An ever-increasing range of grinding applications from Kapp/Niles are geared toward achieving lower noise, longer service life, and improved performance.
This article reviews the technologies, products, and factors leading to the transformation of gear production for parallel-axis gears 400 mm to 2,000 mm in diameter, and modules 8 to 40. Higher productivity, lower costs, and superior reliability are realized over this wide range of gears, now making gear grinding a preferred tooth finishing method even for moderate-quality, low-volume applications.

**INTRODUCTION**

The advent of profile grinding technology for large gears with modern non-dressable CBN—and later, ceramic-bonded dressable tools—led to widespread replacement of single-index generating machines in the late 1980s throughout the 1990s. High productivity grinding was demonstrated under controlled conditions, achieving impressive grinding times and stock removal. \( Q'w > 15 \) could be demonstrated when pre-grind quality was known. The reality of production variations resulted in higher stock amounts that starved the grinding zone of the necessary coolant, causing thermal damages. Due to the high cost of large gears, productivity was frequently sacrificed and expectations were lowered. Onboard measurement was introduced to shorten setup time, in-process and post-process control. Although a time savings, the measurement on the machine simply replicated traditional methodology and was too slow to be used economically in advance of grinding. As such, achieving the promised grinding potential remained elusive.

Grinding methods continued to advance dramatically in the last decade, driven in part by demanding applications for wind turbine transmissions and subsequent larger volumes. In general, the growing demand for sources of energy, raw materials, and infrastructure leads to a higher demand for ground gears. The shortage of capacity and the low productivity of older machines created the necessity for rapid advancement. The introduction of threaded wheel generating grinding machines (such as the Niles ZX-series, fig. 1) to grind up to module 10 addresses one segment of this demand. Further efforts focused on profile grinding development for larger modules and diameters.

**NEW DEVELOPMENTS IN PROFILE GRINDING**

The elimination of no-contact grinding passes, or air grinding, is essential for the lowest cycle times. The integration of modern electromechanical drive systems and imbedded intelligence through modern software allows high-speed measurement of the pre-ground gear. This method reveals the quality—and the distortion, most importantly—prior to grinding. Knowing the gear quality and exact stock allows for optimal metal removal rates at low risk. When the stock condition around the circumference and across the face is known, grinding passes can be minimized. In other words, full contact grinding is achieved. This method is called high-speed measurement for full contact grinding (fig. 2). The new methods are pre-process or predictive in nature. We will describe the new predictive approach to gear finishing and how the art of gear grinding is being transformed into a science.

After pre-machining and heat treatment large gears may have considerable distortion, resulting in a large number of air cuts. Figure 3 clearly depicts this condition by example of complete measurement. In order to avoid “grinding air,” the true amount and position of stock in each gap must be determined. Early onboard measuring systems allowed for slow measuring speeds only, resulting in shortened measurements. The ensuing uncertainty was compensated by excessive grinding stock, leading to a high number of grinding strokes without contact between the gear and grinding wheel.

Due to the introduction of direct drives, modern control, and drive technologies, as well as intelligent software, measuring speeds have increased dramatically. This makes it feasible and economical to measure a sufficient number of teeth to insure optimal grinding conditions while lowering risk. Not only is the radial runout consid-

| Table 1: \( z=91, \ m_n=8, \ b=180, \ \beta=16^\circ \) stock/flank=0.57 mm. |
|-----------------------------------|-------------------|-------------------|
| **Profile grinding** | **Generating grinding** |
| Roughing | 7 mm³/mm² | 5 start worm |
| Indexing/overrun | 13 min | 1 stroke |
| Dressing | 3 min | 0,5 min |
| Grinding material | 11 min | 5 min |
| Roughing time | 27 min | 5,5 min |
| Finishing | 1500 mm/min | 1 stroke |
| Index/overrun | 14 min | 0,5 min |
| Dressing | 9 min | 5 min |
| Grinding material | 18 min | 5,5 min |
| Finishing time | 41 min | 1 min, roll W-Z-MK |
| Dressing generating grinding | | 3 gears/dressing |
| Total time | 68 min | 12 min |
ered, but also the helix distortion and axial runout. During the measurement, the intelligent software finds the best possible alignment between the grinding wheel and teeth to minimize stock removal and insure that all teeth are completely ground. The software also identifies flanks that may not be fully ground. This allows the operator the option of changing the grinding parameters before the grinding begins to eliminate grinding strokes with little or no contact. This increases safety and saves time by eliminating rework.

