# Grinding Slow, Grinding Fine

## Reducing nonproductive time increases large-gear production

Aaron Fagan, Senior Editor

**While the Greek proverb "the mills of the gods grind slowly, but they grind fine," coined by Sextus Empiricus, was meant as a figurative expression of justice, it does hold true to gear grinding in the sense that there is a right way and a wrong way to do things because rushing the process only causes problems.** Like justice, grinding takes the time it takes, but the grind is fine. So, the way to increase production, especially with the godlike largest gears, is to decrease nonproductive time with improved strategies.


**Figure 1 Gleason P6650G.**

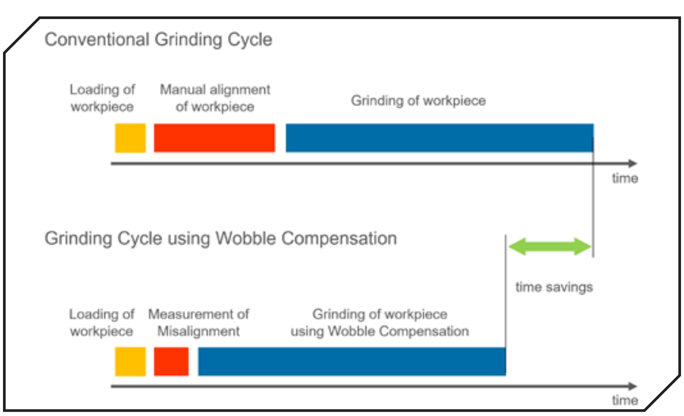


**Figure 2 After measuring misalignment, a wobble compensation feature reduces nonproductive time.**

Inaugurated in April 2021, CMD in France now owns Europe's largest profile grinding machine—a Gleason P6650G designed to produce gears weighing in at as much as 70 tons with diameters in excess of 6 meters. The machine arrives just in time to add much-needed capacity for the largest helical, planetary, and worm gears in industries from cement to chemical plants, mines to steel mills, water treatment to wind power. In the specialized world of giant gear production where only a relative handful of companies like CMD dare to tread, the inherent risks of equipment investments are enormous. And discontinuous profile grinding large gears has distinct and significant production challenges from their smaller counterparts—but the volume of demand for colossal gears is not huge, so, for the purposes of this discussion, *large* is defined as a diameter of 400 mm or greater. To learn more about the unique manufacturing challenges large gears present, *Gear Technology* spoke with Gleason and Norton|Saint-Gobain Abrasives about their solutions.

As with grinding at all scales, there is forever looming the threat of burning parts if production is rushed or the right parameters have not been established, so the key to success is in the reduction of costly nonproductive time because, to make high-quality parts, the runtime will be calculated as a fixed parameter. In the case of the very largest gears, many hours are typically required for workpiece setup, parts programming, parts inspection, grinding wheel dressing, and anything else that isn't actual profile grinding—and, therefore, profitmaking.

Setup time, for example, is greatly reduced with Gleason's system for wobble compensation, which automatically compensates radial runout and wobble of gears with imperfect alignment, rather than relying on an operator and a painstaking manual process for loading and adjusting the gear to the machine table. On-board inspection of both internal and external gears is fully integrated into Gleason machines, saving enormously on the time needed after grinding is complete to evaluate gear characteristics—a process that can take hours to bring heavy parts to the quality inspection department. In its drive to reduce nonproductive time, Gleason has also optimized the position of the dressing unit to shorten dressing cycles and use their dressing process, which reduces actual dressing time to just a fraction of the time conventionally required.

With respect to having a grinding wheel that's compatible with a grinding process, Josh Fairley, a product engineer for bonded abrasives at Norton|Saint-Gobain Abrasives, says, "Gleason is very good at this, the technology that goes into their equipment tells an operator what the correct tool to use is, automatically adjusting grinding parameters based on what's

