Innovative Concepts for Grinding Wind Power Energy Gears

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Management Summary

Over recent years, wind power energy has gained recognition as a way to reduce CO_2 emissions and thus counteract global warming. The development of wind power technology is driven by increased performance, which requires larger wind turbines and gearboxes. The quality demands of those gears are increasing while the production costs must decrease. This requires new production methods to grind the gears at low cost and at a high quality level. Profile grinding is known as a process to achieve the highest possible quality, even for complex flank modifications, while threaded wheel grinding is known for high productivity. New machine concepts now make it possible to use both advantages at the same time. The reduction of non-productive auxiliary time is a key aspect to becoming more productive.

This paper will show the newest developments to reduce the overall cycle time, including aspects to reduce setup time, idle time, productive time and dressing time.

Productivity in Profile Grinding

The gears used in wind turbine gearboxes have to transfer high loads, which requires hardened material on one hand and an exact geometry on the other. Thus, those gears have to be hard-finished. Discontinuous profile grinding with dressable wheels is an effective process to hard-finish gears of large modules (m > 8 mm:DP < 3). Due to the ongoing boom in the wind energy market, gearbox manufacturers are focusing on increasing the capacity and productivity of existing machine tools.

In profile grinding, the total cycle time to grind a gear consists of idle time and main production time. Many efforts at optimizing cycle time simply concentrate on improving the production time itself, without considering the idle time. The idle time, which can cover up to 50% of the total cycle time, consists of setup time, centering time, dressing time, time for over travel and pitch movements during grinding, as well as on-machine measuring time.

Figure 1 shows typical times for profile grinding large gears. The effective grinding time in rough grinding (41 min) is only 34%, or just 17% of the total cycle time (240 min). This example shows a dramatic inefficiency of the process.

The grinding time can be calculated with the specific material removal rate $Q'w$, which represents the productivity of a grinding process—the higher the $Q'w$, the shorter the grinding time. Figure 2 shows the definition of $Q'w$ for discontinuous profile grinding. $Q'w$ is the product of radial infeed Δx and axial feed speed f_a. To reduce the grinding time, $Q'w$ has to be increased either by larger radial infeed or faster axial feed speed, or even both. The limiting factor for such an increase is usually the appearance of grinding burn.

Figure 3 shows the principal relation between the radial infeed Δx and the axial feed speed f_a. As an example, a specific material removal rate of $Q'ww = 10\ mm^3/mms$ can be achieved by using a radial infeed of $\Delta x = 0.15$ mm, and an axial feed speed of $f_a = 4{,}000$ mm/min as well as using a radial infeed of $\Delta x = 0.05$ mm and an axial feed speed of

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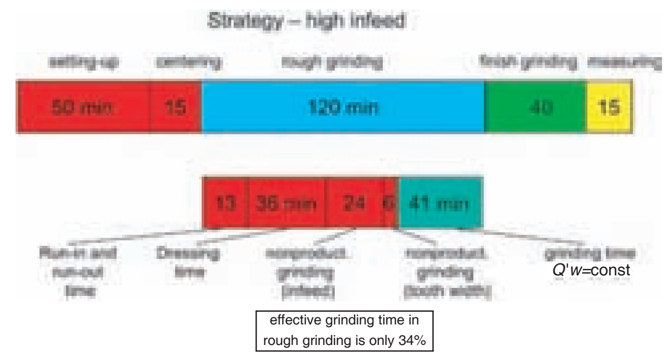

Figure 1—Typical cycle time in profile grinding of large gears.

f_a = 12,000 mm/min. In principle, there are two strategies to reduce the total amount of stock Δxx_{total}. One is using high feed speeds, and the other is using a high radial feed. It is obvious that using a higher axial feed, for example, by a factor of three, results in an increase of strokes by a factor of three as well. Running more strokes effects a longer cycle time because each stroke needs an approach travel to accelerate the axis to the axial feed speed as well as an over travel to decelerate as shown in figure 4.