Figure 5 illustrates indexing past the teeth that don’t require grinding during the roughing rotation. The stock can be removed in the finishing process, which in some applications reduces roughing time up to 30 percent. Meanwhile, for teeth with the most stock or distortion, the appropriate number of strokes is automatically selected.

Figure 1: Niles ZP series profile grinding machine.

Figure 2: High-speed measuring for full-contact grinding.

Figure 3: Stock analysis of a large module gear.

Table 2: z=41, mn=10, b=265, β=8.5°, stock/flank=0.77 mm.

<table>
<thead>
<tr>
<th>Roughing</th>
<th>Generating grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qw: 12 mm³/mm</td>
<td>Qw: 3 mm³/mm</td>
</tr>
<tr>
<td>Stroke speed: 13 mm/min</td>
<td>Stroke speed: 3 mm/min</td>
</tr>
<tr>
<td>Roughing time: 27 min</td>
<td>Roughing time: 7 min</td>
</tr>
<tr>
<td>Indexing/ overrun: 13 min</td>
<td>Indexing/ overrun: 1 min</td>
</tr>
<tr>
<td>Dressing: 10 mm/min</td>
<td>Dressing: 10 mm/min</td>
</tr>
<tr>
<td>Finishing: 2250 mm/min</td>
<td>Finishing: 2250 mm/min</td>
</tr>
<tr>
<td>Roughing time: 40 min</td>
<td>Roughing time: 20 min</td>
</tr>
</tbody>
</table>

Table 3: z=192, mn=4, b=70, β=18.5°, stock/flank=0.10 mm.

<table>
<thead>
<tr>
<th>Roughing</th>
<th>Generating grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qw: 5 mm³/mm</td>
<td>Qw: 13 mm³/mm</td>
</tr>
<tr>
<td>Stroke speed: 3 m/min</td>
<td>Stroke speed: 8 m/min</td>
</tr>
<tr>
<td>Roughing time: 57 min</td>
<td>Roughing time: 25 min</td>
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</table>

An additional example for productivity improvement is achieved from the grinding process itself. A lifetime test grind (criterion: grinding burn) conducted by the FVA (the German association for drive technology) as part of a research project uncovered an interesting effect. Despite the increase of feed rates with the same in-feed amount, the lifetime did not change. Further research confirmed this, and ultimately roughing times could be cut in half as proven by the following example:

**Conventional process**

- Rough grinding: Infeed 0.1 mm
- Stroke speed: 3 m/min
- Qw’: 5 mm³/(mm-s)
- Roughing time: 57 min

**Advanced process**

- Rough grinding: Infeed: 0.1 mm
- Stroke speed: 8 m/min
- Qw’: 13 mm³/(mm s)
- Roughing time: 25 min

Other important aspects of obtaining these productivity improvements include the application of modern sintered corundum grinding wheels, an optimized supply of cooling lubricant, and modern drive technology to control the increased process dynamics.
A SINGLE CLAMPING SETUP

Significant productivity improvements have always resulted from careful control of the concentricity of the bore and the face datum to pre-ground gear teeth, in order to minimize the amount of grinding stock. Even with best efforts and skill, however, the tools to control the concentricity are at best marginally capable and usually unavailable for general use. Therefore the reality is that significant errors occur, and stock must be added to insure that all teeth are ground.

We know from other processes that qualitative and economical advantages can be achieved by complete machining in one clamping setup. This is also true for gears, with obvious—and not so obvious—benefits. The obvious benefit is studied in detail by the example of a planetary gear (m=16, z=35, β =10°, b=320 mm, bore diameter 400 mm). The teeth, bore, and face are to be ground in a single setup. The strategy is measured against the conventional method, where the bore is machined first after hardening, since the bore represents the reference for subsequent gear grinding. With complete machining of both the bore and teeth on a single machine, the workpiece can be aligned to the unground teeth by the onboard measuring unit and a quick run-out alignment device. By aligning the teeth first the amount of excess stock created by using the conventional method can be removed, which results in both productivity improvements and a shorter carburizing cycle for the same hardness and case depth. Then the bore datum is ground with slightly higher stock removal, still yielding a net benefit. Positive results include:

- The difference between maximum and minimum grinding stock is less (more uniform hardening depth);
- The quality of concentricity of teeth to bore is higher;
- The quality of the bore is improved, especially if compared to the quality after turning;
- This makes new planetary gear designs possible, where the bore is the load-bearing race.

The advantages for quality are clearly visible, but there are also positive aspects regarding
costs. Actual benefits go further than is obvious. When the new complete machine process is compared to the old process, hard turning and gear grinding on separate machines, the following is found:

- 20-percent reduction of change-over time to a new type of planetary gear;
- 48-percent reduction of auxiliary time for every planetary gear;
- 5-percent reduction of machining time based on a stock optimization;
- 30-percent increase of productivity.

