different hardness profiles achieved in C61 using different carburization and heat treatment cycles.

This flexibility in creating hardness profile depths and profiles provides gear designers and manufacturers the opportunity to optimize the material for best performance. To achieve this variation, several boost cycles ranging from 20–120 seconds and diffuse cycles ranging in time from 15–45 minutes have been used to achieve targeted case depths of about 0.040" with the various profile shapes. Various carburizing cycles have been developed for C61 in order to develop different case depths and profile shapes. It is anticipated that SAE AMS 2759/7 (when issued) will provide specific thermal processing guidelines for C61. One independent review of low-pressure carburization process cycles, including for C61, is also available in the recent literature (Ref. 11).

Ferrium C61 has found considerable success in off-road racing, and in particular in the 1600 class of the SCORE off-road desert racing series. The rules for the 1600 class in the SCORE racing series require 1600 cm^3 engines and 091 Volkswagen transaxles, which were originally designed to accommodate 40–60 horsepower in street vehicles. When used in off-road racing, the modified engine power output is double that of the stock engine, and the drivetrain experiences severe impact loads due to the rough terrain, which results in these transaxles being loaded far in excess of their design limits. Ring and pinion sets made from C61 have proven to be far more durable than those made of other gear steels. The C61 ring and pinion set was officially introduced in January 2005 at the SCORE Laughlin Desert Challenge, with over 40% of the cars adopting C61 sets by the end of the first season. C61 gear sets do not typically need to be replaced after each race, as is commonly necessary for sets manufactured from 8620. Ring and pinion sets made of C61 are typically replaced only once per racing season, whereas 9310 sets were often replaced after each race (which greatly increases the time and cost to prepare the car before each race). In general, ring and pinion gear sets manufactured from C61 are achieving at least 3–4 times greater lifetimes than the same sets manufactured from 9310, with some C61 ring and pinion sets lasting as long as two full racing seasons. C61 has also been applied in process machinery and other power transmission applications.

C61 can offer an attractive combination of properties for integral power shaft and gearing applications, where both the core strength and the fatigue strength of an alloy are critical. As an example, C61 is being evaluated for main rotor shaft applications on the Boeing-designed CH-47 Chinook helicopter in a U.S. Army Small Business Innovation Research (SBIR) program. Main rotor shafts, specifically those used on the CH-47, are among the largest, heaviest, and highly loaded single components on rotorcraft. With its improved core properties (Fig. 3), use of C61 in lieu of the currently used carburized 9310 may be able to reduce the weight of the main rotor shaft on the CH-47 by 15–25% without requiring significant changes in the production process of the component. C61 may also provide benefits in thermal resistance, ballistic performance, and stress-corrosion cracking resistance; i.e., a material upgrade may hold promise for both weight reduction and performance enhancement. Data developed under this SBIR program demonstrates the superior axial fatigue life performance of C61 versus 9310 (Fig. 7).

Ferrium C61 material is commercially available from a major commercial alloy producer operating under a license from QuesTek. QuesTek anticipates licensing additional producers in order to establish a robust, competitive market for C61. The composition of C61 is covered under U.S. Patent Number 6,176,946 B1. QuesTek also anticipates beginning the process of obtaining an SAE Aerospace Material Specification for C61.

Ferrium C64. QuesTek is currently developing Ferrium C64 under a U.S. Navy STTR program to achieve higher surface hardness than C61 while retaining superior core hardness, fracture toughness, high allowable operating temperature, and other manufacturing benefits. The platform sponsor is the V-22 Osprey and an ultimate improvement in rotorcraft transmission power density is sought relative to Pyrowear Alloy 53, the incumbent carburized gear steel. Ferrium C64 material is commercially available from a major commercial alloy producer, operating under a license from QuesTek.

The primary anticipated benefit of this STTR program is to demonstrate dramatic increases in main gearbox power densities within the Navy's rotorcraft fleet. New materials to increase power load and reliability without increasing the size of these components would have a significant impact. While C64 was designed and developed within this STTR program specifically for helicopter gears, it is expected to be applicable to other non-military, high-performance power transmission applications where weight, compactness, durability and high-temperature capability are valued.

This establishment of the design requirements and the development of the alloy was a collaborative effort among materials design engineers at QuesTek and the Navy; gear and drivetrain engineers from Bell Helicopter Textron Inc.; and gear testing experts from the Gear Research Institute (GRI) at The Pennsylvania State University.

Ferrium C64 has been produced at full industrial scale (multi-ton) in final product sizes of 4.5" OD and 6.5" OD. Vacuum carburized surface hardness profiles show a marked increase in surface hardness over C61 with a carburized surface microstructure that is substantially free of primary carbides

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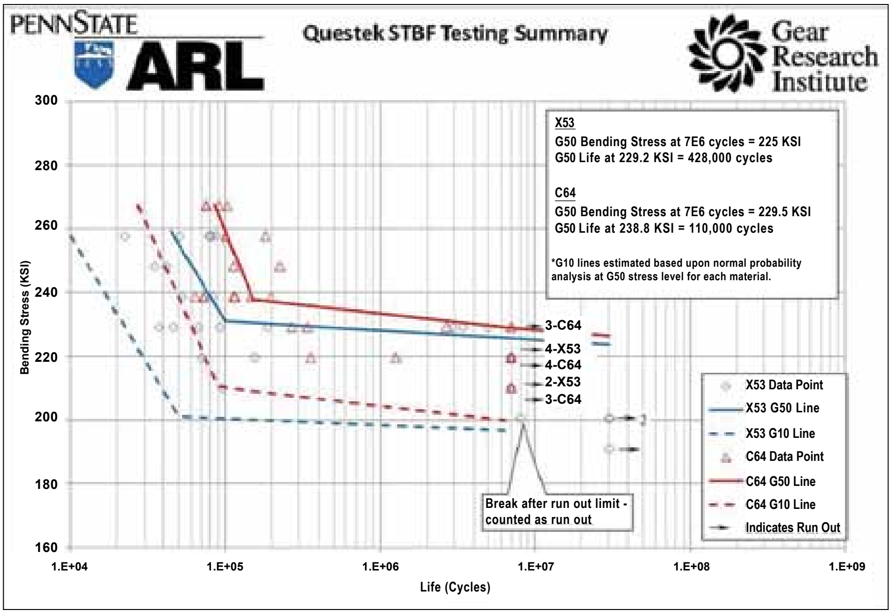

Figure 9—Results of single tooth bending fatigue (STBF) tests of C64 in comparison to X53.

(Fig. 8). Development of fatigue data is ongoing under the Navy STTR program, and single-tooth bending fatigue (STBF) results have been developed (Fig. 9). With fatigue performance comparable to that of X53, C64 is particularly attractive as a "drop-in" X53 replacement due to its high hardenability, ease of manufacturing and processing, and temperature resistance.

Rotating fatigue tests (contact fatigue, bending fatigue, scoring fatigue) are currently being planned for C64 in conjunction with Penn State. Other evaluations may include temperature resistance tests ("oil-out" testing) and full (planetary) gear rig testing.

The rapid development of Ferrium C64 illustrates the power and speed of using a computational material design approach to capitalize on specific product design needs as well as opportunities for product/material improvement. The material design goals and the Design Chart (i.e., Figure 1) were formulated in September 2005, under Office of Naval Research contract #N00014-05-M-0250 (issued August 9, 2005). In less than one year, the basic alloy composition and processing route were computationally designed, and the alloy was produced at a 30 lb. prototype size. In less than two years, the material was successfully produced at full industrial scale (i.e., 10,000 lbs.).

Ferrium C69. Ferrium C69 is a high case hardness variant that can be tempered to achieve a case hardness of up to 67 HRC, and yet be substantially free of primary carbides in the microstructure. These surface properties can allow higher power density or greater surface wear resistance than conventional commercial carburized gear steels, with potential uses such as select gearbox applications, camshafts and bearing surfaces.

High case hardness is correlated with high contact fatigue resistance and bending fatigue resistance. The NASA Glenn Research Center performed contact fatigue testing on C69 using its spur gear fatigue rigs, the same rigs used for identical tests on current commercially available gear steels. A set of C69 gears that was tested represent the best-performing set of "standard-ground finished" gears tested to date on the NASA Glenn Research Center's gear test apparatus. C69 demonstrated almost a threefold increase in fatigue cycles at the L50 life and almost a twofold increase at the L10 life over Pyrowear X53. Microhardness traces were taken from the flank, mid-flank and root to verify consistent properties. In each instance the case hardness was 65 to 66 Rc, which is well above the 60—62 Rc observed in 9310 and Pyrowear X53. Figure 10 shows data generated by NASA Glenn on both C69 and Pyrowear X53. Additional data from these tests has been published elsewhere (Ref. 12). A high hardness case material such as C69, C64 or C61 can maintain increased residual compressive stress upon shot peening or laser shock peening, which has additional benefits for fatigue resistance. QuesTek fully expects an additional, sizeable benefit in contact fatigue performance from shot peening of C69, C64 or C61. However, for a fair comparison and for consistency with previous NASA tests, none of the C69 specimens tested for Figure 10 were shot peened.

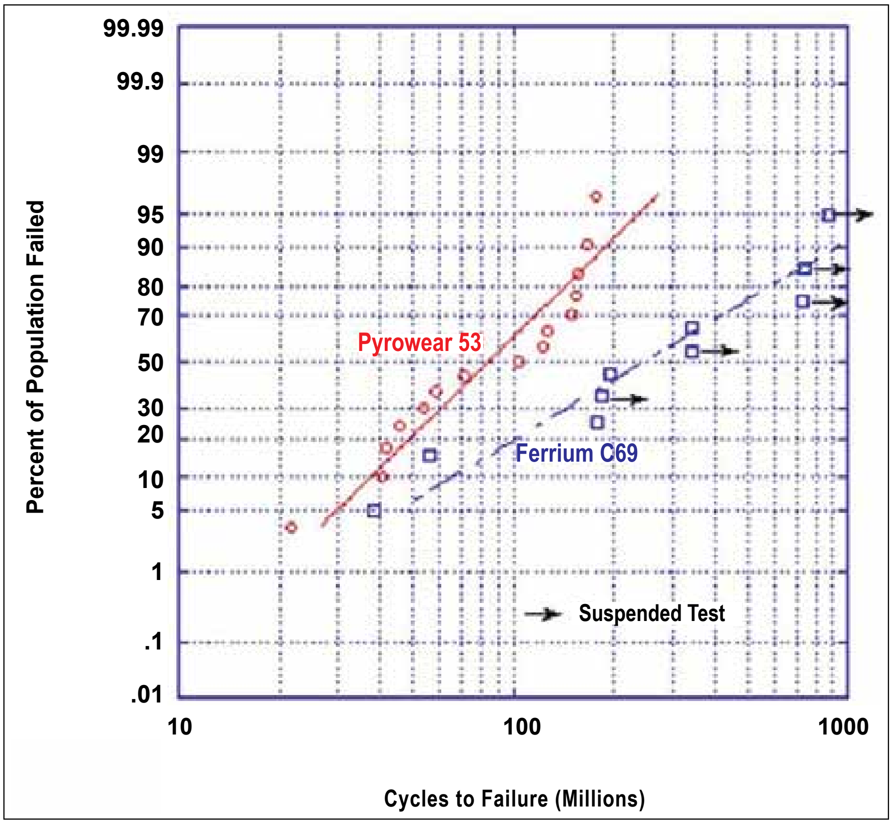

Figure 10—Surface contact fatigue probability plot for Ferrium C69 and Pyrowear X53 generated by NASA Glenn Research Center.

Ferrium C69 is currently available in prototype quantities directly from QuesTek. QuesTek expects to license the production of C69 to commercial alloy producers in response to market demand. The composition of C69 is covered under U.S. Patent Number 6,176,946 B1.

Conclusions

Integrated computational design methods, models and property databases continue to rapidly advance and improve, yielding rich design insights into controlling key property performance issues such as strength, thermal stability, fatigue resistance, ductility and corrosion resistance. These cutting-edge tools apply to the design of both materials as well as material processing and manufacturing, and can quickly and efficiently find optimal solutions, identify failures, and search optimums in previously unexplored concept spaces.

The design of Ferrium C61, C64

and C69 alloys provides a case study illustration of computational material design tools and principles applied to iron-based material microstructures. This new class of gear steel alloys utilizes an efficient M_2C precipitate strengthening dispersion, and offers a number of key benefits in manufacturing, as well as performance, over incumbent alloys such as: reduced manufacturing complexity and variability by using low-distortion gas quenching and by eliminating liquid quenchant systems and steps; reduced gear set weight and increased power density due to increased surface fatigue resistance; improved "oil-out" survivability (due to a 500°F + increase in thermal stability); and increased core material properties. In summary, the computational design process has yielded three interesting, highly processable alloys that appear to offer significant advantages over several traditional material alternatives for power transmission applications.

Acknowledgements

The authors would like to thank the U.S. Navy for support via Contracts #N00014-05-M-0250 and #N68335-06-C-0339; the U.S. Army for support via Contracts W911W6-04-C-0023 and #W911W6-09-C--0001; the DOE for support via Contract #DE-PS07-01ID14026; and Batelle/NASA for support via Grant #169855.

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Producing Profile and Lead Modifications in Threaded Wheel and Profile Grinding

Dr. A. Türich

Management Summary

Modern gearboxes are characterized by high torque load demands, low running noise and compact design. In order to fulfill these demands, profile and lead modifications are being applied more often than in the past. This paper will focus on how to produce profile and lead modifications by using the two most common grinding processes—threaded wheel and profile grinding. In addition, more difficult modifications—such as defined flank twist or topological flank corrections—will also be described in this paper.

Introduction

The main reasons for gear modification are to compensate for the deformation of the teeth due to load and to ensure a proper meshing to achieve an optimized tooth contact pattern (Fig. 1). Figure 2 shows typical flank modifications that may be subdivided into profile and flank modifications (Ref. 1). Both modification types are defined separately but can be superimposed. The most common modifications—profile and lead crowning—are utilized in order to achieve a good contact pattern without having contact on both ends of the flank at either the tip or root area. Other designs are tip and root relief, and end relief. Profile or lead angle modifications are used to compensate for deformation of the teeth themselves, but also for shaft deformation within the gearbox resulting in non-parallel axes. All of these modifications can be combined and thus result in complex flank modifications (Refs. 2–3).

Beyond these "standard" modifications, it is also possible to define so-called topological modifications where each point on the tooth flank has its own amount of modification (Ref. 4). These kinds of modifications are much more difficult to produce than the standard modifications. Scores of publications deal with methods and ways of determining the optimized modification for gear sets under load considering gearbox and shaft deflection, as well as dynamic effects (Refs. 5–6). This paper does not concentrate on such an approach, but describes how to produce these kinds of modifications in the two most common fine finishing technologies, i.e.—threaded wheel and profile grinding.

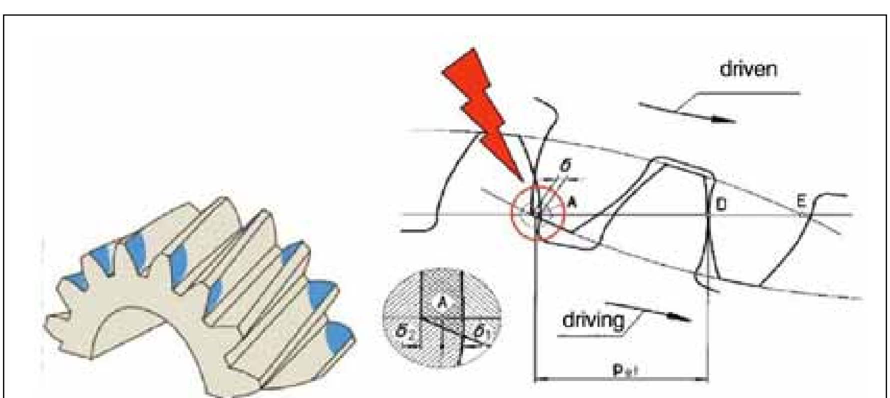

Figure 1—Reasons to modify gears.