Table 1 shows a cycle time comparison for different grinding strategies. The first strategy is running the cycle with a high radial infeed. For a given specific material removal rate of 10 mm^3/mms, and an axial feed speed of 4,000 mm/min, the radial infeed per stroke results in 0.15 mm. To remove the total amount of radial infeed Δx_{total} of 3.0 mm, 20 strokes are necessary. The second strategy is running the cycle with an axial feed speed of 12,000 mm/min, which effects 60 necessary strokes to remove the total amount of stock. The idle-time-per-stroke depends on the acceleration and deceleration time of the axial axis. Figure 5 explains the relation between the acceleration and deceleration time per stroke in dependency of the acceleration rate of the axis. The accelerating and decelerating time per stroke at a typical axis acceleration rate of 1 m/s^2 for 4,000 mm/min axial feed speed takes about 0.35 s, while this time increases to 0.6 s at a speed level of 12,000 mm/min. The effect of this increase can be seen in Table 1. The pure grinding time for both strategies is still the same, but the idle time is getting much longer. This is the reason for a total cycle time that is 34% longer compared to the strategy of high infeed. Even when running the machine at an acceleration rate of 2 m/s^2 (strategy No. 3 "high speed 2"), the total cycle time is still increased by 23%.

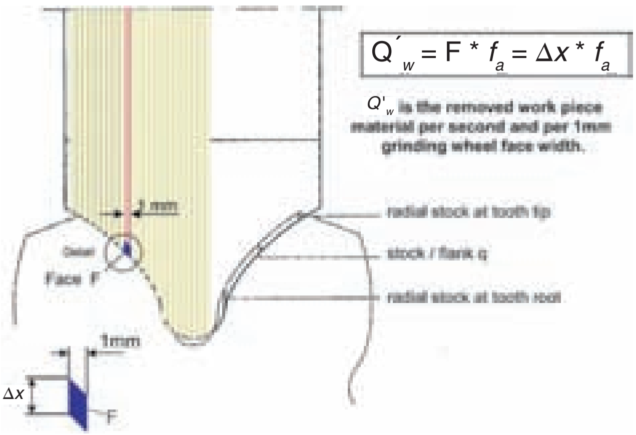

Figure 2—Definition of *Q'w* in discontinuous profile grinding.

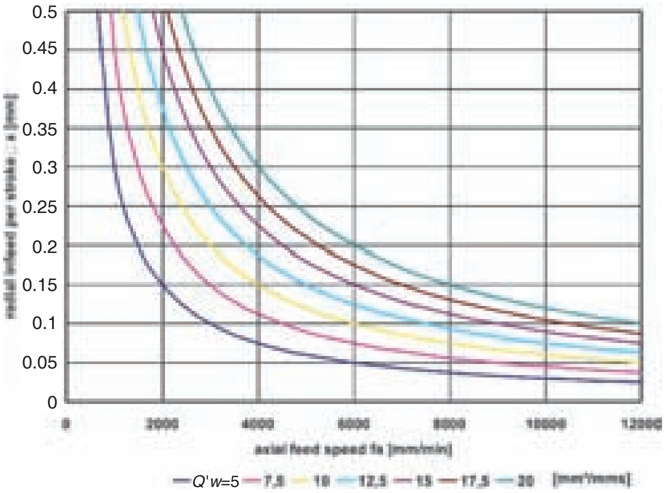

Figure 3—Relation between radial infeed and axial feed speed at constant *Q'w*.

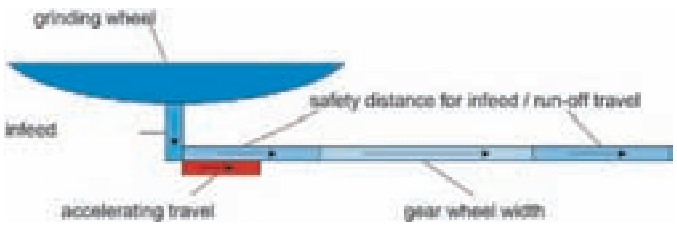

Figure 4—Approach and overtravel in profile grinding.

Furthermore, an increase of axis acceleration has limitations due to the higher load of all mechanical components such as bearings, spindles and guide ways.

The strategy of grinding at higher axial feed speeds finally results in longer idle times, although the specific material removal rate stays constant and thus is not appropriate. Experimental trials done at Gleason Pfauter have shown that grinding typical wind turbine gears at 12,000 mm/min axial feed speed have 36% longer idle times (Table 1) than grinding at 4,000 mm/min axial feed speed and higher radial infeed. To offset this time delay, an increase of the specific material removal rate from $Q'w$ = 10 mm^3/mms to $Q'w$ = 14 mm^3/mms would be necessary. But this would tremendously increase the risk of grinding burn. In other words, it is not possible to achieve a higher productivity by higher feed speeds without an increased risk of burn. In addition, such an increased material removal rate would just affect the 41-min effective grinding time as shown in Figure 1, which again is just 17% of the total cycle time. Increased mechanical load on axis components and increased electrical power consumption are disadvantages at this comparison.