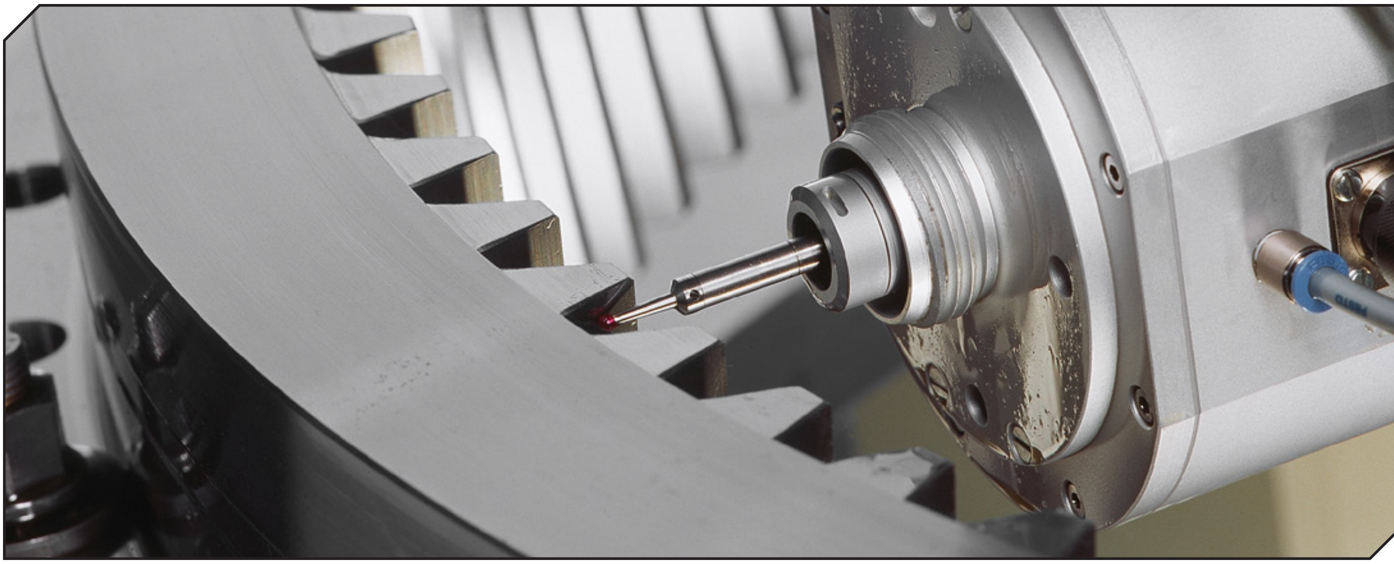

**Figure 3** **On-board inspection of both internal and external gears is fully integrated on Gleason machines.**

happening during the process — so from the abrasive tool side, we want to deliver the most consistent product possible so that their process is repeatable."

Understanding the degree of quality the customer is looking for is Norton's main approach to assigning the right grinding-wheel technology. Quality means not introducing heat into the part along with superior formholding and surface finish. There are many different metallurgical considerations to account for when dealing with gears. Depending on what type of metal is being ground, there can be a careful selection of a secondary abrasive that's chemically the best fit for that material. While quality standards need to be met first, finding opportunities to control cost by factoring for parts per dress, wheel life, dress depth, and cycle time are all considered and optimized to save the most money for the customer. Fairley adds, "Aerospace has historically been the most precise industry, but now there is less difference between various industries because the efficiencies in the gearbox are worth the customer's time and money."


**Figure 4** **The new Gleason 1200G profile grinding machine.**

## A Large Market

Discontinuous profile grinding is the best hard finishing option for large gears because it offers high flexibility and precision, but a downside is the lower productivity inherent to the process of grinding each individual profile. The principal markets that utilize large gears include:

- Wind
- Industry
- Marine
- Construction
- Agriculture
- Mining

Most of the global commitments made to the Carbon Neutrality Coalition in 2021 are centered around 2050, so the push for net-zero emissions has become the driving force behind the wind market in particular. Windmills have very demanding quality requirements that include both internal and external gear applications. Gleason offers a wide range of products serving these different market requirements.


**Figure 5** **Gleason's Titan 1200H has a tool changer that allows greater versatility.**

Gleason's profile grinding machines are numbered by their maximum diameter in millimeters, and the P-series ranges from P400G up to the P6650G at CMD in France. Very large machines serve lower volume markets like the mining and cement industry, but the current mainstream market for large gears is the wind industry where the grinding machines range from 800–4,000 mm. Larger sizes are mainly for the internal gears, but the most popular size is 1200 mm because it covers the majority of external gears for wind.