Threaded Wheel Grinding

Threaded wheel grinding is characterized by high productivity due to the continuous process kinematic, and is used mainly for small-to-mid-size gears up to module 7–8 with a minimum diametral pitch of 3.175. As such, this technology is used mainly in automotive and light truck applications, but also for larger gears with high numbers of teeth and small modules. Examples include printing machines or industrial gearbox applications. Figure 3 shows the required kinematic for threaded wheel grinding (Ref. 1). A machine for threaded wheel grinding needs several axes to perform the required kinematic. First of all, the gear to be ground and the threaded grinding wheel have to be swiveled into a certain angle that is the sum of the gear helix angle β and the wheel lead angle γ_0. Both gear and wheel are mating together like a gear set. Hence the rotation of the wheel n_s, which results in the cutting speed v_c (red arrows in Fig. 3) and the rotation of the gear n_w, have to be synchronized. In order to remove material from the teeth, the gear or the wheel needs a radial infeed motion (blue arrow) perpendicular to the gear axis. In addition, the wheel has to perform an axial feed motion (green arrow) along the gear axis. In cases where the gear is helical, as shown in this figure, it must fulfill an additional rotational movement in order to follow the lead. Since the contact area between the wheel and the gear is smaller than the wheel width, a fourth motion is required (yellow arrow) to shift the wheel along its face width, thus using the full face width. This is the so-called shifting, which can be done continuously during the axial movement or non-continuously after a grind cycle. All of the above-described movements must be synchronized precisely in order to achieve good gear quality (Ref. 1). This synchronization is done by the machine axis following the mathematical equations presented in the bottom section of Figure 3.

When cutting the wheel and the gear along the working section, we get the normal section shown on the right-hand side of Figure 3. One can see the rack profile of the wheel characterized by the wheel pressure angle α_0 and the lead, which is module m_{n0} times π times number of threads z_0. Due to the mating movement, this rack profile is finally generating the involute shape of the gear. The shown kinematic will result in a perfect gear without any modifications.

The above-mentioned flank modifications can be achieved by using threaded wheel grinding. Thus, all profile modifications have to be generated by the dressing tool since this is defining the exact shape of the rack profile. All flank modifications are produced by the machine kinematic (Fig. 4).

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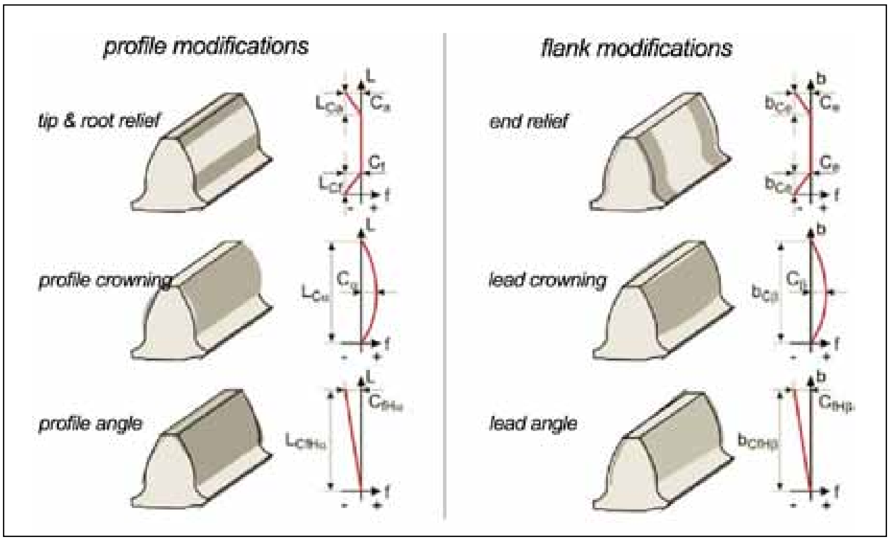

Figure 2—Typical flank modifications.

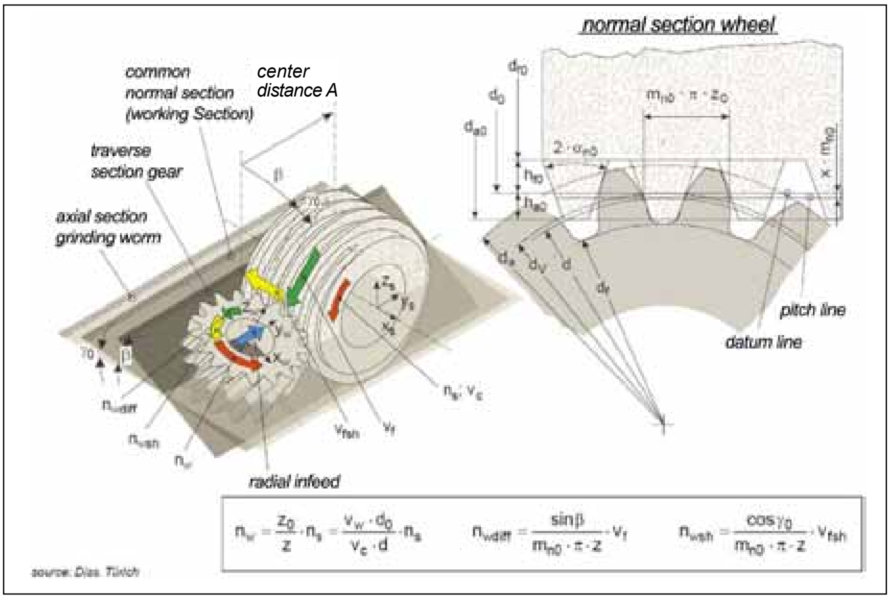

Figure 3—Kinematics in threaded wheel grinding.

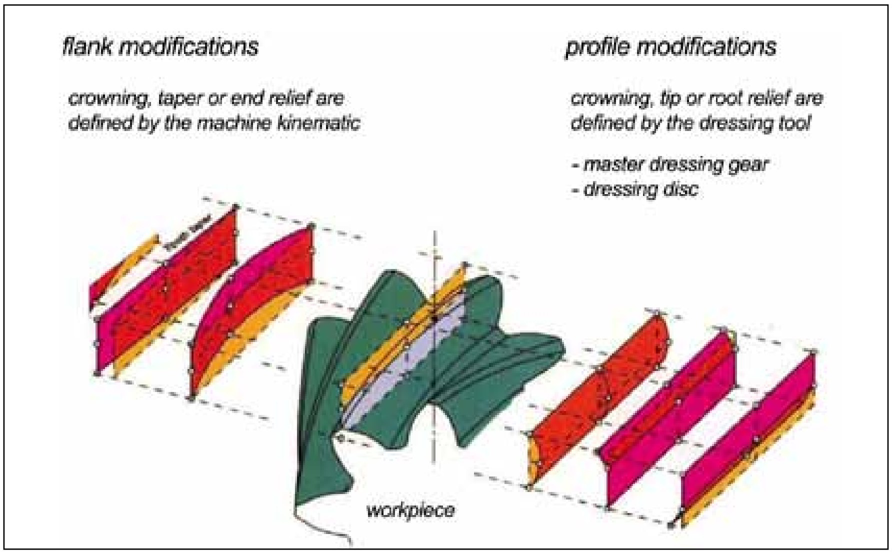

Figure 4—Modifications in threaded wheel grinding.

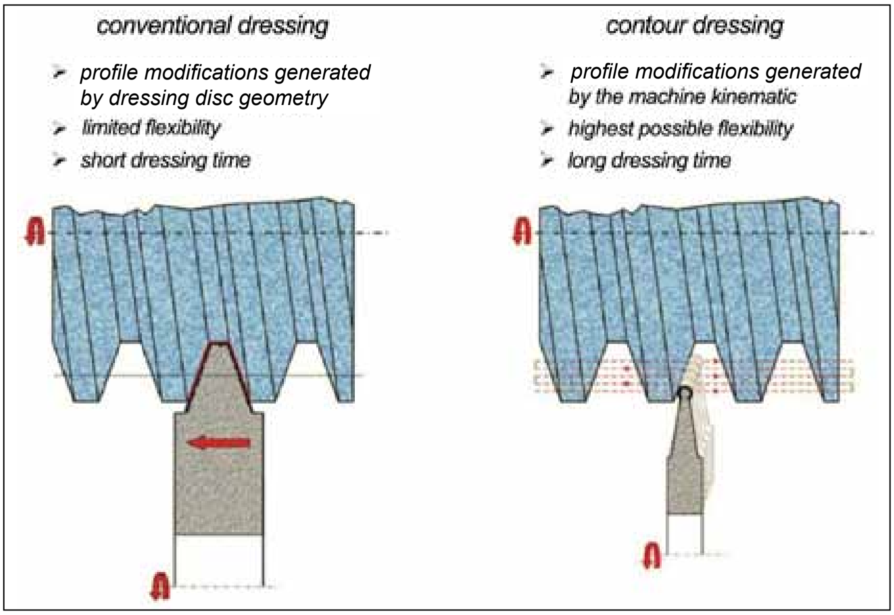

Figure 5—Dressing principles in threaded wheel grinding.

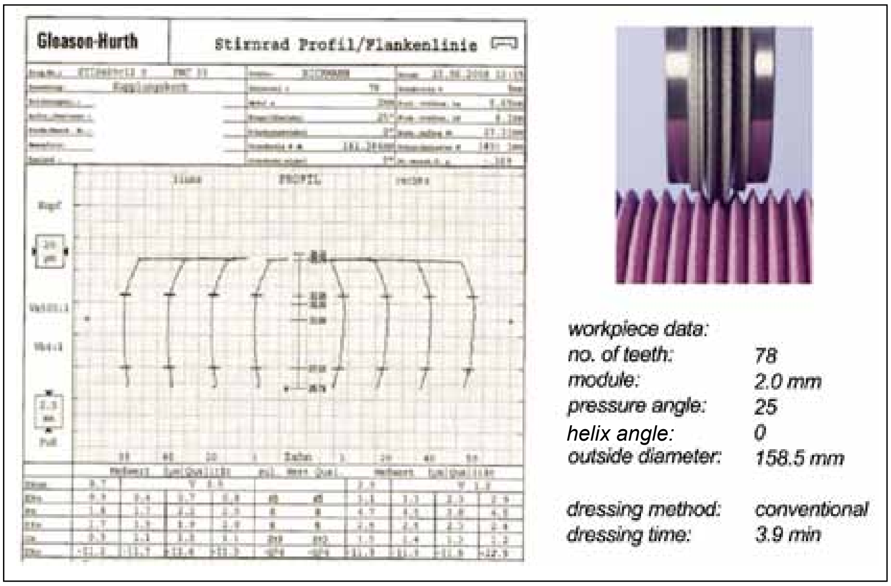

Figure 6—Profile generation by conventional dressing.

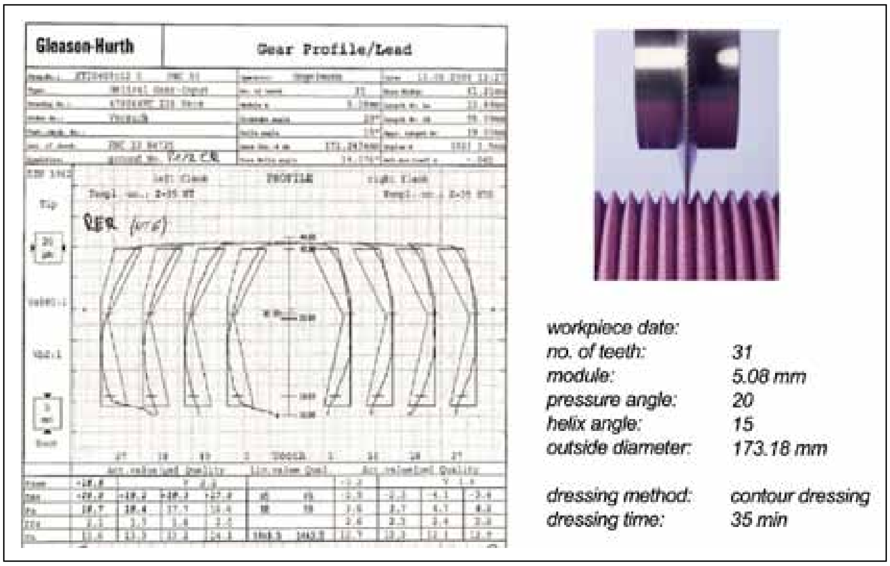

Figure 7—Profile generation by contour dressing.

Where the gear needs a certain profile modification—such as crowning—a corresponding shape has to be dressed into the rack profile in order to generate the required amount of profile crowning during the grind cycle (Ref. 7).

Figure 5 shows two different dressing principles used in threaded wheel grinding (Ref.7). The left-hand side shows the most common method, using dressing discs that are copying their shape into the rack profile. But the shape of the profile modification must be known when designing and producing such a dressing disc. A typical result using such dressing discs is shown in Figure 6. The profile on the left and right flank includes a tip relief as well as a slight profile crowning. The flexibility of such a dressing tool is very limited and, in principle, can only be used for one type of gear. But due to the line contact between the dressing tool and the grinding wheel, the dressing operation is relatively short (3.9 min, for example, shown in Figure 6).

Considering the long lead times for conventional dressing tools, it might be necessary in some cases to be more flexible. Contour dressing, shown on the right-hand side of Figure 5, can be used to achieve the highest possible flexibility. In this case, a dressing tool is used that is generating the required wheel shape by NC motions. The shape of the dressing disc itself is independent from the wheel rack profile. This opens a wide area for profile modifications, but on the other hand, the dressing operation needs much longer dressing time (Ref. 7).

A typical result using contour dressing is shown in Figure 7. The required profile was defined by so-called K–charts and was programmed using the machine interface presented in Figure 8. Such a contour dressing cycle needs about 30–40 minutes, compared to 4–5 minutes for conventional dressing in normal dressing conditions. So the advantage of contour dressing is offset by longer dressing times.

Figure 8 shows a typical interface

of modern machine software for programming profile modifications in contour dressing. Left and right flanks can be programmed separately. The user defines the target profile of the gear, and the machine automatically calculates the corresponding rack geometry and all required movements for the contour dressing cycle.

As mentioned, lead modifications are generated by the machine kinematic. Therefore, the kinematic for threaded wheel grinding described in Figure 3 has to be superimposed by additional movements to achieve the modifications. Figure 9 explains the two main principles that are used for these movements. As presented on the left-hand side, a change in the radial infeed (x-axis) results in more or less stock removal on left and right flank. So if a symmetrical lead crowning is required, as shown in Figure 10, a curved shape x–movement dependant upon the z–position (face width of the gear) is necessary, defined by a function x(z).

Changing the tangential feed (Y–movement), as shown on the right-hand side of Figure 9, without changing the rotational position of the gear results in more stock removal on one flank and less stock removal on the opposite flank.

By superimposing the two functions x(z) and y(z), any kind of lead modifications can be achieved. An example how to achieve an unsymmetrical lead crowning is shown in Figure 11.

In this case, a parabolic function has been chosen for both additional movements y(z) and x(z). The parabolic y(z) function leads in a hollow-shape crowning on the left flank and a barrel-shape crowning on the right flank, while the same parabolic function for the additional x(z) movement results in a barrel-shape crowning on both flanks. Since both functions are superimposed, the result is a straight-lead flank on the left flank and a crowned flank on the right flank. Figure 12 shows a grinding result using this method and

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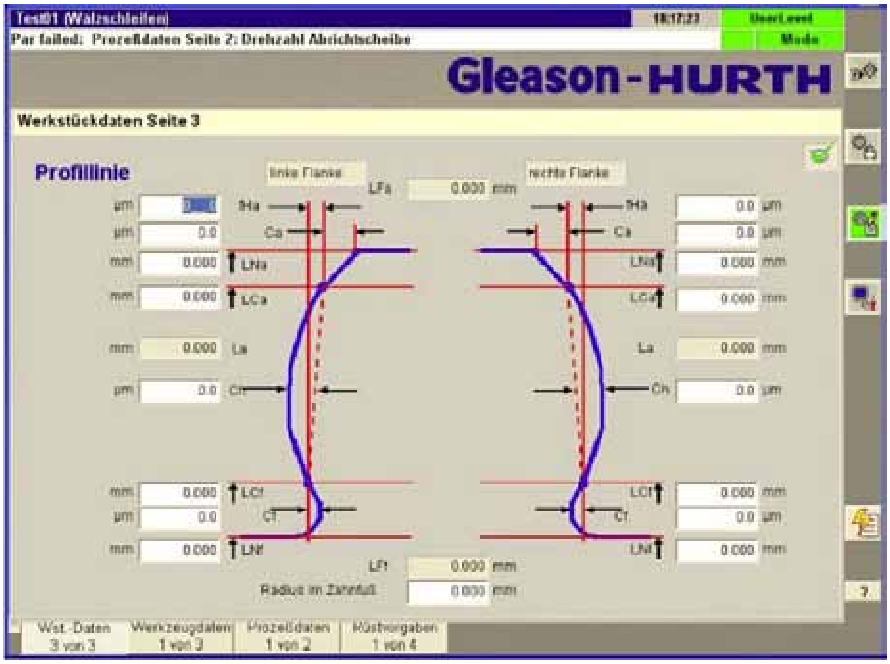

Figure 8—Contour dressing programming interface.