Thus, focusing on other strategies to increase the productivity on both sides is needed, i.e.:

- The main grinding time
- The non productive times

Multiple-Wheel Profile Grinding

The use of multiple-wheel profile grinding offers several possibilities to increase the performance or the workpiece quality. In a case where the teeth have no special profile modifications, four instead of two flanks can be ground simultaneously in roughing and finishing operations, which will reduce the grinding time by a factor of two. Just as well, it is possible to reduce the risk of burn significantly without impacting the productivity when compared to conventional profile grinding. Therefore, just the two external wheels are grinding and the middle one is not touching the teeth. This affects a smaller contact angle between the grinding wheels and the tooth flanks. Schlattmeier (Ref. 3) describes the risk of grinding burn as becoming lower the smaller the contact angle gets. The reverse conclusion allows an increase of the specific material removal rate at the same burning risk when grinding with just the external wheels; thus the cycle time will be reduced.

Another possibility is to grind four instead of two flanks at a time with a lower *Q'w*; thus the productivity is the same but at a much lower burning risk.

An attendant important point for ground gears is the surface finish. Investigations (Ref. 6) have shown that the load capacity of a ground gear can be tremendously increased by a very good surface finish of Ra < 0.2 µm. In conventional profile grinding, using just one grinding wheel, such a good surface finish is not achievable because the grinding wheel is designed as a compromise for rough and finish cutting. Therefore, for high-quality gears an additional process called barrel finishing is used to achieve this surface finish. The use of multiple wheels as shown in Figure 6 allows the use of different grinding wheel specifications for rough and finish operation, thus providing the capability to achieve a good surface finish of Ra < 0.2 µm without the additional barrel finishing process. To realize such good surface finish, the two external wheels are only used for the roughing operation; and the middle one, with a fine grit size, is used for the finish operation. During roughing, the middle wheel is dressed to a smaller diameter in order to avoid touching the flanks, while during finishing the two external wheels are dressed to a smaller diameter.

Last—but not least—it is even possible to increase performance when using the anti-twist grinding method. The unique point in this method is to achieve the twist modification in dual-flank grinding, as opposed to doing it flank-by-flank, which doubles the grinding time. With the use of multiple grinding wheels, it is now even possible to further enhance performance by using four flanks for roughing and two flanks for finish grinding—including the anti-twist modification.

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Table 1—Cycle time comparison for different grinding strategies.

			High Infeed	High speed 1	High Speed 2
Total radial infeed	Δx_{total}	mm	300	300	300
Axial feed speed	f_a	mm/ min	4,000	12,000	12,000
Spec. material removal rate	*Q'w*	mm3/ min	10	10	10
Radial infeed per stroke	ΔX	mm	0.05	0.05	0.05
Face width	b_{eff}	mm	278	278	278
Grinding time per stroke	$t_{h\ stroke}$	s	4.17	1.39	1.39
Axis acceleration rate	a	m/s^2	1	1	2
Acceleration and deceleration time per stroke	t_{n1}	s	0.35	0.6	0.4
Idle time for radial infeed and pitch movement	t_{n2}	s	0.1	0.1	0.1
Number of strokes	n	--	20	60	60
Total grinding time	t_h	s	83.4	83.4	83.4
Total idle time	t_n	s	9	42	30
Total time per tooth slot	$\mathbf{t_{total}}$	**s**	**92.4**	**125.4**	**113.4**
				+36%	+23%
Time ratio (idle time/grinding time	t_n/t_h	--	11%	50%	36%

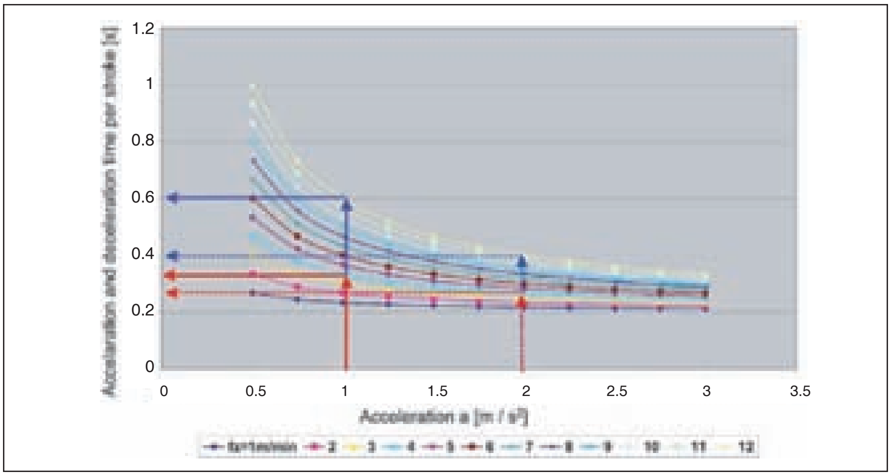


Figure 5—Acceleration and deceleration time per stroke.