In the 1200 mm size, Gleason offers two machine models. The new 1200G is a highly flexible and universal machine that is intended to suit most grinding needs, particularly the demands of the wind market, and it covers a wide range of applications with one grinding wheel. It is a compact, one-piece machine bed for increased rigidity and stiffness, and it can be outfitted with one of three different internal or external grinding-head options. It also supports worm-grinding options.

The other 1200 mm option is the high-performance Titan 1200H from the Titan series which has a tool changer — a feature that remains unique to the industry — for excellent surface roughness, higher productivity, and quality by using separate grinding wheels with optimized grit sizes for roughing and finishing. The machine can also be utilized to grind two different gear profiles on a single workpiece, such as a spindle with timed gears on each end, which is ideal for this machine, because it doesn't require separate setups.

## Think Big

When it comes to large gears, the parts have already passed through a long value chain in their creation by the time they come to the grinding procedure. They have generally been hobbed or milled; hardened; face and bore ground; and the very last process may be the profile grinding, which means a scratch or error on your part at this stage is detrimental. In a smaller automotive gear application, there might be some sacrificial flexibility, but not with large gears. It must be correct right out of the gate.

Getting things right begins with loading and centering the workpiece on the machine table, and conventionally, this time-consuming manual alignment requires a lot of time and effort to hammer large gears into place because they can weigh tons. A crucial aspect of reducing nonproductive idle time is the ability to load a part quickly and accurately. Workpiece changeover time is now reduced up to 70% compared to manual clamping thanks to the innovation of zero-point clamping systems for automated loading. This modular system for centering and clamping automatically pre-adjusts parts on a separate setup table to reduce idle time. It's not as rapid as it would be for a small parts changer on something which would be seconds, but this does reduce idle time in changeover significantly to 5 to 10 minutes.

Manufacturability is essential. Prior to software like Gleason's KISSsoft, there were gear designers and the people who made them — two different worlds — one trying to imagine in theory the stress peaks, writing it down into a gear drawing, and the other in production struggling to make them as they were designed in theory. This was a very expensive and time-consuming trial-and-error process, and given the relative difficulty of loading large gears, that could lead to a very protracted cycle time. So, KISSsoft and technology like it bring the abstraction of design to physical reality in terms of what's possible within manufacturing parameters.

Twist influence is a KISSsoft parameter that evaluates contact patterns of gear mesh and makes micron-level adjustments to influence the stress distribution called the normal force curve. Quality demands for surface roughness — which affects NVH, durability, and service life — in the wind market are very high, which requires tightening tolerances through complex geometrical modifications onto the basic shape of the involute gear geometry itself. That ensures the gear is twist free with good surface roughness (Rz ~ 1 μm). These modifications could include additional crowning or an end relief at the tip or the root of the profile to avoid partial overload in the stress distribution. The importance of integrated design software and production can't be overstated in achieving manufacturability.