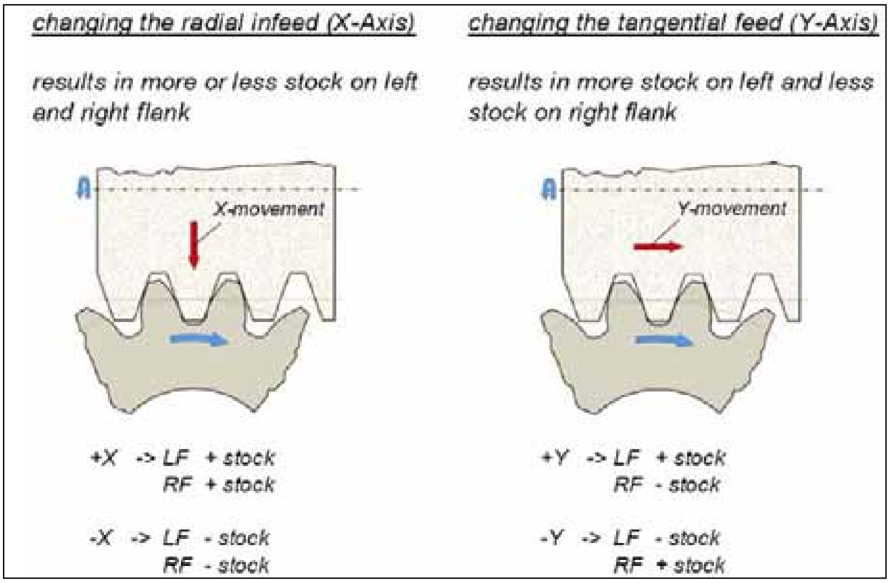

Figure 9—Generation of lead modifications.

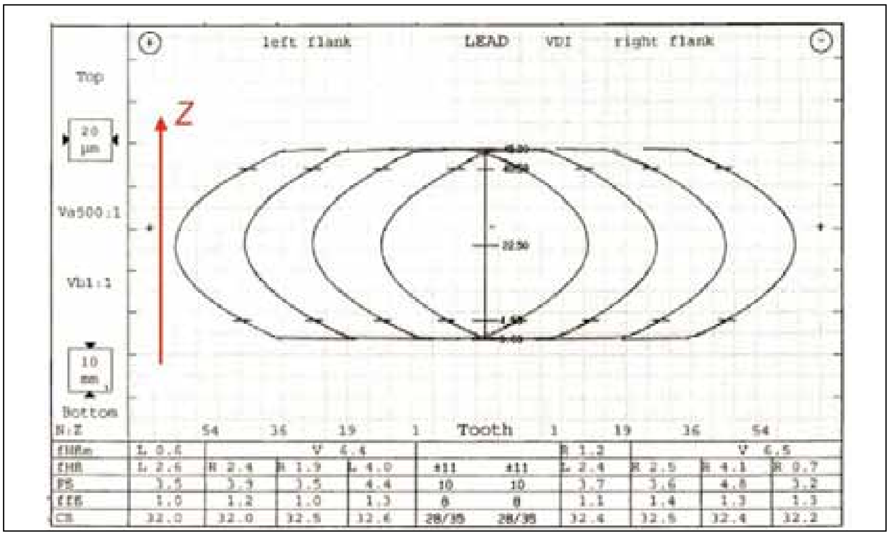

Figure 10—Example of symmetrical lead crowning generated by a parabolic function: x(z).

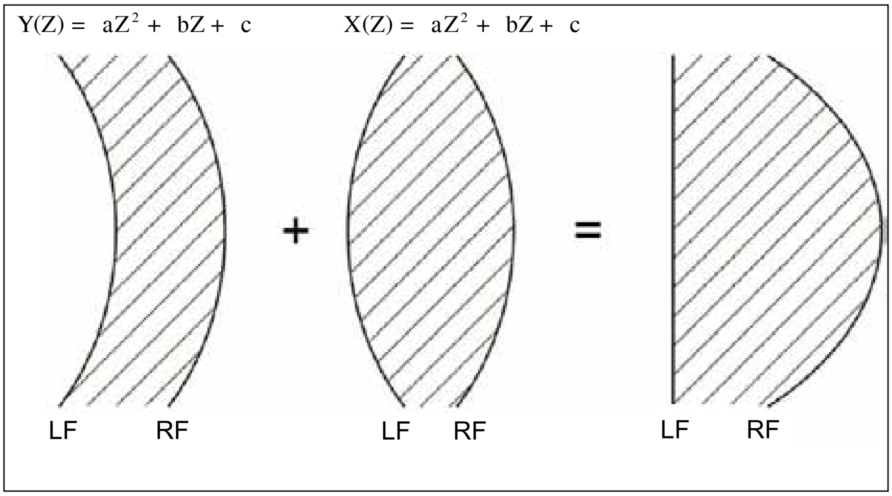

Figure 11—Principle to achieve unsymmetrical lead crowning.

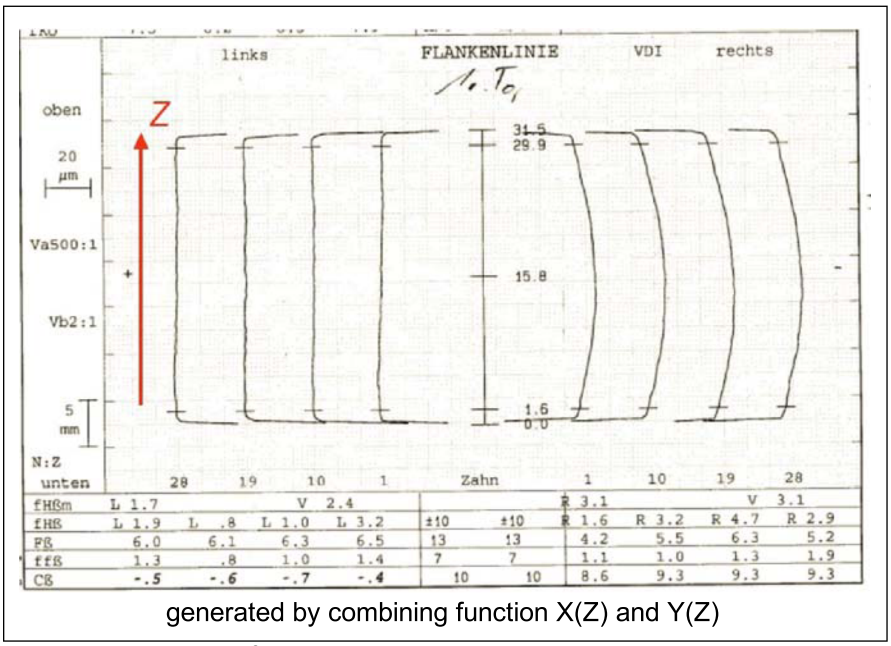

Figure 12—Example of unsymmetrical lead crowning generated by combining functions x(z) and y(z).

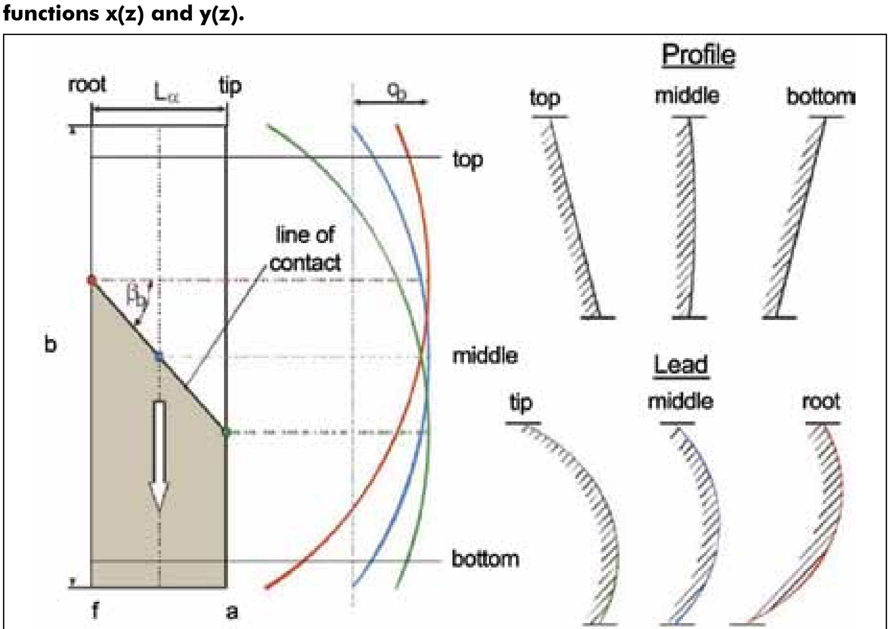

Figure 13—Contact line and twist generation in threaded wheel grinding.

proves how beautifully this method works. This principle can also be used to achieve much more complex modifications.

Up to now, profile and flank modifications were handled separately. But when grinding helical gears, lead modifications always influence the profile modification. The reason for that is the contact line between the grinding wheel and the gear tooth, which runs diagonal over the tooth as shown in Figure 13. Thus all points along this line are generated at the same time. In the case of grinding a symmetric lead crowning, a parabolic function x(z), as mentioned above, will result in a change of radial infeed over the face width "b" of the gear. Usually, the high point of a crowning is set to the middle of the teeth in terms of face width and profile height as represented by the blue point in Figure 13. Since all points along the line of contact are generated at the same time, the result is that the root area, represented by the red point, achieves its crowning high point displaced to the top of the gear. The tip area, which is represented by the green point, achieves its highpoint displaced to the bottom of the gear. The lead crowning is only symmetrical in the middle of the gear. If we measure the lead crowning in the root (red line) and tip area (green line) of the tooth, the crowning would be displaced, looking like a lead angle error. At the same time, this also affects the profile modification. The middle section has no profile error, save for a slight crowning effected by the lead crowning. The top and bottom profile lines are showing a clear profile angle error. The above-described effect is what is known as the twist phenomena, and appears when grinding helical gears with a lead crowning. Figure 14 shows a grinding result where this effect can be seen. The amount of twist error—which is defined as the absolute change in profile angle error from top to the bottom—is for this example about 25 mm, and much more than the allowed tolerance. This phenomenon is not desired.

The question now is how can this effect be compensated for and/or controlled? When looking to Figure 13 or 14, it becomes obvious that a method is required that allows grinding different profile modifications at different sections along the gear face width, which is nothing else than topological modifications. So in order to compensate or control the twist phenomena, it is necessary to at least partially compensate for the profile angle error, which changes from top to bottom on the gear. In addition, it is different in terms of its sign on the left and right flank. Gleason has a patented method to do such a compensation, which can also be used to grind topological modifications.

This method works with a modified wheel shape, along the wheel face width. As shown in Figure 15, the right-hand side of the grinding wheel is not dressed in a cylindrical shape, but rather in a hollow shape. This can easily be done during the dressing cycle by infeeding the dressing tool perpendicular to the wheel axis, again using a parabolic function across the wheel face width with no additional machine axis necessary. When looking to the detail on the left-hand side of Figure 15, one can see how such a dressed hollow-shape grinding wheel affects the grinding result. One can assume the gear being ground in this area would generate teeth with different pressure angles on the right and left flank. The right flank would be ground with a pressure angle that is the pressure angle α of the rack profile, plus an angle $\Delta\alpha$, while the left flank would be generated with a pressure angle of α minus $\Delta\alpha$. The angle $\Delta\alpha$ is the angle deviation between the perpendicular and the shortest distance between the gear center and the curved datum line (dotted line) of the rack profile.

It then becomes obvious that by choosing different positions along the wheel face width, one can influence the profile pressure angle generated on the gear teeth. Since the above-described profile angle error is nothing more than a different pressure angle, it is clear how to compensate or control this effect. The gear is therefore continuously shifted along the wheel face width while performing the axial stroke as shown in Figure 16. The result is that the right side of the wheel grinds the top part of the gear, while the wheel middle portion grinds the middle

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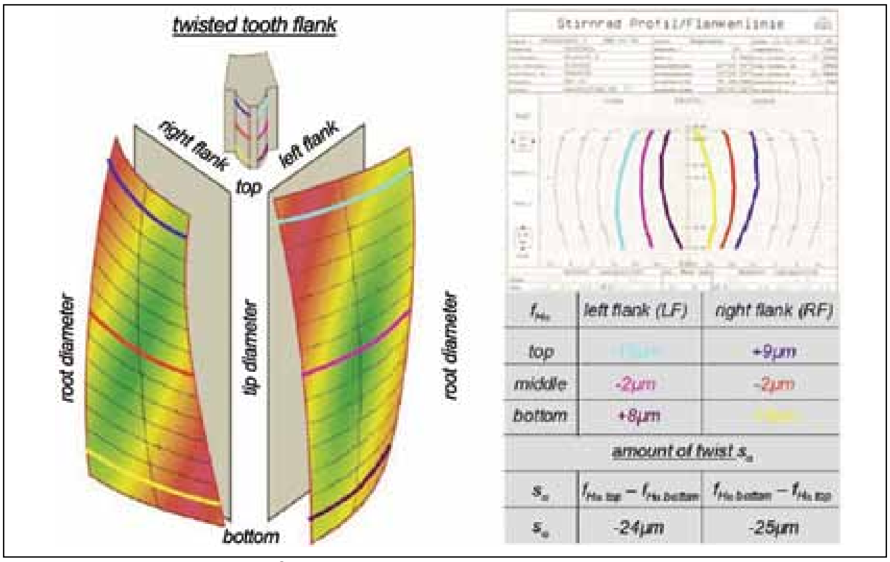

Figure 14—Twisted tooth flank.

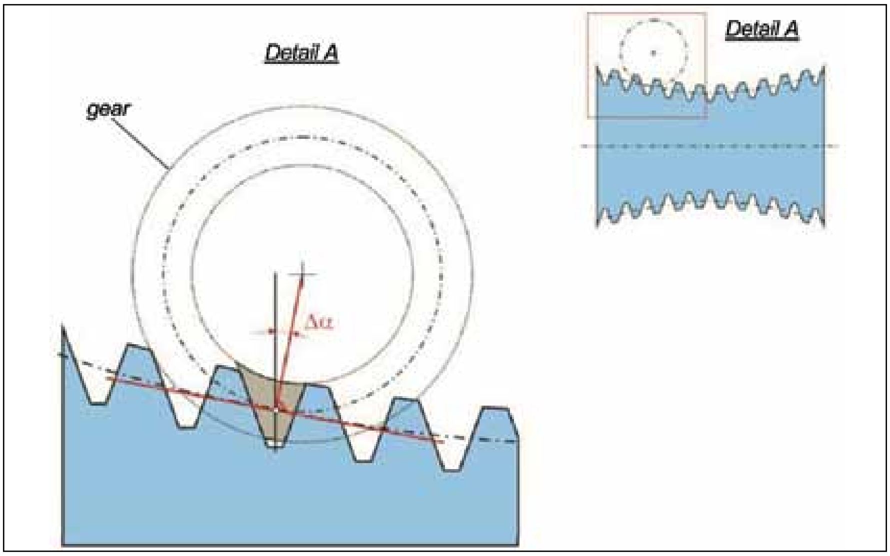

Figure 15—Principle of twist compensation.