Threaded wheel and profile grinding in combination. Threaded wheel grinding is known as a much faster grinding process because there are no idle times for pitch movements between the teeth, and it is thus appropriate for grinding gears with a large number of teeth. But threaded wheel grinding of large-module gears has limitations regarding the achievable quality.

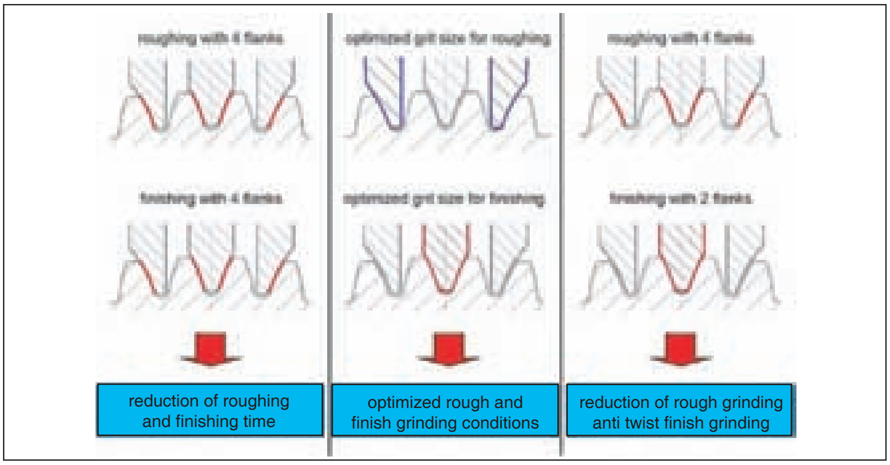


Figure 6—Multiple wheel profile grinding.

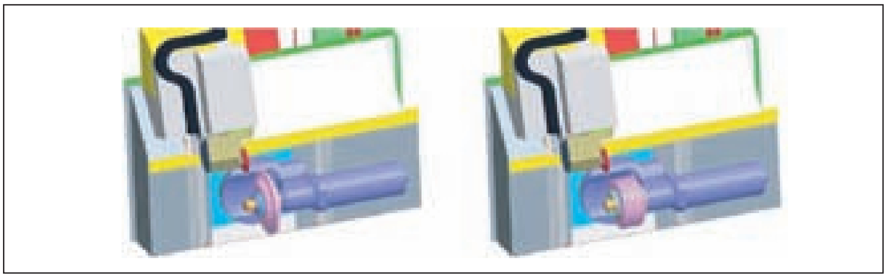
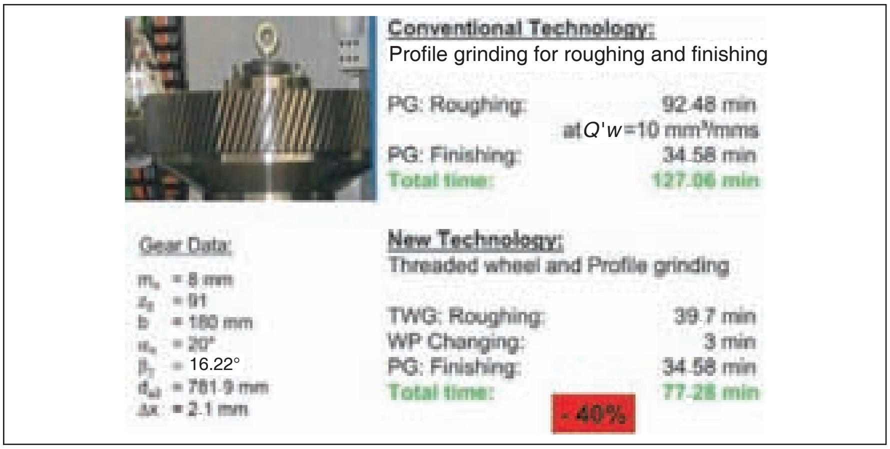


Figure 7—Grind head for profile and threaded wheel grinding.