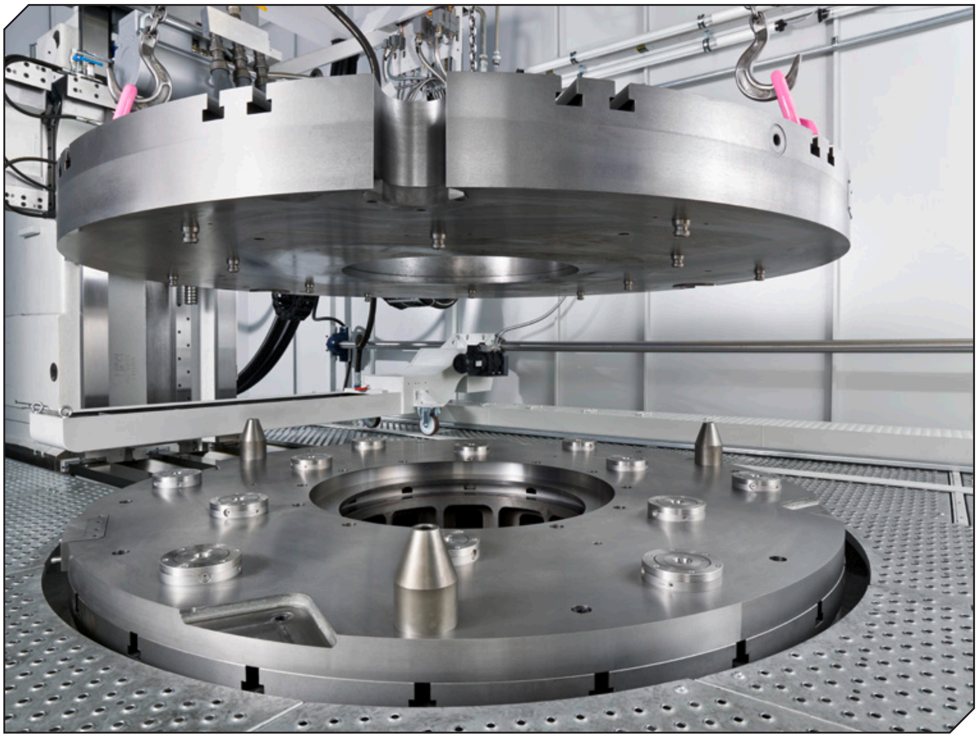

**Figure 6 Zero-point clamping is crucial to reducing nonproductive time when loading and centering large gears.**

Quality demands are extremely high in the wind market—not just for the required efficiency of power transmission but also because premature wear or even failure of gear drives will result in high maintenance and repair costs, especially with large turbines installed offshores. The need for the best surface qualities is one of the reasons why Gleason's Titan series was developed with a tool changer—to switch to a grinding wheel with different specifications required for extremely good surface finishes. A tool changer in other kinds of machining processes is not uncommon, but for gear grinding, the Titan machines remain unique in the industry and, by eliminating extra setups, it reduces a lot of nonproductive time.

## Grinding Smarter, not Faster

Typically a machine is set up with a grinding wheel of a particular grit size, and while the dressing parameters can be adjusted to achieve different finishes from the same grinding wheel—say one for roughing and another for finishing—the finish will only be as good as its actual grit size, meaning it will not be up to the level of superfinishing allowed by switching over to a separate tool with a finer grit size. Hence, when there is only one tool to work with, the grit size is always prone to compromise with its dual task of material removal in the roughing strokes and surface finishing in the final strokes.

The temptation in grinding is to speed up the production time by adjusting the speeds and feeds of the machines, but this will invariably affect part quality and tool life, which will ultimately lead back to waste of both time, money, and other resources in the form of bad gears, energy, and undue machine wear. Stock-specific grinding eliminates any potential empty grinding strokes by using a touch probe to evaluate the orientation of the gear in relation to the grinding wheel in the event of distortion from heat treatment. The algorithm determines the high and low points from a representative sample of measurements. It averages them based on the typical ovaloid distortion of a large gear being hung in an oven for hardening. The machine will only rough pass those high teeth profiles skipping teeth that are already within range until in subsequent passes more teeth are ground until all have been brought to their finished pass dimension.

The main task of dressing is to generate the correct wheel geometry, sharpen the wheel topography, and establish a minimum runout of the wheel. The three primary dressing methods are base dressing to create a new wheel geometry, rough dressing for material removal, and finish dressing for quality surface finish and precision. The wheel can be dressed to have a more aggressive microgeometry for roughing strokes, and a finer one for finishing strokes. Smart dressing utilizes the base strokes to establish geometry by utilizing more of the dressing wheel tool surface area than just one edge, which can be preserved for dressing the grinding wheel for roughing and finishing.

With a conventional infeed strategy, a gradual amount of stock per flank is ground and hence the real material removal is increasing from stroke to stroke, but that means most of the material is removed in the last roughing stroke, which creates a high risk for thermal damage in the last stroke and greater power consumption on the grinding spindle. An infeed strategy with a distributed material removal per stroke improves productivity and process reliability. Degressive infeed means taking a more aggressive first stroke and then less with subsequent strokes hence degressive, and an A(x) infeed strategy means a slight tilt on the A-axis for the x-axis infeed ensures contact with the whole tooth profile, which means less infeed required hence fewer strokes and increasing productivity.