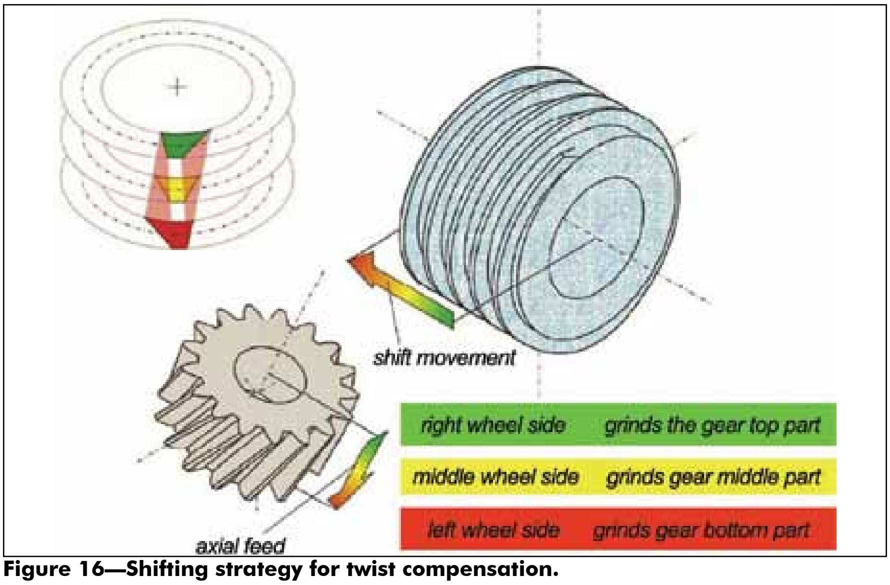

Figure 16—Shifting strategy for twist compensation.

section of the gear and the left wheel side grinds the bottom section of the gear (Ref. 8).

By considering the effect described in Figure 15, this method will result in gear teeth having different pressure angles from the top to bottom, and different signs on left and right flanks. Since this effect is superimposed with the natural amount of twist, it is obvious that by using this method one can compensate for, or control, the amount of twist. But this method can also be used to create different kinds of profile modifications along the face width of the gear that may be other than a topological modification.

Figure 17 shows two grinding results demonstrating the effect of this twist compensation method. The left-hand inspection diagram represents a gear ground without the compensation method described above. And so one can see a clear amount of twist in profile and lead. The right-hand diagram represents a result of the same gear type, but ground with this twist compensation method. It is very clear that the amount of twist has been compensated and demonstrates how well this method works.

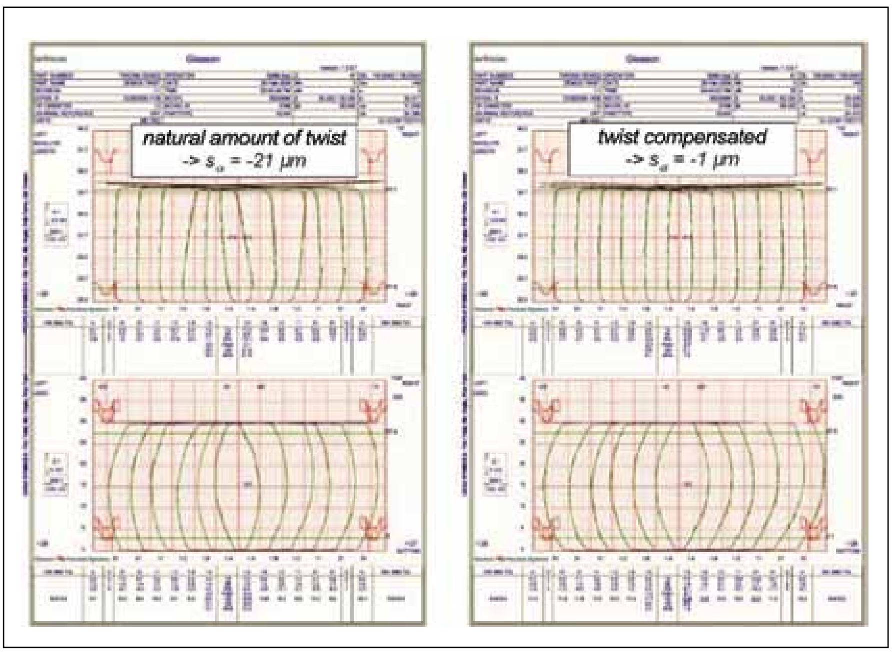

Figure 17—Result of twist compensation.

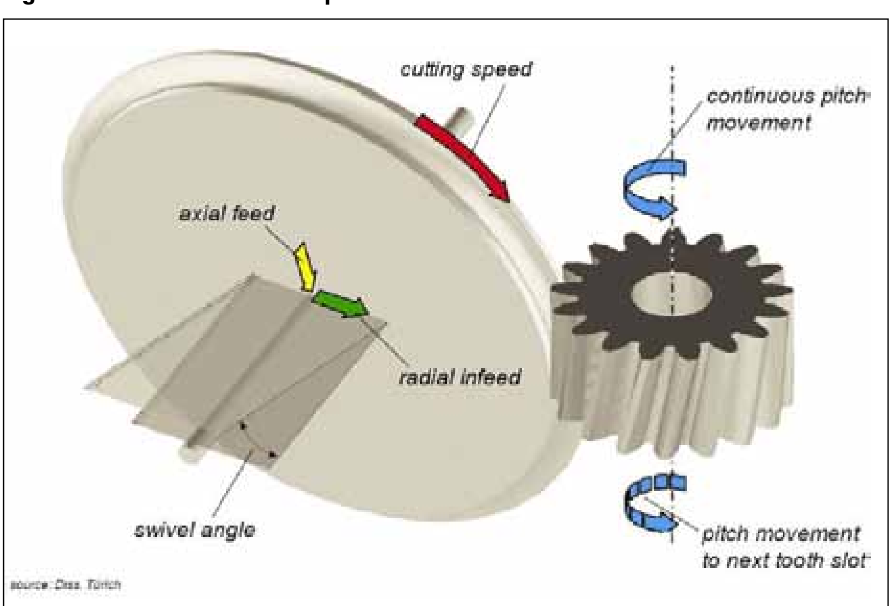

Figure 18—Kinematics in profile grinding.

Profile Grinding

Profile grinding is a process that provides great potential with respect to flexibility and quality, and can be used to grind a wide variety of gears. Thus profile grinding is used in job shop applications but also in applications that are not possible with threaded wheel grinding; e.g., large-module gears (Ref. 9). The kinematics of profile grinding presented in Figure 18 are much easier than in threaded wheel grinding since this process does not require so many synchronized movements.

A profiled grinding wheel is used, which is swiveled to the helix angle of the gear and rotates to perform the cutting speed (red arrow). In addition, the wheel must be able to be moved in a radial direction (green arrow) to remove stock from the flanks, and in an axial direction along the gear axis (yellow arrow). If the gear is helical, it requires a continuous rotational movement in order to follow the lead and a discontinuous pitch movement to grind all teeth.

Similar to threaded wheel grinding, profile modifications are generated by the grinding tool—which must be dressed in a special manner—while the lead modifications are generated by the machine axes. In profile grinding, the wheel profile shape depends on the gear data and the wheel diameter; it thus has to be recalculated for each diameter, which is no longer a problem when using modern machine software (Ref. 1). The user has to make inputs concerning the gear data and the desired modifications. Then the machine automatically calculates the required wheel profile and the corresponding movements for the dressing tool. In profile grinding, a dressing tool is used independent of the gear data; thus one dressing tool can be used to dress all kinds of wheel shapes. Such a typical dressing operation is shown in Figure 19. Beyond "standard" involute profiles, any other kind of profile can be defined and dressed, which is another advantage of profile grinding against threaded wheel grinding.

In order to achieve different flank modifications, a concept similar to threaded wheel grinding of superimposing additional movements of different axes is used. While a change in radial infeed results in more or less stock removal on the left and right flank, a change in the gear rotation position results in more stock removal on one flank and less on the opposite flank. With this concept, it is possible to achieve different flank modifications on the left and right flank. One example is presented in Figure 20, where the left flank was programmed with a 30 mm taper and the right flank with a 40 mm lead crowning. The real grinding result is shown on the right-hand side and proves how well this method works.

Threaded wheel grinding a lead modification also affects the profile, thus presenting similar problems in creating a twist error. The main reason in profile grinding is that a change in radial infeed, as it is necessary for a lead crowning, immediately results in a profile angle error (Refs. 1, 9). In addition to that phenomenon, the contact lines between the grinding wheel and gear are also running diagonal over the tooth flank.

Gleason has developed a patented method to compensate for the amount of twist in profile grinding as well. Figure 21 shows a grinding result when grinding a gear without this compensation, and one can clearly see significant change in profile and lead from the top to the bottom section of the gear. This method of compensating for or controlling a specific amount of twist uses five-axis interpolation, including a continuous swivel axis. This method allows for doing this in dual-flank grinding mode and thus saving a significant amount of time, compared to single-flank grinding, which would not require such a complex, five-axis interpolation. The result of this process can be seen in Figure 22. The amount of twist is almost eliminated. But this method not only enables compensating for twist. It can also be used to grind topological flank modifications.

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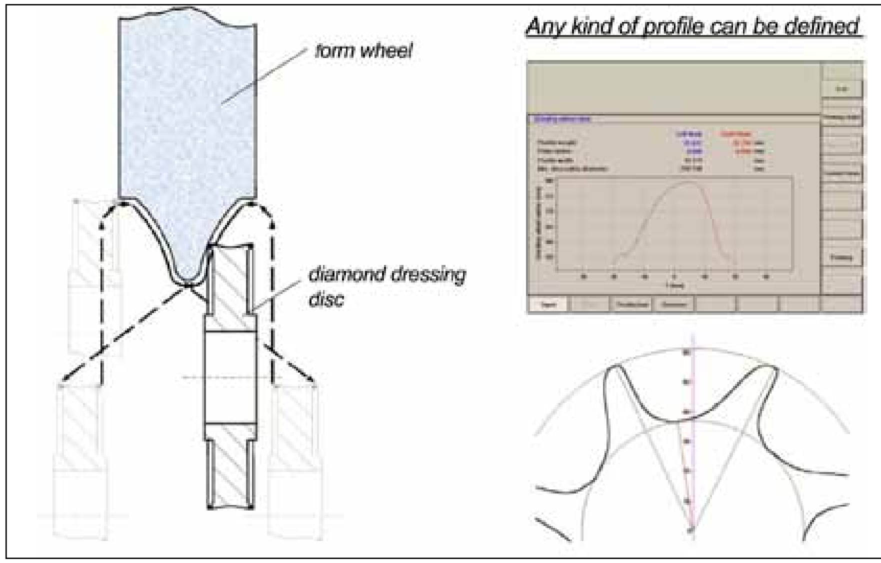

Figure 19—Dressing of form wheels.

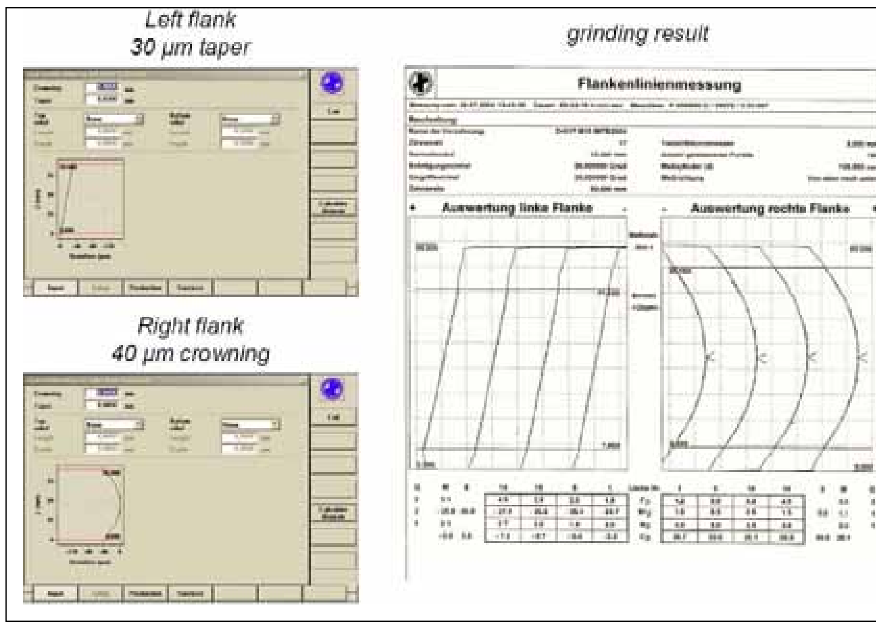

Figure 20—Grinding of different lead modifications.

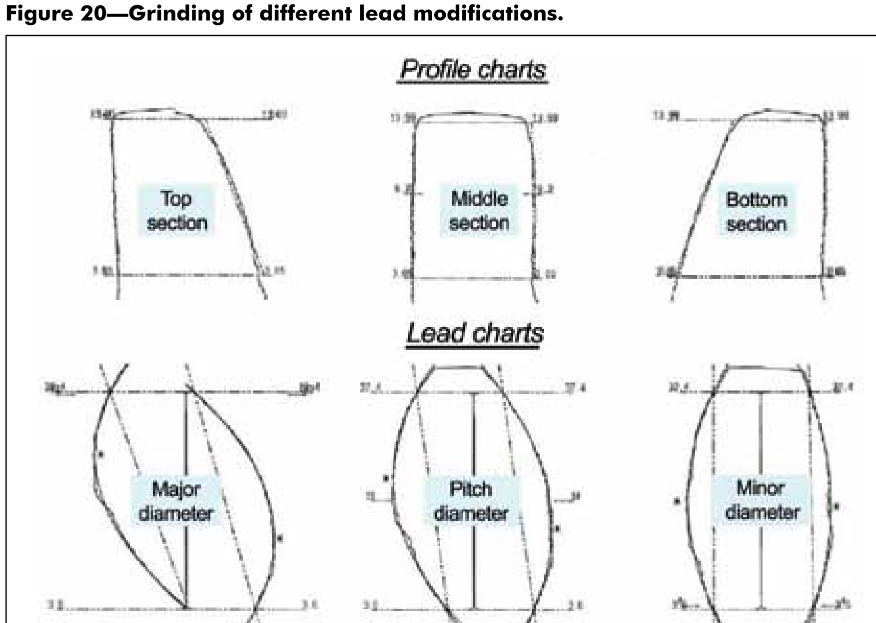

Figure 21—Natural twist in profile grinding.

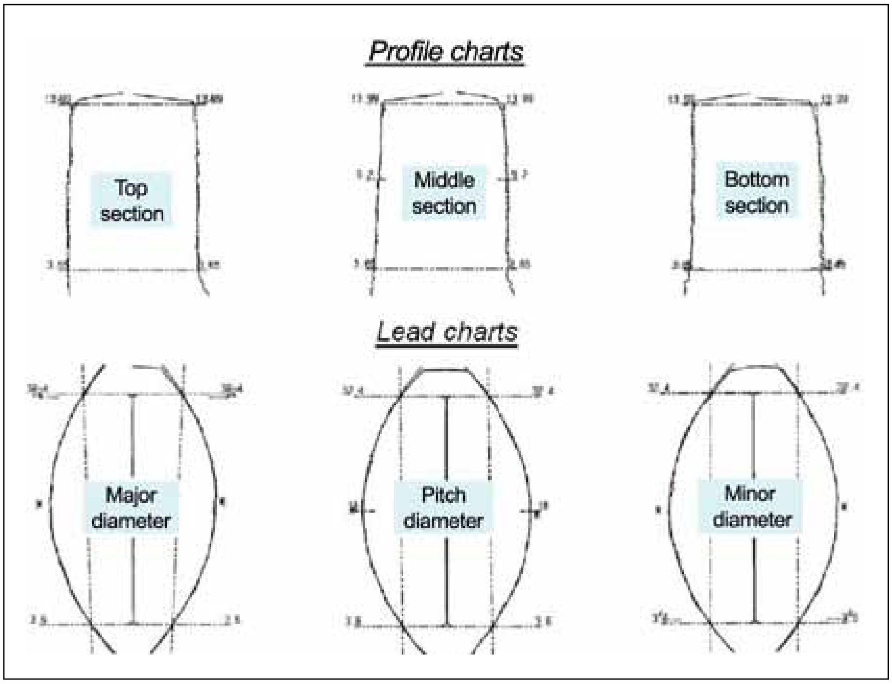

Figure 22—Compensated twist in profile grinding.