Additional effects include:

- Reduced manufacturing lead and delivery times, with less work in process;
- Avoids bottlenecks on bore grinding machines;
- Same-kind machines;
- Improved multi-machine operation;
- Smaller floor space needed;
- Reduced rework and reject rates.

Niles delivers combined gear and bore grinding machines up to a gear diameter of 4,000 mm. Figure 10 shows a machine for gears up to 3,000 mm.

**TOPOLOGICAL PROFILE GRINDING**

Gear designers have been demanding topologically modified tooth flanks for helical teeth, which means a relief of a tooth flank normally at the first and at exit contact area, or vice versa. This modification improves either the load bearing capacity or noise level. Modifications to the profile angle ($f_{ha}$) have always been possible via single flank grinding both in profile grinding and in generating grinding (single tooth oscillating ram method). Until recently, however, profile grinding had not allowed for topological modifications or a change in profile form across the tooth length in the transverse plane (fig. 11).

Niles now offers topological modifications for profile grinding using simulation software and five-axes interpolation. The result is greater flexibility to achieve optimum and demanding gear designs, as well as greater productivity with reduced setup time. Figure 12 shows a
comparison between the target and simulated grinding result of the flank of the following gear: $z = 38$, $m = 10$, $\beta = 22^\circ$, $b = 100$ mm.

The image shows that the grinding result with five-axes interpolation is very close to the desired flank shape. To accomplish this the gear designer must identify the exact topological flank modifications and enter the data into the machine control.

**CONTINUOUS GENERATING VS. PROFILE GRINDING**

For years continuous generating grinding has been the dominant technology for gear finishing, particularly in medium- and large-series production for workpieces up to 400 mm in diameter and module 6. Hundreds of these generating machines are delivered globally by Kapp and other manufacturers, particularly for automotive applications.

Extending this technology to gear diameters up to 1,000 mm and module up to 10 was another logical step. Niles adapted the well-proven elements of the Kapp KX-series grinders by simply enlarging the machine bed and developing a more powerful direct table drive to handle heavier loads and higher inertia. In our comparison of continuous generating grinding to the discontinuous profile grinding, special attention was given to the application of dressable grinding worms for gear diameters up to 1,000 mm and modules between 6 and 10.
DRESSING

With profile grinding, a dressing roll with a single or dual radius is traversed across the grinding wheel to create the exact complementary profile of the tooth space. One dressing roll can generate any profile on all kinds of different gears.

Generating grinding offers various dressing possibilities. Dressing form roll type “W” with radius offers the same dressing flexibility as the dressing roll for profile grinding: the grinding worm is dressed to the desired profile in single passes. The high number of single passes does impact the dressing time, but this extra time is a worthwhile tradeoff for higher flexibility, even for small batch production.

The other available dressing methods dress the entire flank of the grinding worm in one pass. A double flank profile roll (W-L-OK) dresses only the flanks, but not the tip. This allows for dressing different modules with one single dressing method. The tip of the grinding worm is dressed by a separate dressing bar. Dressing time is approximately five minutes. Profile modifications already in the dressing tool restrict flexibility but, of course, enhance productivity.

The single flank dressing roll of type W-Z-MK offers very short dressing times of around three minutes. Both the flanks and the tip of the grinding worm are dressed at the same time. Consequently, these dressing tools are mainly suited for specific workpieces.

![Fig. 7: Test grinding results.](image)

![Fig. 8: Planetary gear z=34, mn=16, β =9°, b=322.](image)

![Fig. 9: Gear and bore grinding machine ZP10B with quick run-out alignment device.](image)

![Fig. 10: Gear and bore grinding machine ZP30B.](image)

![Fig. 11: Topological tooth modification.](image)
With generating grinding, there is a multipoint contact between the gear and the worm wheel. The generating feed rate runs at approximately 150 m/min. With profile grinding, however, there is line contact. The feed rates are about 6 m/min. In terms of thermal impact on the marginal zone, there is no doubt that the shorter contact time provided by generating grinding is more advantageous.

In contrast, profile grinding offers the advantage of using different dressing strategies to obtain an aggressive, sharp-cutting roughing wheel on one hand, and a form-stable, smoothened finishing wheel on the other. With generating grinding, the same tool is used for both roughing and finishing, meaning that the roughing cut is performed by the same tool that does the final cut, which must meet the quality of the required specifications and dressing technology.