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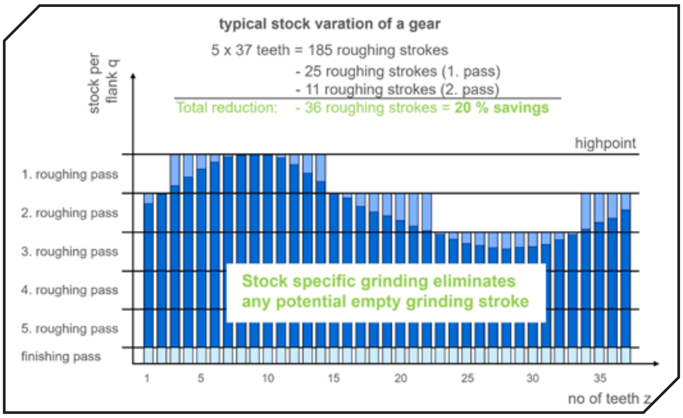


**Figure 7** Stock-specific grinding eliminates the potential for empty grinding strokes.

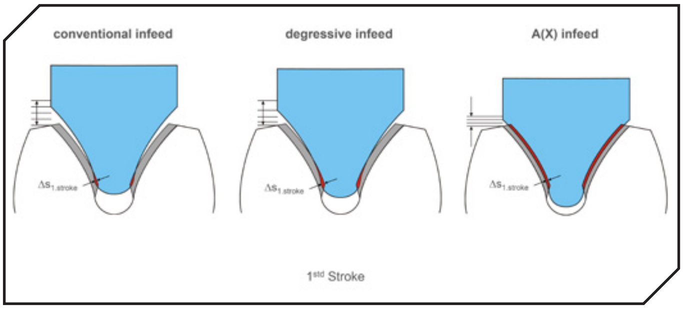


**Figure 8** Infeed strategies with distributed material removal per stroke improves productivity and process reliability.

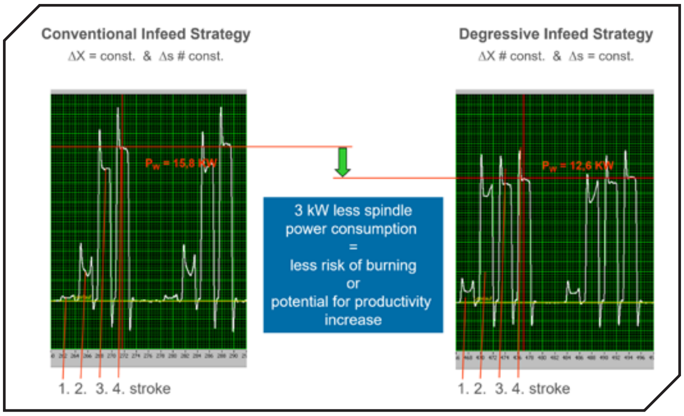


**Figure 9** Graph demonstrates the spindle power comparison between infeed strategies.


**Figure 10** Norton Xtrimium is an example of a profile grinding wheel that uses TQ and TQX technologies.

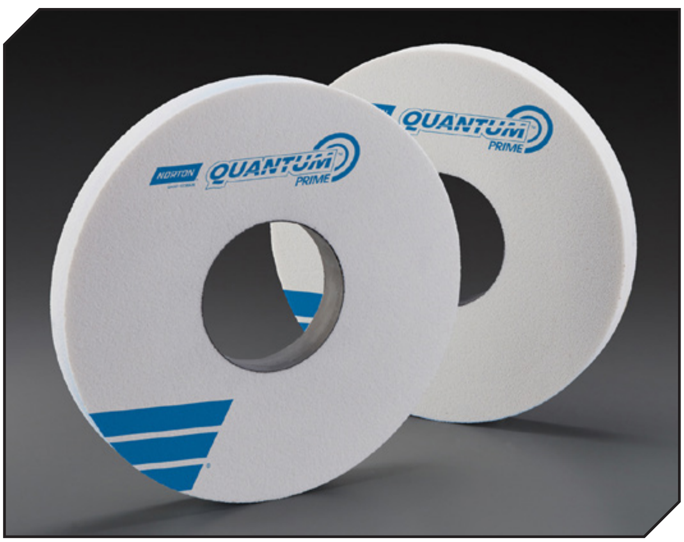


**Figure 11** Norton Quantum Prime is a new ceramic grain technology designed for high productivity and quality with low power draw.