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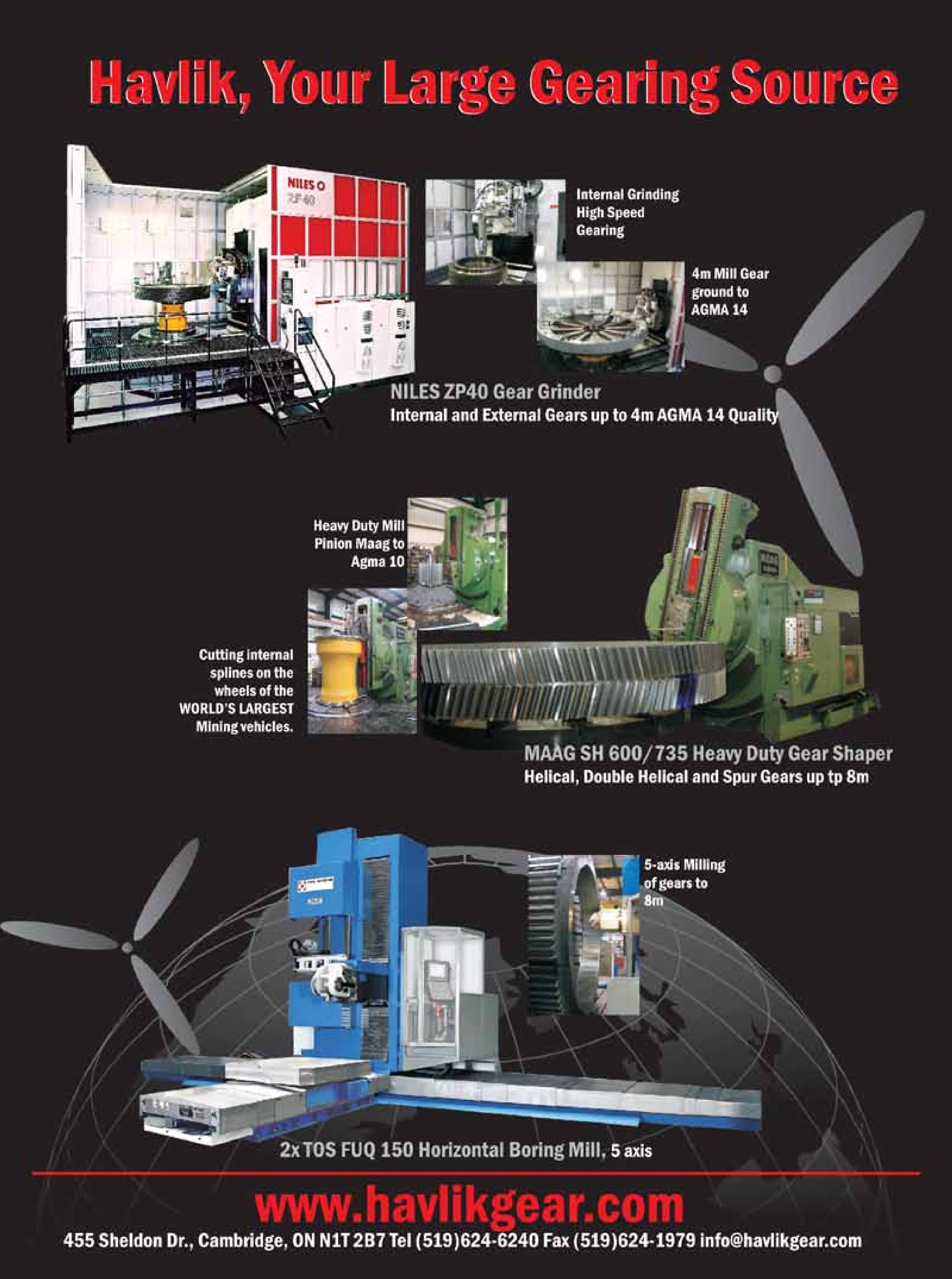
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Area of Existence of Involute Gears

Alexander Kapelevich and Yuriy Shekhtman

Management Summary

This paper presents a unique approach and methodology to define the limits of selection for gear parameters. The area within those limits is called the "area of existence of involute gears" (Ref. 1). This paper presents the definition and construction of areas of existence of both external and internal gears. The isograms of the constant operating pressure angles, contact ratios and the maximum mesh efficiency (minimum sliding) isograms, as well as the interference isograms and other parameters are defined. An area of existence allows the location of gear pairs with certain characteristics. Its practical purpose is to define the gear pair parameters that satisfy specific performance requirements before detailed design and calculations. An area of existence of gears with asymmetric teeth is also considered.

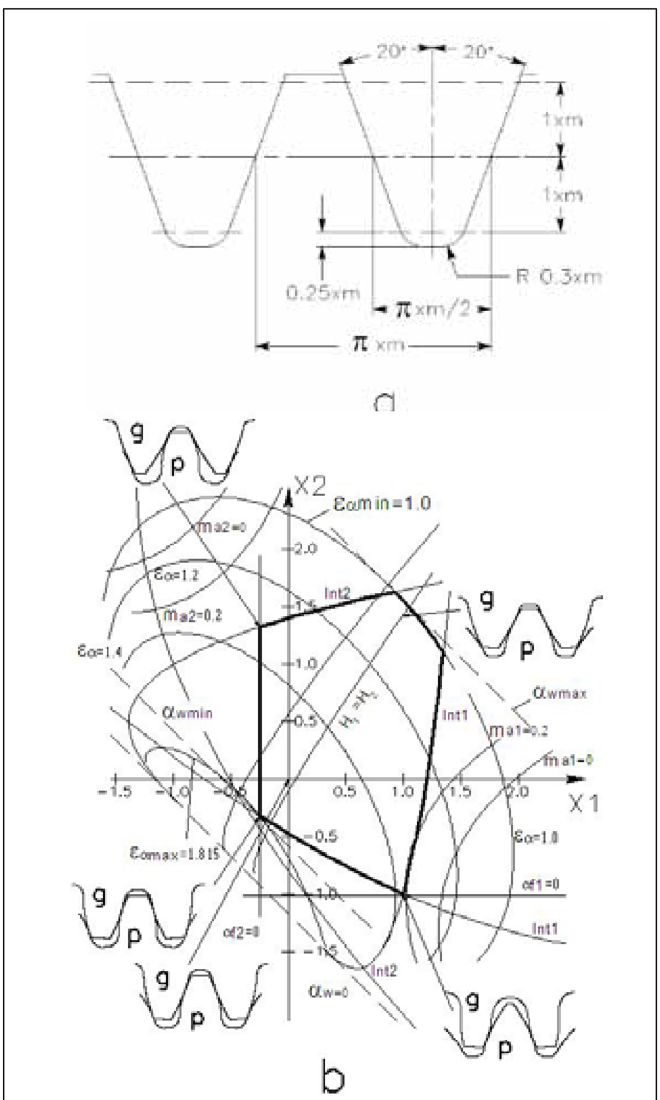

Figure 1a—Standard 20° pressure angle generating rack; b: its block-contour for the pair of gears with number of teeth n_1 = 22 and n_2 = 35.

Introduction

In traditional gear design, the pre-selected basic or generating rack's parameters and its X-shift define the nominal, involute gear geometry. The X-shift selection for the given pair of gears is limited by the block-contour (Refs. 2–3). Borders of the block-contour (Fig.1) include the undercut isograms, the tooth-tip interference isograms, the minimum contact ratio (equal to 1.0 for spur gears) isogram and the isograms of the minimum tooth tip thickness to exclude the gears with the pointed tooth tips. Each point of the block-contour presents the gear pair with a certain set of parameters and performance. If the basic or generating rack parameters (pressure angle, addendum or whole depth) are changed, the block-contour borders will be changed accordingly and will include the gear pair parameters' combinations, which previously could not be achieved yet could present the optimal solution for a particular gear application.

Area of Existence for Symmetric Gearing

The Direct Gear Design method (Refs. 4–5) does not use a pre-selected basic or generating rack to define the gear geometry. Two involutes of the base circle—the arc distance between them and the tooth tip circle— describe the gear tooth (Fig. 2). The equally spaced teeth form the gear. The fillet between the teeth is not in contact with the mating gear teeth, but this portion of the tooth profile is critical because it is the area of the maximum bending stress concentration.

In Direct Gear Design, the selection of parameters for the given gear pair is limited by the area of existence, which was introduced by Prof. E. B. Vulgakov in his "Theory of Generalized Parameters" (Ref. 1). The angles v_1 and v_2 are used as a coordinate system for the area of existence of the involute gear pair with number of teeth n_1 and n_2. The involute profile angles at the tooth tip diameters $\alpha_{a1,2}$ of the mating gears also can be used as a coordinate system for the area of existence. They are:

$$\alpha_{a1,2} = \arccos \frac{d_{b1,2}}{d_{a1,2}} \quad (1)$$

An area of existence is built for the gear pairs with number of teeth n_1 and n_2, and for pre-selected relative tooth thicknesses at the gear tooth tip diameters $m_{a1,2}$. This guarantees avoiding the pointed gear tooth tips and makes the area of existence independent of the gear size. In the metric system, $m_{a1,2} = S_{a1,2}$ / m, where m is operating module in mm. In the English system, $m_{a1,2} = S_{a1,2}$ x DP, where DP is the operating diametral pitch in 1/in. Typically, thicknesses $m_{a1,2}$ are in the range of 0.1– 0.5.

The relation between the involute profile angles ν and α_a is described by equations:

for gears with the external teeth:

$$inv(\nu_{1,2}) - inv(\alpha_{a1,2}) = \frac{S_{a1,2}}{d_{a1,2}} = \frac{m_{a1,2} \times \cos\alpha_{a1,2}}{n_{1,2} \times \cos\alpha_w} \quad (2)$$

for the gear with the internal teeth:

$$\pi / n_2 - inv(\nu_2) + inv(\alpha_{a2}) = \frac{S_{a2}}{d_{a2}} = \frac{m_{a2} \times \cos\alpha_{a2}}{n_2 \times \cos\alpha_w} \quad (3)$$

where: inv(x) = tan(x) - x – involute function.

An area of existence presents a number of isograms that describe gear pairs with certain characteristics, such as the constant operating pressure angle, contact ratio, interference condition or maximum mesh efficiency, etc.

The pressure angle α_w = const isogram equations are (Ref. 1):

for the external gearing:

$$\frac{1}{1+u}(inv(\nu_1) + u \times inv(\nu_2) - \frac{\pi}{n_1}) = inv(\alpha_w) \quad (4)$$

for the internal gearing:

$$\frac{1}{u-1}(u \times inv(\nu_2) - inv(\nu_1)) = inv(\alpha_w) \quad (5)$$

where: $u = n_2/n_1$ – gear ratio.

The contact ratio ε_α= const isogram equation is:

for external gearing:

$$\frac{n_1}{2\times\pi}(\tan\alpha_{a1} + u \times \tan\alpha_{a2} - (1+u) \times \tan\alpha_w) = \varepsilon_\alpha \quad (6)$$

for internal gearing:

$$\frac{n_1}{2\times\pi}(\tan\alpha_{a1} - u \times \tan\alpha_{a2} + (u-1) \times \tan\alpha_w) = \varepsilon_\alpha \quad (7)$$

The external gearing interference isogram equations are:

for the pinion root undercut beginning ($\alpha_{p1} = 0$):

$$\tan((1+u) \times \tan\alpha_w - u \times \tan\alpha_{a2}) = \tan\alpha_{p1} = 0 \quad (8)$$

for the gear root undercut beginning ($\alpha_{p2} = 0$):

$$\tan(\frac{1+u}{u} \times \tan\alpha_w - \frac{1}{u} \times \tan\alpha_{a1}) = \tan\alpha_{p2} = 0 \quad (9)$$

For internal gearing, interference when the pinion root undercut beginning (α_{p1}= 0) is:

$$\tan(u \times \tan\alpha_{a2} - (u-1) \times \tan\alpha_w) = \tan\alpha_{p1} = 0 \quad (10)$$

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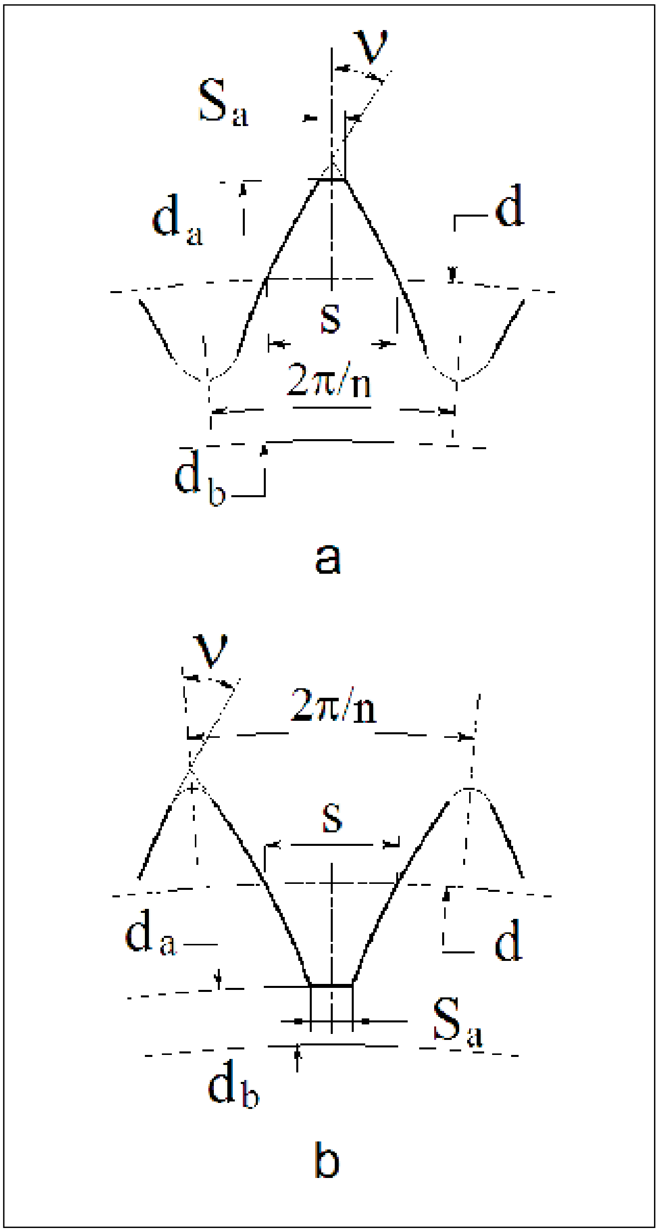

Figure 2—Tooth profile. a: external tooth; b: internal tooth; n: number of teeth; d_a: tooth tip circle diameter; d_b : base circle diameter; d: reference circle diameter; S: circular tooth thickness at the reference diameter; v: involute intersection profile angle; S_a: circular tooth thickness at the tooth tip diameter.

For the gear with internal teeth, the root undercut does not exist. However, there is another "tip-tip" interference possibility in internal gearing. Its equation is:

$$\lambda_1 - u \times \lambda_2 = 0 \qquad (11)$$

where angles:

$$\lambda_{1,2} = \gamma_{1,2} + inv(\alpha_{a1,2}) - inv(\alpha_w) \qquad (12)$$

$$\gamma_1 = \pi - \arccos\left(\frac{\left(\frac{n_1 \times \cos\alpha_w}{\cos\alpha_{a1}}\right)^2 + (n_1+n_2)^2 - \left(\frac{n_2 \times \cos\alpha_w}{\cos\alpha_{a2}}\right)^2}{\frac{n_1 \times \cos\alpha_w}{\cos\alpha_{a1}} \times (n_1+n_2)}\right) \qquad (13)$$

$$\gamma_2 = \arccos\left(\frac{\left(\frac{n_2 \times \cos\alpha_w}{\cos\alpha_{a2}}\right)^2 + (n_1+n_2)^2 - \left(\frac{n_1 \times \cos\alpha_w}{\cos\alpha_{a1}}\right)^2}{\frac{n_2 \times \cos\alpha_w}{\cos\alpha_{a2}} \times (n_1+n_2)}\right) \qquad (14)$$

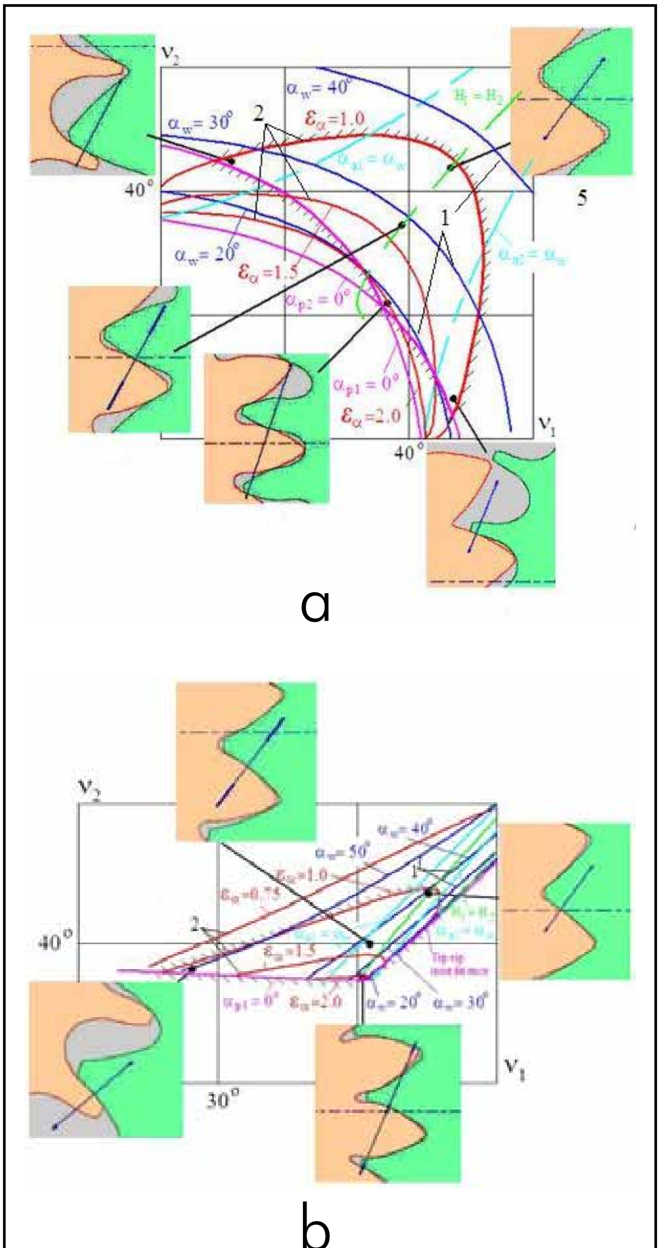

Figure 3—Area of existence for the pinion and gear with n_1 = 18 and n_2 = 25; m_{a1} = 0.25 and m_{a2} = 0.35; Accordingly—*a*: external gearing; *b*: internal gearing; 1: family of the pressure angle isograms α_w = const.; 2: family of the contact ratio isograms ε_α = const.; interference isograms α_{p1} = 0, α_{p2} = 0, and "tip-tip" (for internal gearing); maximum mesh efficiency isograms $H_1 = H_2$; $\alpha_{a1} = \alpha_w$ and $\alpha_{a2} = \alpha_w$: isograms separating the gear meshes with the pitch point laying on the active portion of the contact line.