Conventional Technology:
Profile grinding for roughing and finishing

PG: Roughing: 92.48 min
at $Q'w=10$ mm³/mms
PG: Finishing: 34.58 min
Total time: 127.06 min

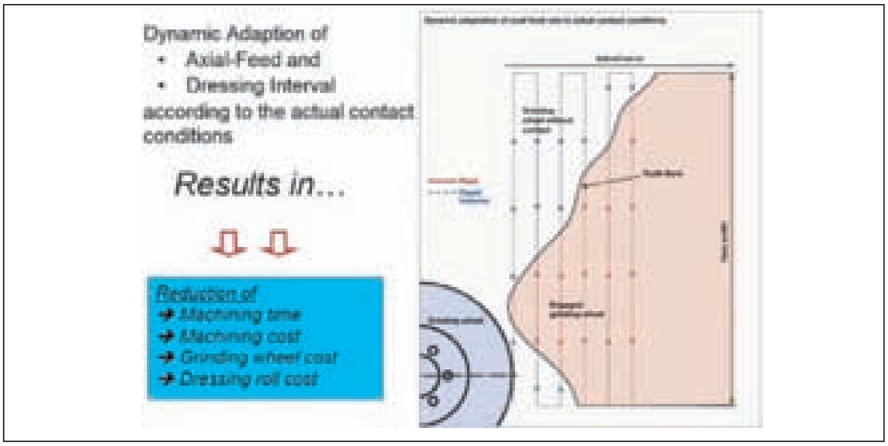
Gear Data:
m_n = 8 mm
z_2 = 91
b = 180 mm
α_n = 20°
β_2 = 16.22°
d_{a2} = 781.9 mm
Δx = 2.1 mm

New Technology:
Threaded wheel and Profile grinding

TWG: Roughing: 39.7 min
WP Changing: 3 min
PG: Finishing: 34.58 min
Total time: 77.28 min

- 40%

Figure 8—Comparison between conventional and new technology.



Dynamic Adaption of
- Axial-Feed and
- Dressing Interval

according to the actual contact conditions

Results in…

Reduction of
- → *Machining time*
- → *Machining cost*
- → *Grinding wheel cost*
- → *Dressing roll cost*

Figure 9—Adaptive technology to reduce cycle time and dressing time.

The highest quality level can still be achieved by profile grinding, but a lot of investigations are being made to use threaded wheel grinding for rough- and finish-grinding of large-module gears (Ref. 5). One new strategy is to use threaded wheel grinding as a fast roughing cycle and profile grinding to achieve a high quality level, which for high-module gears is typically in the range of DIN 1–2. But this technology requires new machine concepts capable of running both cycles. New machine series are in development capable of combining the advantages of both cycles. The grinding head of that machine is designed to use threaded grinding wheels, as well as profile grinding wheels, as shown in Figure 7. In addition, the machine is capable of changing those wheels automatically within a grinding cycle via a special tool changer.

Figure 8 shows an example for cycle time reduction when using threaded-wheel grinding for roughing, and profile grinding for finishing. The total cycle time can be reduced from 127 to 77 min.—a reduction of 40%.

Adaptive Grinding Technology

Another important aspect in reducing main grinding time is to avoid so-called "air grinding." If using the conventional technology as described above, the maximum amount of stock is subdivided into a certain number of strokes, which will be passed through with the programmed axial feed speed. But due to hardening distortions, the amount of stock is not constant over the tooth flanks and around the gear, as shown in Figures 9 and 10, resulting in a considerable amount of stroke length not grinding the gear.

To avoid this unproductive air grinding, an acoustic emission sensor technique is used to detect whether the grinding wheel has contact with the workpiece. In case the wheel is running without contact, the axial feed speed is increased to a maximum speed, effecting time savings. Additionally, the dressing intervals can be increased as well. Instead of dressing the wheel after a certain number of strokes, the wheel is dressed after a certain amount of effectively ground stroke length. This is reducing dressing time as well as tool cost, i.e., grinding wheel and dresser. The adaptive technology allows time savings up to 33%. So the more critical the hardening distortions, the more effective the adaptive technology.

Power Dressing

The reduction of dressing time is another important aspect for productivity improvement. When mounting a new grinding wheel, the shape does not fit to the required profile and thus has to be dressed.