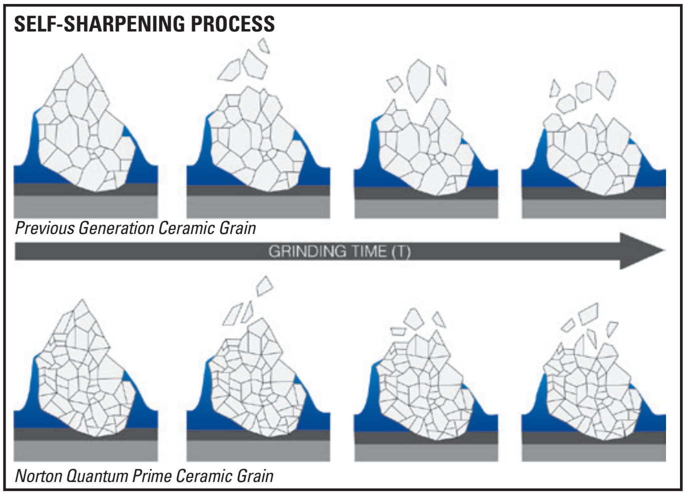


**Figure 12** Ceramic grain is designed to break down smaller so it will last longer, but Norton Quantum Prime is drastically smaller than the typical ceramic grain. Illustration courtesy of Norton | Saint-Gobain Abrasives.

## True Grit

Norton's straightforward approach to grinding wheel formulation is to understand what the customer is looking for, identify their pain points, and then apply three of their different technologies (TQ, Quantum Prime, or TQX), which are like ingredients because, depending on what type of metal is being ground, it's important to select the right percentage of an appropriate secondary abrasive that's both chemically the best fit for that material and cost-effective. Grinding wheels are not purchased stock, they are predominantly made to order. However, there are blank wheels of certain common compositions that are kept in an unfinished state, which allows for a quick turnaround.

TQ, Norton's go-to profile gear technology, is a shape-engineered aluminum-oxide grain that economically offers speed and quality, which is the best of both worlds. To meet the highest quality demands, Quantum Prime is used because it provides the smallest tooth-to-tooth variability in flank and profile at very low power levels. This is possible due to the combination of three critical technologies: Quantum Prime, Vortex2, and Vitrium3. Quantum Prime is a brand-new ceramic grain technology designed for high productivity and quality with low power draw, meaning a lower risk of grinding burn. Vortex2 utilizes agglomerated aluminum oxide to create an engineered porosity that maximizes coolant in the grind zone and improve formholding due to improved homogeneity of the porosity. Vitrium3 is a strong bond that allows the abrasive grains to be used to their fullest before introducing new sharp grains. Quantum Prime works well at a high speed but not as much as a shaped abrasive like TQX, which is built for speed. With its long shaped-grain abrasive, TQX allows very high removal rates while keeping cool. A high-quality surface finish is sacrificed at those speeds, but for certain applications that's acceptable.

Quality is the number one priority which means not introducing heat into the part while maintaining superior formholding and surface finish. And secondly, finding opportunities to control cost—by factoring for parts per dress, wheel life, dress depth, and cycle time—are all considered and optimized to save the most money for the customer.

## The Secret Ingredient

It may seem counterintuitive, but the secret ingredient is nothing—in a grinding wheel, empty space is as important as the physical ingredients. The more consistent the size and spacing of the pores, the better the wheel will perform. Problems of variation will cause different parts of the wheel to break down at a faster or slower rate than others. You *do* want the wheel to break down—that means it is resharpening itself—but you want it to break down very consistently. Consistency ensures there is no heat buildup or excessive breakdown. These are concepts that are basic to grinding but considering the precision requirements for gears, they need to be harmonized.