The pitch point position isograms separate an area of existence into three zones:

- with the pitch point position before the active part of the tooth contact line;
- with the pitch point position on the active part of the tooth contact line (typical for most gears);
- with the pitch point position after the active part of the tooth contact line.

The pitch point position isograms' equations for external gearing are from (Ref. 2 and 4):

isogram $\alpha_{a1} = \alpha_w$,

$$(inv(\alpha_{a2}) - inv(\alpha_{a1})) \times n_2 + m_{a1} + m_{a2} \times \frac{\cos\alpha_{a2}}{\cos\alpha_{a1}} - \pi = 0 \qquad (15)$$

isogram $\alpha_{a2} = \alpha_w$,

$$(inv(\alpha_{a1}) - inv(\alpha_{a2})) \times n_1 + m_{a1} \times \frac{\cos\alpha_{a1}}{\cos\alpha_{a2}} + m_{a2} - \pi = 0 \qquad (16)$$

The pitch point position isogram's equations for internal gearing are from (Refs, 2, 3 and 5):

isogram $\alpha_{a1} = \alpha_w$,

$$(inv(\alpha_{a2}) - inv(\alpha_{a1})) \times n_2 - m_{a1} - m_{a2} \times \frac{\cos\alpha_{a2}}{\cos\alpha_{a1}} + \pi = 0 \qquad (17)$$

isogram $\alpha_{a2} = \alpha_w$ is also defined by equation 16.

The maximum mesh efficiency isogram is defined by condition of the equal specific sliding velocities at the tips of the mating gear teeth $H_1 = H_2$ (Ref. 6). These equations are:
for external gearing:

$$\tan\alpha_{a1} - u\tan\alpha_{a2} + (u-1) \times \tan\alpha_w = 0 \qquad (18)$$

for internal gearing:

$$\tan\alpha_{a1} + u\tan\alpha_{a2} - (1+u) \times \tan\alpha_w = 0 \qquad (19)$$

Area of existence for external gearing (Fig. 3a) is limited by the interference isograms and isogram of the minimum contact ratio (for spur gears it is 1.0). Area of existence of the internal gear pair can also be limited by the "tip-tip" interference isogram.

Every point of the area of existence presents a gear pair with a certain set of the geometric parameters. A few of these gear pairs are shown in Figure 3. Some of them do not look conventional, but they may be practical for some applications.

Area of existence is much greater than the block-contour (Fig. 4) of any particular generating rack. It actually includes any gear pair combinations, generated by all possible block-contours and also the gear pairs, where two different racks generate the mating gears.

Area of Existence for Asymmetric Gearing

The design intent of asymmetric gearing is to improve performance of primary drive profiles at the expense of performance for the opposite coast profiles. The coast profiles are unloaded or lightly loaded during a relatively short work period. Asymmetric tooth profiles also make it possible to simultaneously increase the contact ratio and operating pressure angle beyond conventional gears' limits.

Direct Gear Design represents the asymmetric tooth form by two involutes of two different base circles (Refs. 7 and 8), with the arc distance between them and tooth tip circle describing the gear tooth (Fig. 5). The equally spaced teeth form the gear. The fillet between the teeth is not in contact with the mating gear teeth, but this portion of the tooth profile is critical because it is the area of the maximum bending stress concentration. The fillet profile is designed independently, providing minimum bending stress concentration and sufficient clearance with the mating gear tooth tip in mesh.

The relation between involute profile angles of opposite flanks of an asymmetric tooth is:

$$\frac{\cos\alpha_{xc}}{\cos\alpha_{xd}} = \frac{d_{dc}}{d_{bd}} = k \geq 1.0 \tag{20}$$

where α_{xd} and α_{xc} are involute profile angles at the $d_x \geq d_b$ diameter. Then:

$$\frac{\cos\alpha_{ac1,2}}{\cos\alpha_{ad1,2}} = \frac{\cos\alpha v_{c1,2}}{\cos\alpha v_{d1,2}} = \frac{\cos\alpha_{wc}}{\cos\alpha_{wd}} = \frac{d_{dc}}{d_{bd}} = k \geq 1.0 \tag{21}$$

where k is the asymmetry coefficient.

If $d_{bd} = d_{bc}$, $k = 1.0$ and tooth is symmetric.

The area of existence of asymmetric gears (Fig. 6) is built very similarly to the area of existence of symmetric gears. It basically presents an overlay of two areas of existence: one for the drive flanks and another for the coast flanks of the asymmetric tooth.

The isogram equations for asymmetric gears are very similar to the equations for the symmetric gears.

Application of Area of Existence

A computer program generates the area of existence of involute gears for the given numbers of teeth n1 and n2, relative tooth tip thicknesses m_{a1} and m_{a2}, and asymmetry coefficient k. Then, any selected point in the area presents a

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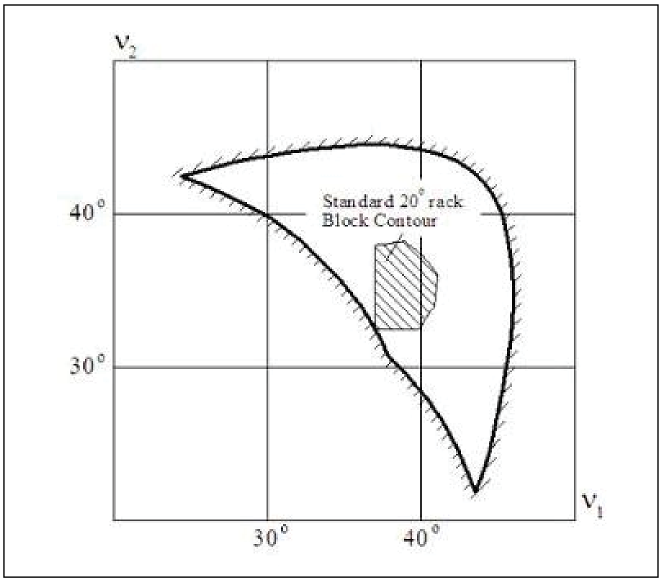

Figure 4—Area of existence for the gear pairs with n_1 = 22 and n_2 = 35 and their standard 20° pressure angle generating rack block-contour.

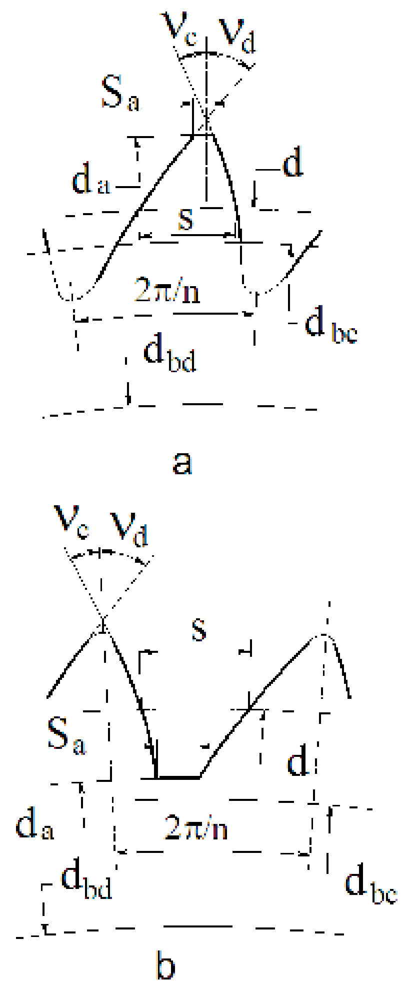

Figure 5—Asymmetric tooth profile (fillet portion red); a: external tooth; b: internal tooth; d_a: tooth tip circle diameter; d_b: base circle diameter; d: reference circle diameter; S: circular tooth thickness at the reference diameter; v: involute intersection profile angle; S_a: circular tooth thickness at the tooth tip diameter; subscripts "d" and "c" are for the drive and coast flanks of the asymmetric tooth.

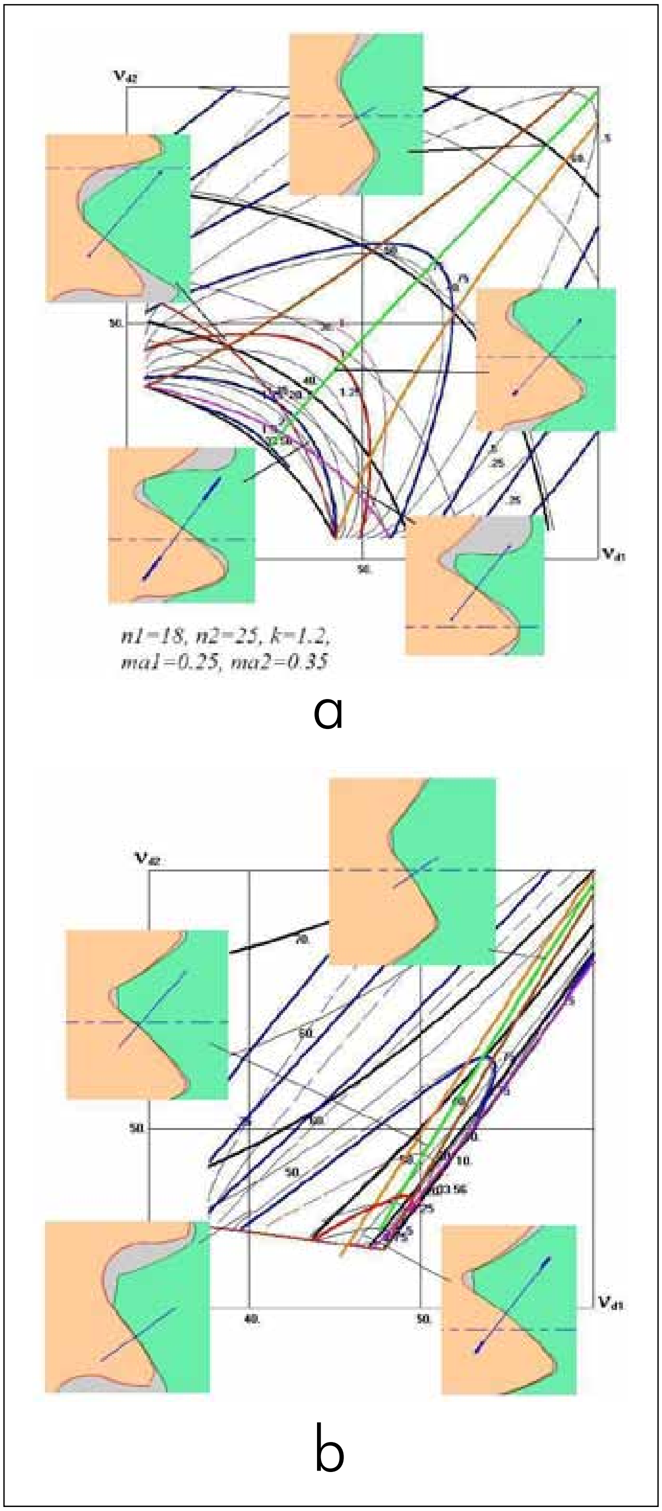

Figure 6—Area of existence for the asymmetric pinion and gear with: n_1= 18 and n_2 = 25; m_{a1} = 0.25 and m_{a2} = 0.35; and k = 1.2. a: for external gearing; b: internal gearing. The isograms related to the drive flank meshes are thick, the isograms related to the coast flank meshes are thin.

set of gear pair mesh parameters, considering its module (or its diametral pitch) and the face widths of the mating gears equal to one. Selection of the relative tooth tip radii and construction of the fillets between the teeth complete the gear geometry definition.

The relative tooth tip radii are: $r_{a1,2} = R_{a1,2}/m$ in the metric system and $r_{a1,2}= R_{a1,2}$ x DP in the English system, where $R_{a1,2}$ are the tooth tip radii of the mating gears. Typically, thicknesses $m_{a1,2}$ are in the range 0.00–0.05.

In traditional gear design, the fillet profile is typically a trajectory of the pre-selected (usually standard) generating gear rack. Any point of the block-contour presents the gear pair with completed (including the fillet) tooth profiles. In Direct Gear Design, the tooth fillet profile is a subject of optimization to minimize bending stress concentration (Refs. 9–10). However, the tooth fillet profile optimization is a time-consuming process that is used for the final stage of gear design. It is not practical for browsing the area of existence, analyzing many sets of gear pairs in limited time period. The tooth fillet profile should be quickly constructed, without tooth tip-fillet interference, and provide relatively low bending stress concentration. In order to achieve this, the virtual ellipsis arc is built into the tooth tip that is tangent to the involute profiles at the tip of the tooth. As a result, the tooth fillet profile is a trajectory of the mating gear tooth tip virtual ellipsis arc (Fig. 7). This fillet profile can be called "pre-optimized" because it provides lower bending stress concentration than the standard rack-generated fillet profile.

The fillet profile construction completes the mating gears teeth geometry definition. This allows the program to demonstrate an animation of the gear mesh right after selection (clicking on) any point of the area of existence.

The next step of area of existence analysis is the calculation of the maximum contact and bending stresses. This stress analysis program procedure requires an input of the operating module (or operating diametral pitch for English system), the face widths for both mating gears and the pinion torque. The modulus of elasticity and Poisson ratio are also required to calculate the Hertzian contact stress. The proprietary 2D FEA sub-routine is used for definition of maximum bending stress for both mating gears.

This program assists in finding a suitable gear solution for a particular application, for example:

1. Heavily loaded low-speed gears: Appropriate gears are at intersection of the maximum pressure angle isogram and the maximum mesh efficiency isogram.

2. Lightly loaded high-speed gears: They can be found at intersection of the high contact ratio (ε_α >2.0) isogram and the maximum mesh efficiency isogram.

3. Dissimilar material gears, like a metal pinion and a plastic gear: In this case, the metal pinion should have the minimum and the plastic gear the maximum relative tooth thickness at the tooth tip diameter. The pressure angle should be relatively low. This allows making the plastic gear tooth thicker and the metal pinion tooth thinner to balance

the bending strength of the mating teeth.

4. Self-locking gears: These parallel axis gears work essentially like worm gears. The solution can be found at a very high pressure angle ($\alpha_w >> 60°$, gears are helical) and with pitch point position after the active part of the tooth contact line.