It turns out that in a production environment the maximum stock removal rate for large modules is similar between generating and profile grinding. The great advantage of generating grinding is that a big portion of the total machining time is dedicated to the actual cutting operation. With discontinuous profile grinding, however, a considerable amount of time is consumed for indexing and over-travels. Tables 1-3 show comparisons of three different gears.
As shown, the productivity advantage of generating grinding varies between 1 and 6; finishing, in particular, is always faster. The advantages of generating grinding are proportional to:

- Greater number of teeth (due to lack of indexing time compared to profile grinding);
- Smaller face width (many over-travels related to the entire axial traverse);
- Smaller grinding stock (more time for finishing);
- Less hardening distortion (full-contact grinding offers little efficiency only);
- If profile dressing rolls can be used.

**PROCESS DEVELOPMENT**

On one hand, generating grinding offers very interesting productivity potential, but on the other there is a clear need for further research and development. For decades profile grinding has been utilized for large module gears and today represents a fully controlled technology. It has also been a science: The user inputs the gear and process parameters, grinds a pilot (or test) tooth gap, measures the tooth inside the machine (making any necessary corrections), and completes the grinding process. This technology is ideal for single job production.

With generating grinding the process development is considerably more complex. There is little experience with large module gears. The technology is characterized by very high process dynamics. Many variables influence the production quality: speed, number of starts, and specification of the grinding worm, speed and clamping fixture of the gear, and feed and shift strategies, etc. Finding a suitable process for a new workpiece is time-consuming, at times requiring that a small number of gears be ground close to their final form in order to identify which process is appropriate.

The process stability within the series is another factor to be taken into account with generating grinding. Dressing the grinding worm changes its diameter. If the speed of the grinding worm remains constant, the surface speed changes. Leaving the surface speed constant results in a change of the speed of the grinding worm and gear. The consequence is that the process parameters must be readjusted.

**CLAMPING FIXTURES**

Profile grinding is a quasi-static process. As for the fixtures, a simple design as shown in fig. 17 will do. Such a fixture is unsuitable
for generating grinding. The high process dynamics demand very stiff and, in most cases, custom design fixtures.

This clamping aspect reveals that generating grinding is not the appropriate method for the grinding of pinions, since stable clamping setup is difficult to achieve. In addition, the profile-S for pinions is difficult to solve due to the intricate contact conditions. Since productivity hardly differs with small numbers of teeth between generating and profile grinding, profile grinding is the first choice for the machining of pinions. With this in mind Kapp and Niles designed their generating grinding machines with the ability for profile grinding as well. In order to obtain the highest potential of generating grinding productivity, more work must be invested in process development and fixtures.

**QUALITY**

Both generating grinding and profile grinding technologies allow for the required quality specs; up to quality grade according to DIN 2. Generating grinding makes it easier to obtain very good indexing quality, while profile grinding is the better alternative for very specific profile and lead modifications. In addition to the standard applications—i.e. grinding of external involute spur and helical gears—other applications can be handled with both technologies, as well.

**SUMMARY**

For profile grinding technology, great progress has been made in recent years in
terms of productivity. The machining times can be cut to half thanks to novel grinding tools, new machines featuring latest drive technology, and intelligent software. The stock removal rate with roughing can clearly be increased with fast feed-rate grinding. The nonproductive auxiliary times—such as air grinding, for example—have been considerably reduced. A lot of attention has been paid to process and auxiliary times, but there is still much potential left to explore.

Complete machining is another interesting topic. For certain types of gears, both the quality and economy can be improved. As for machining of tooth flanks, bore, and face, there are solutions for gear diameters from 600 up to 4,000 mm. Other process combinations are conceivable, such as OD or in-process grinding burn checks, for example.

Continuous generating grinding has recently been introduced for large module gears. Step by step, this technology will gain ground. The productivity potential is enormous, but investments into process development and fixtures must be made. As for defined workpieces such as pinions, profile grinding will remain the most appropriate process. New machines covering these applications must be capable of both technologies: continuous generating grinding, and discontinuous profile grinding.

All of these developments will contribute to a decrease in the per-piece cost for precise hard machining. This is a remarkable contribution to the ever-increasing range of grinding applications geared to achieve lower noise, a longer lifetime, and an improved mass-to-performance ratio.

**Fig. 18:** Special applications of profile grinding.

**Fig. 19:** Special applications of generating grinding.

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**ABOUT THE AUTHORS:**
Sascha Ungewiss is product manager at NILES Werkzeugmaschinen GMBH and Bill Miller is vice president of sales at Kapp Technologies. To learn more visit [www.kapp-usa.com].