Grinding wheel design has several priorities and grinding without burn is number one and formholding second. Speed affects both. The goal is to get a surface finish that minimizes the amount of variation as you grind. The chemistry of holding the abrasive grain in the bond matrix for a precise amount of time is referred to as "grain adhesion science." Bond posts — the optimal amount of bond needed to hold the grain in place without burning and to maintain the form — hold the grain in place and then the grain itself does the grinding while promoting a more controlled breakdown of the abrasive. That leads to less variation in the profile and flank and consistency in surface finish. Quantum Prime breaks down into extremely small pieces. Ceramic grain is designed to break down smaller so it will last longer, but Quantum Prime's crystal size is drastically smaller than the typical ceramic grain. With gears specifically, the finish it achieves addresses the issues of NVH very well because it is so controlled and consistent along with a low risk of burning.

## Dress to Impress

Once you move away from conventional abrasives with very low or no ceramic grain, you can use normal lower-tier diamond rolls called infiltrated diamond rolls which use a certain type of metal bond to secure the diamond. But once you get into the ceramic-grain grinding wheels used for greater material removal on large gears, Norton recommends a chemical vapor deposition (CVD) reinforced diamond roll for dressing, which is larger and very precisely sized and shaped for those applications. Because the chemical nature of the CVD is tougher, it will last longer when dressing the ceramic-grain grinding wheels. That's recommended particularly on larger wheels where you have a 6 or 8 in. diamond roll but you have a 12 or 14 in. grinding wheel.

Profile gear wheels typically range from 100–450 mm in diameter. Sizing is driven by the parameters of the machines which have a minimum and maximum OD they accept. For large gears, the minimum might be 300 mm because you want to be able to dress the double bevel into the wheel itself but also reach the full depth of the gear tooth. But you also want the wheel to be large enough to last an appropriate amount of time because tool changing is time-consuming, so ideally that same wheel will complete the entire gear or multiple workpieces.

One thing is clear from speaking with Gleason and Norton: toolmakers don't sell tools, they sell process solutions to technical problems. That is an essential point of view to take into consideration when quality and precision are paramount. These relationships often begin with a part drawing and then a process to support the creation of that part is developed according to appropriate time and quality standards. Tools are not bought in isolation but as part of a whole. A process acceptance involves a proving demonstration. So it's not like buying a suit off the rack, it is like having a team of tailors make one bespoke to your exact measurements just as you need a process that suits your needs.

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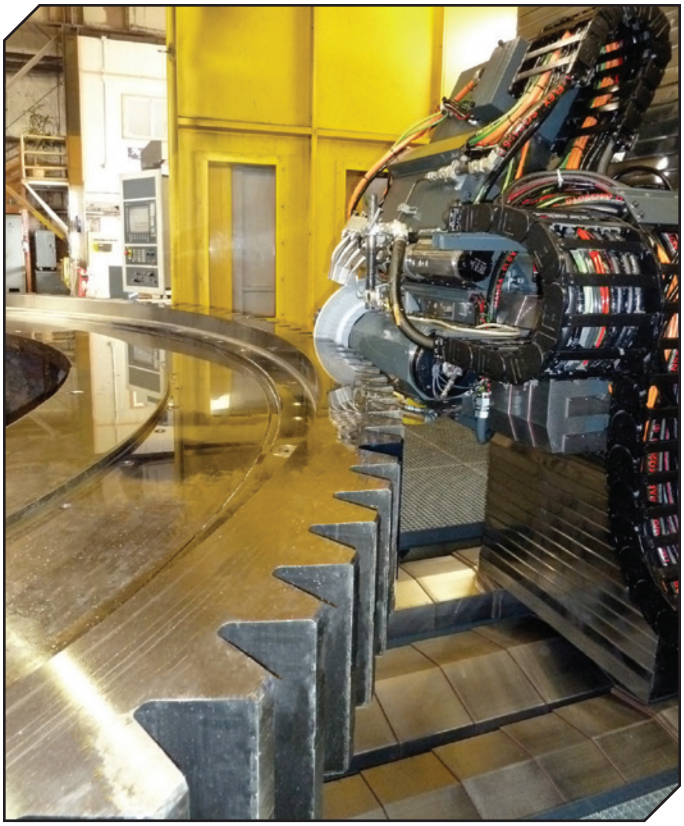

**Figure 13** For large gears, the diameter of a grinding wheel is sized to reach the full depth of the gear tooth but also last long enough to avoid a mid-operation wheel change. Image Courtesy of Norton | Saint-Gobain Abrasives.

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