Conclusions

The area of existence and its program allow for quickly defining limits of parameter selection of involute gears, locating feasible gear pairs, animating them and reviewing their geometry and stress levels. Benefits of using the area of existence are:

- consideration of all possible gear combinations;
- instant definition of the gear performance limits;
- awareness about non-traditional, "exotic" gear design options;
- quick localization of area suitable for particular application;
- optimization of the gear design solution.

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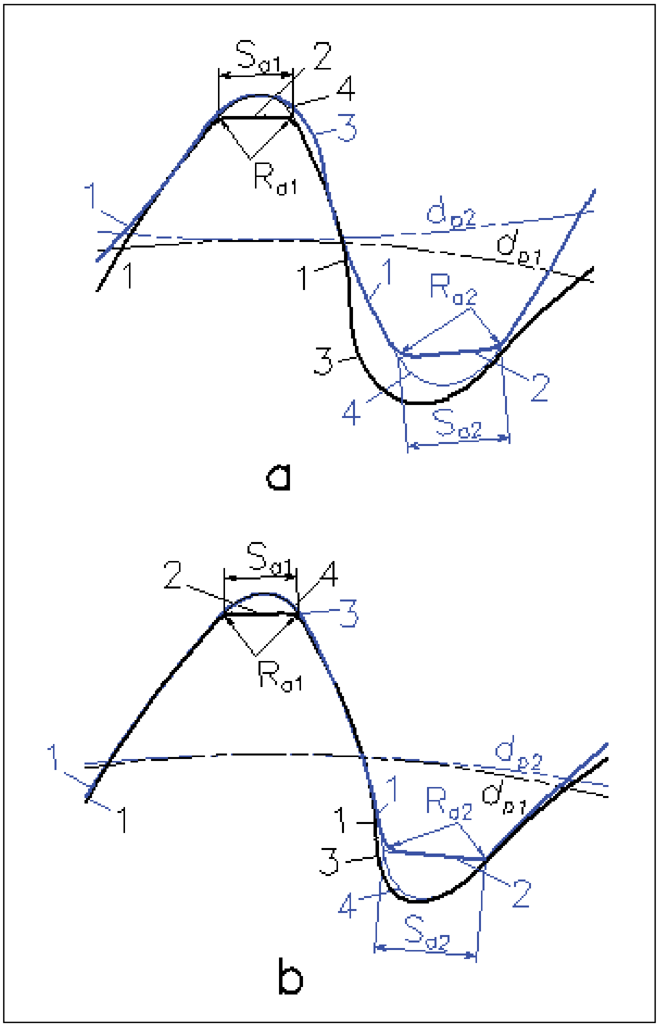
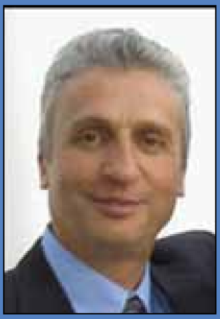


Figure 7—The fillet profile construction. a: external gears; b: internal gearing; 1: involute profiles; 2: tooth tip lands; 3: fillet profiles; 4: ellipsis arcs that are used to generate the fillet profiles.



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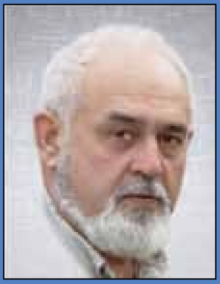

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Havlik International Machinery has been in the big gear business for more than 100 years with an emphasis on mining applications (courtesy of Havlik).

Sizing Up Big Gears

QUALITY, MATERIALS AND TECHNOLOGY CONTINUE TO CHALLENGE MARKET

Matthew Jaster, Associate Editor

It comes as no surprise to suggest we're living in an age of reduction. The automotive industry is now manufacturing smaller cars on tighter budgets, companies are consolidating instead of expanding and the manufacturing community has less experienced workers with little or no knowledge of the machines they need to be working on. The less is more philosophy is alive and well in 2010.

This makes it difficult to get things done when your company is in the business of being big. Large gear manufacturers have all the same problems as their smaller counterparts with a few significant exceptions. These companies need to invest in more equipment, tackle greater production demands and maintain lead times that typically use the word "years" instead of "months."

The bar on quality standards continues to rise in this market even though many mining and off-highway projects are being cut or temporarily shut down. It's a mad, mad world for large gear manufacturers, but if you've got the right technology, equipment and experience, it's an industry segment that can be highly profitable.

Big Gears: 6–8 Meters

There are big gears and then there are BIG gears. Companies like HMC Inc., Havlik International and Horsburgh & Scott fit the BIG gear category. These gears are typically found in mining, steel and construction applications and come with a list of supply, material and quality concerns.

While big gears can be more profitable than other industry segments, new opportunities have cooled down recently. There's still plenty of business, but the game is changing, and companies are learning to adapt to a shrinking manufacturing base that is pinching every penny.

Horsburgh & Scott, headquartered in Cleveland, Ohio, specializes in the design, manufacture, service, rebuilding and repair of large industrial gears and gear drives. The company recently lost two customers due to economic hardships.

"One mining operation shut down for a year, and another customer shut down permanently. This is the nature of the beast lately. We see existing customers closing their doors and very few new customers entering the market," says Tom Putnam, chief customer officer at Horsburgh & Scott.

Putnam says the mindset in the big gear industry is no different than that of the typical homeowner right now.

"Customers aren't willing to spend money right now on new equipment; they're simply replacing what they absolutely must have. Our biggest challenge is getting the orders. The demand for large gears has changed in this economy."

Havlik International Machinery, Inc. has been in large gear manufacturing for more than 100 years. John Havlik, president and CEO, considers the mining industry to be the focal point.

Though business has been good in the past, a recent decrease in orders for Havlik illustrates the shaky manufacturing sector currently affecting large gear manufacturers.

"Our company manufactured 25 large ring gears in 2008, but only five in 2009," Havlik says. "What a difference a year makes. The amount of large gears being manufactured today compared to two years ago is incredible."

There are many reasons why orders were down in 2009—including economic issues and the simple fact that the demand isn't as great—but Havlik suggests that a bigger issue might be the quality standards that are not being met.

"If you want to succeed in this market segment, you have to make major capital investments in order to adhere to the quality standards customers are looking for today," Havlik says.

Havlik believes it's the large gears that present the biggest challenges in the industry.

"Customers want better accuracy, service and extended life on gears in this size range. I'm not convinced enough companies have the right capabilities to meet these standards."

Mining gears, by design, are created to perform in extreme conditions. This means tolerance levels and AGMA standards need to be met no matter the cost. If a company can't afford to produce what the engineering firms are looking for, they lose the

HMC can manufacture and inspect large gears of the highest AGMA quality at its facility in Princeton, IN (courtesy of HMC).

business, Havlik adds.

"It's also a difficult market segment simply because gears of this nature just take longer to produce than their smaller counterparts. It's a fact of life," Putnam says. "There's a gear for the cement industry that we've been working on for eight years, and they still haven't bought the thing. Industry, in general, is being affected the same way across the board; doesn't matter what your size, weight, height dimensions are, people are still cutting back."

"Getting the materials can also be tricky." Havlik says. "You're often held hostage by what the suppliers can give you, the time it will take to get it as well as the cost. We're seeing this in regards to forged rings. Right now, it takes almost three quarters to a year to get a large ring shipped out."

Another major issue in large gear manufacturing appears to be the shortage of castings.

"We are not having any problems with our forging vendors and/or subcontractors as they relate to our fabricated gearing," says Robert Smith III, president at HMC. "On the other hand, it would be easier in many instances to travel to Mars than it is to get competitive pricing and realistic deliveries for large castings."

And the bearing issue reported in last year's *Gear Technology* big gear update continues in 2010.

"This has become an inventory management issue," Putnam says. "The bearings needed for the machines in the large gear market are often limited in availability. They're typically out of stock or take longer to get a hold of."

Putnam says that bearing distributors often frown upon buying small batches of large bearings because it ruins sales numbers. "They prefer very large orders when it comes to bearings."

Replacing the bearings in gearboxes poses additional challenges.

"We're putting the same bearings back in simply because it's the only bearing that fits on the market. Whether it was made in 1950, 1970 or 1980, we've got to come up with that original bearing and this can be an enormous challenge."

Another problem, particularly in ring gears, is the quality of lubrication.

"Environmental concerns have made many [manufacturers] disappointed in the results of certain lubrications. Oils are either very good or very poor, there isn't much middle ground anymore," says Gary Bish, engineering manager at Horsburgh & Scott. "When customers invest heavily in large gears, they want to make sure things like bearings and lubrication provide exceptional results."

The transportation and shipping of large gears is another area where large gear manufacturers have had to adapt to new laws and regulations.

"Many of these products are overweight, and it becomes an issue of what we can and can't move within the confines of regulations. We can split a

continued

ring gear in half and transport it without a problem, but some large gears can't be disassembled, and you've got yourself a large, unstable gear to transport. State department regulations have tightened since 9/11 and the I-35 bridge collapse in Minnesota. You have to find creative ways to ship gears of this size," Putnam says.

"There's a trend, in fact, right now for complete shaft assembly, and you can't ship something that large," Bish says. "Now, you have to assemble it directly on your customer's premises."

HMC, located in Princeton, IN, is one of a handful of companies today in North America that can manufacture and inspect very large gears of the highest AGMA quality. Smith credits the company's quick response time and fast delivery for its success.

"With the addition of our six and two meter form grinders along with our battery of Maag shapers, we're capable of producing advanced technology spur, helical, herringbone and/or double helical gears," Smith says. "We also have plans in place that will enable HMC to cut rough and finish gears of eight meters by the last quarter of 2010."

A complete rolling mill drive for an Eastern European client of Horsburgh & Scott had to be disassembled and packaged in individual parts for transportation (courtesy of Horsburgh & Scott).

One of the major concerns in the big gear industry is getting the right materials in a decent time frame, according to John Havlik at Havlik International (courtesy of Havlik).

HMC's current market strategy is to offer advanced technology replacement gearing with extended warranties to assist customers with the increasing costs of replacement components. New technology investments in a heavy bay for large weldments and assembly as well as a super size stress relieving oven capable of facilitating up to eight meter gears will also benefit the company's in-house capabilities.

Although green technology typically doesn't apply to the lower quantity levels of large gears, HMC promotes environmental awareness through new machine technology and the "Reband Gear Process," an in-house conservation tool that reuses the center sections and hubs on large gears.

"HMC has and continues to be cognizant of and care for our environment," Smith says. "We use all of the latest in technology to ensure we do not cause negative impacts to our environment here in Indiana. And we have promoted conservation and been green for many years."

Big Gears: 3–4 Meters

While not as big as their counterparts, these gears are found in mining, off-road, construction, marine, wind and transportation applications. Overton Chicago Gear, located in Addison, IL, has made a name for itself with spur, helical, bevel and internal gears up to four meters.

"We have the right equipment in place to meet the standards for gears this size," says Kerry Klein, sales manager at Overton. "Quality levels range anywhere from AGMA 8 to AGMA 12 and our newest machine features have already provided improvements."

Overton's focal point is on new and improved methods of manufacturing and multiple machine setups on a single machine.

"In order to remain competitive, we're going to have to invest in new technology," Klein adds. As far as the industry is concerned, Klein believes there should be support groups in the United States that provide data and analysis on the large gear market, much like the VDMA Mining Equipment Association provides in Germany.

Currently, there isn't much information available or market forecast numbers specifically for the large gear market in the United States. Many companies would like to see some research that deals with the industry potential in the future.

Butler Gear contributes to this segment of the industry with customizable machining capabilities for heavy equipment, paper, machine tool, and agricultural gearing.

Tom Treuden, president of Butler Gear, located in Butler, WI, is facing many of the same challenges as his peers in regards to large gear manufacturing.

John Schnarr of HMC stands in front of a large fabricated gear for the steel industry (courtesy of HMC).

"Getting the right materials on time is an issue right now. We're just starting to expand our capabilities to the large gear market, so things like inspection, heat treating and lead times are all going to present challenges."

There are only a handful of companies that do the heat treating work that Butler Gear needs, according to Treuden. "The sources are limited in

continued

A ring gear for a mining operation gets the final touches at Havlik International before shipping out to the customer (courtesy of Havlik).

many areas of the industry and more players would keep the pricing competitive."

In dealing with gears of this size, Treuden says the overall business philosophy needs to change and companies need to be flexible.

"You need more floor space, you need bigger machines, and it's a whole new set of challenges when you start looking at the AGMA standards and tooth tolerances. The time it takes to manufacture the large gears versus the small ones is a big concern."

Technology seems to be the key no matter the size of the gear. Treuden says machine technology is one of the most important areas to look at.

"If you don't have sufficient technology, you've got to catch-up. It's simply a matter of obtaining the right equipment to do the job most effectively in this market."

Which leads to the most basic question of all, why get involved with gears this size?

"There's always going to be a market. I believe the industry will grow significantly in the next five to ten years. The large gear contracts are the ones that keep you afloat during slow periods and recessions. These contracts play a huge role in the success of an organization."

In the future, Butler Gear may start to look at producing larger products.

"I'm open to anything at this point. It's a scary time in manufacturing, but it's also exciting; there's still business out there."

The Future of Big Gears

The lack of skilled workers has been troubling the manufacturing community for years, and it's still a major sore spot in the large gear sector.

"There just aren't people coming into the workforce that want to learn manual work anymore," Treuden says. "Nobody is beating down the door to become a gear cutter. The people that do come in want to immediately sit down behind a computer."

At Horsburgh & Scott, Putnam says the new employees just don't have the knowledge or experience necessary to succeed.

"You see it in project management, you see it in inquiries and purchase orders. It's not about old farts getting old and jaded. The retiring workers know the machines they're working on. They know the history of each machine, and it's impossible to replace them. Today, new employees are thrown into the mix without any real training."

Without mentoring or training programs, the lack of skilled workers can really cause problems on the shop floor, Putnam adds.

"Our entire world is like this; everything is accelerated. Everyone is doing more work with fewer people. It's not just gear manufacturing, it's happening at Best Buy, Ford Motor Company and Boeing. The apprenticeship days are the good ole days; they're long gone."

And yet, the companies move forward. Despite material concerns, quality issues and technology costs, large gear manufacturers overall seem confident that the industry will soon start picking up.

The growth potential in the international markets, for example, has Putnam intrigued heading into 2010.

"What we're seeing right now is more international business in areas like India, Eastern Europe, Central America and Asia. Central America is particularly interesting in the big gear market as sugar mills continue to present opportunities to gear manufacturers," Putnam says. "This is a bright spot in the industry, and it will go up and down with the price of sugar."

Although new customers are hard to come by, Horsburgh & Scott's Bish has seen plenty of opportunities for repair/replacement parts in the mining sector.

"The industry is going to be flat, but we'll have plenty of replacement and upgrade potential in the large gear market," Bish says. "This is an area that will continue to present opportunities for large gear manufacturers."

Smith, at HMC, has no complaints about the current state of the market. "Overall, our business was strong throughout 2009. Our sales manager is confident that we will see, from our well diversified customer base, at the very least, the same volume of sales in 2010."

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March 9—Shot Peening Workshop. Tokyo. This one-day intensive instruction workshop covers all aspects of shot peening. Targeted attendees include product design engineers, machine operators, foremen, supervisors and maintenance and quality engineers. The courses are accredited by the FAA for specialized training for Inspector Authorization Renewals. A reference book of each class session is provided to students. The opportunity to earn shot peening certification is available for students who opt to take an FAA recognized exam for Level 1 Shot, Level 2 Shot and Flapper Peening. Exams are conducted at the workshop's conclusion. For more information, visit *www.electronics-inc.com/workshop_japan.html*. A two-day intensive instruction version of the workshop is scheduled for April 28–29 in Toronto. For more information on the Toronto workshop, visit *www.electronics.com/workshop_canada.html*.

March 17—AWEA Supply Chain Workshop. The Sheraton Greensboro Hotel at Four Seasons. Greensboro, NC. The American Wind Energy Association's supply chain workshop comes to the Southeast. Attendees learn about how increasing domestic wind turbine manufacturing and their components can help grow staff and profits. Interact with representatives from a range of industries and learn about what the industry needs, challenges and growth opportunities. Topics include an overview of the wind industry supply chain; tips, tools and resources on how to enter the wind industry; and presentations from wind turbine manufacturers. A pre-conference seminar takes place the day before for those new to the wind industry to hear an overview and status of the industry, learn the anatomy of a turbine and how the industry supply chain works. For more information, visit *www.awea.org/events/supplychain4*.

March 20–23—CastExpo. Orange County Convention Center. Orlando, FL. The American Foundry Society (AFS) and the North American Die Casting Association sponsor CastExpo, the largest trade show for metal casters in North America. The latest equipment, technology and metal casting services will be displayed from over 450 companies worldwide. New to CastExpo in 2010 is a Cast in North America Exhibition for foundries and die casters to exhibit their capabilities for buyers and designers. Also new this year is a Metal Casting Technology Theater, where shop-floor presentations are given for casting buyers and metal casters. The annual Metal Casting Congress is held at CastExpo, where new industry R&D is presented. Various other seminars and keynotes will also take place. For more information, visit *www.castexpo.com*.

March 23–25—WESTEC. Los Angeles Convention Center. The definitive West Coast manufacturing event includes keynote presentations from industry leaders in aerospace/defense, renewable energy and the manufacturing economy. The show also consists of technical sessions on topics that include small parts machining, high-speed alloy machining, milling, drilling, cutting advanced carbon fiber, carbon laminates and advances in additive manufacturing. Attendees view emerging technologies and emerging equipment applications and many other topics. For more information, visit *www.westeconline.com*.

March 30–31. Manufacturing Technology Forum. Gaylord Opryland Resort and Convention Center. Nashville, TN. The Association for Manufacturing Technology (AMT) and the National Center for Manufacturing Sciences (NCMS) host this technology forum, which this year is highlighting new initiatives addressing green in manufacturing. Guest speakers will discuss what the current trends are, what is necessary and what manufacturers can expect regarding new requirements. As with past forums, attendees will learn about current R&D activities. A networking reception and dinner event will take place as well. For more information, visit *www.amtonline.org/calendar/2010amtncmsmanufacturingtechnologforum.htm*.

April 21–22—Machine Shop Workshop. Renaissance Cleveland Hotel. Cleveland. The business of running a machine shop is the focus of this workshop that brings together hundreds of U.S. shop owners and managers. Educational sessions cover shop operations, lean manufacturing programs, workforce development and supply chain management. Real-world problems and solutions are presented in the sessions to help attendees improve performance and competitiveness in the global metalworking market. New to the 2010 program is a plant tour, where attendees visit a world-class machine shop to witness its best practices, lean strategies and other means for operations success. A lineup of over 10 speakers discusses various subjects that include wind turbine supply demands and automotive retooling. The workshop is conducted by American Machinist. For more information, visit *www.machineshopworkshop.com*.

In Memoriam

Brenda Sudzum

1960-2009

Brenda L. Sudzum.

Brenda L. Sudzum of B&R Machine and Gear Corporation, passed away November 26, 2009 at the age of 49. Born September 20, 1960 in Elgin, IL, Brenda was the youngest daughter of the late Bennie L. Boxx and Doretta Boxx.

Bennie and Doretta founded B&R Machine and Gear Corporation in Addison, IL in 1974. By 1980, Brenda moved with her family to Tennessee where she played a key role and was a driving force behind B&R's accomplishments. Throughout her career, she continually strived to advance B&R's achievements and success.

"Everyone who was involved with the AGMA or attended industry events knew that Brenda was a beacon of energy and enthusiasm both for B&R and for the gear industry," says Michael Goldstein, publisher of *Gear Technology*. "She will be missed for her contribution to the company and the industry. More importantly, I've known Brenda and her family for most of my professional career, and I'm sure I'm not alone in saying that I'll miss Brenda most as a friend."

Brenda is survived by her mother, Doretta Boxx; her husband, Nick Sudzum; two sons, Niko Sudzum and Ben Michael Sudzum; her daughter and son-in-law, Michelle and David Maddox; her brother, Terry Boxx; and her sister, Suzette Kelly.

She was preceded in death by her father, Bennie L. Boxx; one brother, Bennie R. Boxx; and one sister, Doretta Denise Boxx.

QuesTek

AWARDS PRODUCTION LICENSES FOR GEAR ALLOYS

This ring and pinion set manufactured from the Ferrium C61 alloy has been employed in many off-road racing vehicles.

Latrobe Specialty Steel Company was awarded licenses to produce and sell Ferrium C61 and C64 alloys from QuesTek Innovations LLC. Both high-quality, carburizing steels were developed specifically for gear applications as Phase I and Phase II Small Business Technology Transfer (STTR) projects awarded by the U.S. Navy Naval Air Systems Command (NAVAIR).

Ferrium C61 and C64 exhibit high core strength, high fatigue strength, high temperature resistance and high surface (case) hardenability. These licenses are the first QuesTek has granted to commercially produce and market the two alloys using QuesTek's compositions, processing knowledge and intellectual property. Terms of the agreement were not disclosed.

"We're pleased to award these licenses to Latrobe," says Charlie Kuehmann, president and CEO of QuesTek. "These licenses build upon our earlier license to Latrobe of Ferrium S53, our ultra-high strength, corrosion resistant steel used for aircraft landing gear and other applications. We look forward to working further with Latrobe, their customers and design engineers worldwide to identify valuable product applications of Ferrium C61, C64 and S53."

"We sell these premium-quality, high-hardness carburizing steels to customers worldwide to boost the performance

continued

and durability of their products," comments Scott A. Balliet, Latrobe Specialty Steel director of technology and quality. "These alloys are produced in our state-of-the-art vacuum melting (VIM) and vacuum re-melting (VAR) facilities, which include the recently completed VIM and VAR expansion to our Latrobe, PA facility. Working with QuesTek, we accelerate introducing premium alloys to customers for vital defense and commercial applications."

The Ferrium C61 design objective was to develop a high performance, secondary-hardening gear and bearing steel with surface properties similar to conventional gear steels, like AISI 9310 and EC36C; however, the goal was for an ultra high-strength core and fracture toughness. While Ferrium C61 can reach case hardness of 60–62 Rockwell "C" hardness (HRC), Ferrium C64 achieves 62–64 HRC.

The Ferrium alloys have 900–950 degrees Fahrenheit tempering temperature, which is an increase in thermal stability of 400–600 degrees Fahrenheit from that of conventional gear steels. This quality results in improved oil-out survivability. They were designed to allow gas quenching and use conventional low-pressure carburization technology to minimize distortion, lower manufacturing times and provide "dial-in" carburized case hardness profiles.

Typical applications include demanding power transmission shaft and gear applications in aerospace; energy; and racing, off-road and mission-critical vehicles; also, other industries where weight savings, compactness, high temperature resistance and high surface fatigue resistance are important, according to QuesTek's press release.

"Certain product applications benefit from the harder surface that C64 offers over C61, when for example the product design life is limited by contact surface fatigue," explains Rich Kooy, director of sales and marketing for QuesTek. "Other product applications may be limited by the strength and fracture toughness of the core material, where the increased ultimate tensile strength and fracture toughness of C61 over C64 will make it the superior choice.

"These differences may seem small, but the fact that NAVAIR is funding an STTR program for QuesTek to design and develop Ferrium C64 for Navy rotorcraft applications illustrates that they are not."

QuesTek, originally a research arm of Northwestern University, became an independent company separate from the university in 1997. The company recently announced a

Phase II Small Business Innovation Research (SBIR) project from the U.S. Army, and three Phase I SBIR projects were awarded by the U.S. Department of Energy and the Office of Naval Research.

For more information about QuesTek Innovations' gear technology, see the technical paper on pages 46–53.

Mori Seiki

OPENS EXPANDED HEADQUARTERS

Celebrating the completion of its 102,000-square-foot North American corporate headquarters in Hoffman Estates, IL, Mori Seiki hosted a grand opening ceremony and open house in November.

The open house was a three-day event with more than 25 machine and cutting demonstrations, and information about developing technology presented by guest speakers. There were 19 different seminar topics, and guest speakers represented the automotive, medical and energy industries. Five new machines were introduced as well as the latest version of Mori Seiki's CNC software, *MAPPS IV*.

The new facility consists of a 14,000 square-foot showroom, Mori Seiki University and office space. The entire facility is twice the size of the previous headquarters, and it didn't include the university, which has three classrooms and a state-of-the-art learning lab for traditional and hands-on machine instruction. The showroom features two 25-ton cranes to help position and operate the extensive product line housed at the facility.

continued

The ribbon cutting ceremony was attended by Dr. Masahiko Mori, president of Mori Seiki; George Hiseada, consul general for Japan; and William McLeod, mayor of Hoffman Estates. A senior enonomist from the Chicago Federal Reserve provided a regional outlook for manufacturing in the Midwest while Mori Seiki VP of engineering, Greg Hyatt, gave an overview of new technology in development at the company.

"Our goal is to be a resource that brings a difference to the machine tool end user," says Thomas R. Dillon, president of Mori Seiki U.S.A. "Mori Seiki's commitment to this goal can be seen in our emphasis on education, research and development in the design of the new headquarters facility."

Manufacturers that missed the grand opening event are invited to check the facility out at the next major event, Innovation Days, which is being planned for the second week of May 2010.

Sandvik

APPOINTS NEW PRESIDENT


Tom Erixon.

Tom Erixon was promoted from president of Sandvik Hard Materials to president of Sandvik Coromant. He replaces Kenneth Sundh, who was appointed executive vice president of Sandvik Tooling, where he is responsible for global strategic projects.

Prior to his position with Sandvik Hard Materials, Erixon held various positions within Sandvik Group and Boston Consulting Group.

Delta/Tifco

PURCHASES FORMER NEWSPAPER FACILITY

Delta Gear is setting up shop in the former Observer Newspapers facility in Livonia, MI. The 61,000 square-foot facility will be torn down, and a 75,000 square-foot, leading edge, state-of-of-the-art gear facility will take its place.

Three different companies will be housed at the facility. Delta Gear, the parent company of Tifco Gage and Gear, will now handle the Aerospace Gear Operations. Tifco Gage and Gear will remain and continue producing master gears and gages. Delta Testing and Inspection (DTI) will be a 17025 certified and NADCAP certified inspection facility for gear inspection, nital etch, magnetic particle inspection, hydrogen embrittlement x-ray and fluorescent penetrant inspection. Gear roll testing, single-flank roll testing and full service transmission dynamometer testing will be provided.

"This is the next step in our plan to becoming the leading aerospace and gear and gearbox provider in the industry," says Bob Sakuta, owner of Delta Gear.

Construction is slated to begin in April 2010 with planned completion and move-in anticipated for November 2010. The property was deemed a "functionally obsolete" brownfield site by the city earlier this year.

Hainbuch

OPENS MANUFACTURING FACILITY

Mequon, WI is the new home to Hainbuch America. The German workholding company moved into the facility in November, and manufacturing is scheduled to commence in the first quarter 2010.

"With implementing a job shop here we will be able to provide better and quicker service to our customers," says Sylvia Rall, Hainbuch co-owner. "For example, we will offer a next-day-shipping service for all grind-outs of

continued

Spanntop clamping heads.

Rall came to the United States from Germany earlier in the year to aid the transition. She anticipates they will hire 10–12 new employees when full operation is achieved in early 2010.

Jurgen Bettray, president of Hainbuch America, commented, “It was a good time to invest in our future here. Our workholding products have long been known for their exceptional precision. Now our U.S. customers will enjoy almost instantaneous access to them.”

QC American

WELCOMES DIVISION MANAGER

Ross Wegryn-Jones.

Ross Wegryn-Jones was appointed vice president and division manager for QC American, a division of American Broach and Machine Company based in Ypsilanti, MI. He has over 17 years of experience in the machine tool, tooling and workholding fields in sales, marketing and project management capacities.

Wegryn-Jones previously was the owner of RJR Machine Tools, LLC, which served as a machine tool dealer, agent and cutting tool distributor in Michigan, primarily in the high production automotive and truck components manufacturing industry.

Starting in 2004, he maintained his position with RJR Machine Tools while simultaneously serving as national sales and marketing manager of Advent Tool and Manufacturing of Lake Bluff, IL. “I was integral to the formation of a new division wholly owned by Advent Tool named TMFM, LLC, which earned a patent and essentially created a process of spline milling on a vertical machining center,” Wegryn-Jones says. “I quite literally wrote the book (as prescribed by engineers of course).”

December 1, 2009, he left both RJR Machine Tools and Advent Tool to work with QC American.

Prior to 2001, he worked for two other companies since 1991. These were in the independent industrial manufacturer's representative field, handling multiple product lines, including machine tools, workholding, cutting tools, metrology and toolholders.

Wegryn-Jones has a bachelor's degree from Michigan State University and a master's in business administration from Western Michigan University.

QC American, LLC, based in Ypsilanti, MI, sells CNC form and generation gear grinders, CNC and manual OD grinders and gear chamfering/deburring machines. Industries served include aerospace, defense, automotive, power transmission and wind power generation.

Solar Manufacturing

ADDS SALES SUPPORT IN SOUTH

David Gangle, president of Ganco Heat Processing Systems, Inc. (GHPS), formed an agreement with Solar Manufacturing, Inc. to provide sales representation in Alabama, Florida, Georgia and Mississippi.


David Gangle.

GHPS is a manufacturer's representative company focused on thermal processing equipment and services for OEMs and end users of primary and secondary metals, ceramics, food, aggregate drying, mineral processing, petro-chemical and heat treating.

Gangle has 17 years of experience in process heating applications. He has held positions in application engineering as well as sales and commissioning for several leading domestic industrial burner and controls equipment manufacturers. He is involved with several industry associations, including the Association for Iron and Steel Technology, ASM Heat Treating Society, Minerals Metals and Materials Society, MTI, American Ceramic Society, Brick Industry Association, Globe Trotters, American Foundry Society and Industrial Heating Equipment Association. He earned a bachelor's degree at the University of Akron. He currently resides in Birmingham, AL.

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CLASSIFIED SECTION

GEAR MANUFACTURING

SERVICE

HELP WANTED

Global Positioning System: The Early Years

ST. LOUIS GEAR SHEDS LIGHT ON ANCIENT NAVIGATION DEVICE

Before retiring from St. Louis Gear in 2000, Roy Harmon liked to tinker. Since the customer base at the time was seasonal, Harmon was looking for a project to keep himself busy. The engineer decided to challenge himself by designing a "South Pointing Chariot," a device he had read about in the book *The Evolution of the Gear Art* by Darle Dudley.

The book describes the "South Pointing Chariot" as a device dating back to 2,600 B.C. that was used by the Chinese to navigate the Gobi Desert. Considered one of the earliest known relics of gearing from ancient times, the chariot was not only geared but contained a very complex differential gear train. The Chinese were able to produce this equipment using primitive hand tools.

The chariot is a two-wheeled vehicle that includes a small figure connected to the wheels by means of differential gearing. The device was created so that the figure would point south and continue to point south regardless of which direction the chariot was going. This would prevent desert travelers from getting lost while patrolling the Gobi.

The intricate design and engineering capabilities of the chariot suggest that there must have been earlier gear-related devices going back to 3,000 B.C. According to Dudley's book, however, the earliest written records of gearing date back to 330 B.C., leaving a blank space of almost 3,000 years during which gear devices must have been in use. "Since there are no written records covering this interval, we must await the spade of the archeologist to fill in our knowledge," Dudley writes.

Dudley notes that both the Egyptians and Babylonians were probably using gearing devices in prayer wheels, clocks, temple devices and water-lifting equipment as far back as 1,000 B.C. But the "South Pointing Chariot" remains one of the few artifacts unearthed by archeologists that allow gear heads to examine ancient design capabilities first hand.

Using photographs from Dudley's book, Harmon took it upon himself to recreate a model version of the "South Pointing Chariot." Today, the company displays the chariot at trade shows, where they receive many questions and inquiries about the device from gear aficionados—including curious members of the Addendum staff at last year's Gear Expo in Indianapolis.

"It's just one of the many reminders left behind by a man that dedicated 40 years to this company," says Alan Chatfield, vice president of operations at St. Louis Gear. "Employee development and experience such as this is one of the strengths and core values within our company."

Harmon was not alone in his enthusiasm of the chariot project. Some web research has uncovered similar "South Pointing Chariot" projects made from wood, car parts and even LEGOs. More detailed examples of the ancient device can be found at the Museum of Natural History in Bejing as well as the National Palace Museum in Taipei, Taiwan.

From the result of Harmon's work, the replica is spot on, though Chatfield notes that it took the engineer a couple of passes to get the device just right.

"Roy has said that his first attempt would have left you stranded in the desert," Chatfield says. "Once he realized that the diameter of the wheels must match the distance between them, a slight modification easily corrected the problem."

Have any information on historic devices that involved gears? Drop us a line at *publisher@geartechnology.com* and tell us about it for a future article in *Gear Technology*.

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