In conventional dressing, the target profile (red line) is dressed as shown in Figure 11. The dresser is starting to follow path No. 1, then 2, and so on until it reaches the final profile. This means that the dresser is covering a volume (blue), which is shown on the right-hand side of Figure 11. This volume is much higher than the real dressed volume, showing that this dressing method is not very efficient.

To avoid this ineffective dressing volume, Gleason has developed the so-called "power dressing" method (Fig. 12). Instead of dressing pass-by-pass, parallel to the target profile, the dresser works in the radial direction. Therefore, the raw profile of the wheel is programmed to the machine, which allows starting the dressing cycle just outside the wheel and infeeding in the radial direction until the target profile is reached. The effect is that the processed volume (blue) is almost the same as the real dressed volume, representing the high efficiency of this method.

Depending on the raw profile of the grinding wheels, as well as the gear data, the dressing time compared to conventional dressing can be nine times faster, as shown in Table 2.

Workpiece Clamping System to Reduce Setup Time

As shown in Figure 1, setting up the workpiece consumes a large portion of the overall cycle time. This is caused by the workpiece weight, which can easily be up to several tons. Aligning such big gears in order to avoid eccentricity and wobble, which would effect an increase of air grinding, is time consuming.

In order to reduce this time, two technologies exist. The first one is the wobble and eccentricity compensation, which is patented by Gleason. The idea behind this is to avoid the time-consuming alignment of the workpiece and to instead measure the eccentricity and runout. Once these two values are known, the machine software can compensate for this with special machine movements resulting in a ground gear without runout and wobble. Figure 13 shows the possibilities by which to measure the eccentricity and runout. Depending on the application,

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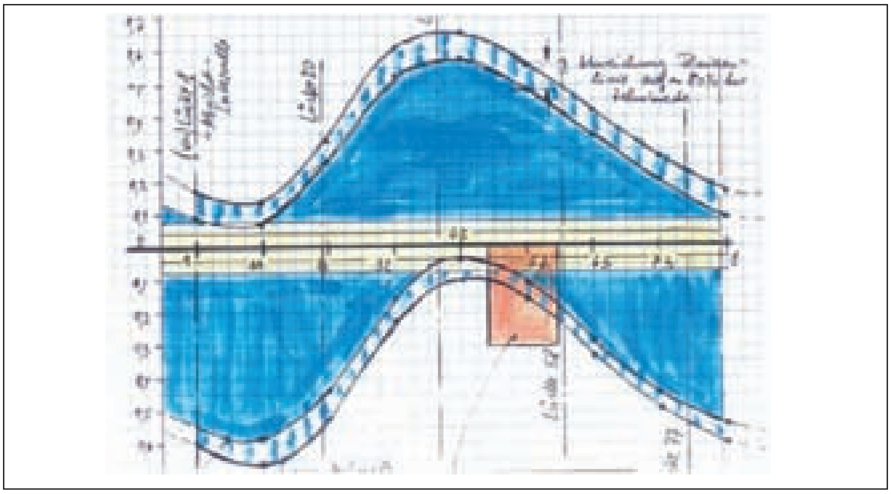


Figure 10—Typical runout of hardened gears.

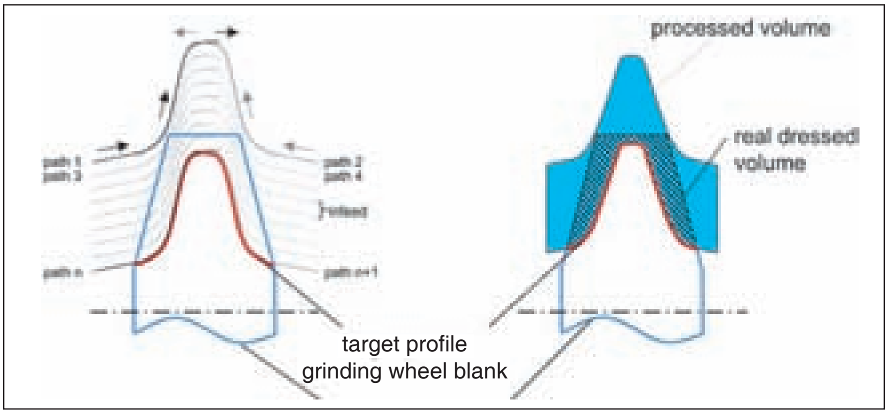


Figure 11—Conventional dressing.

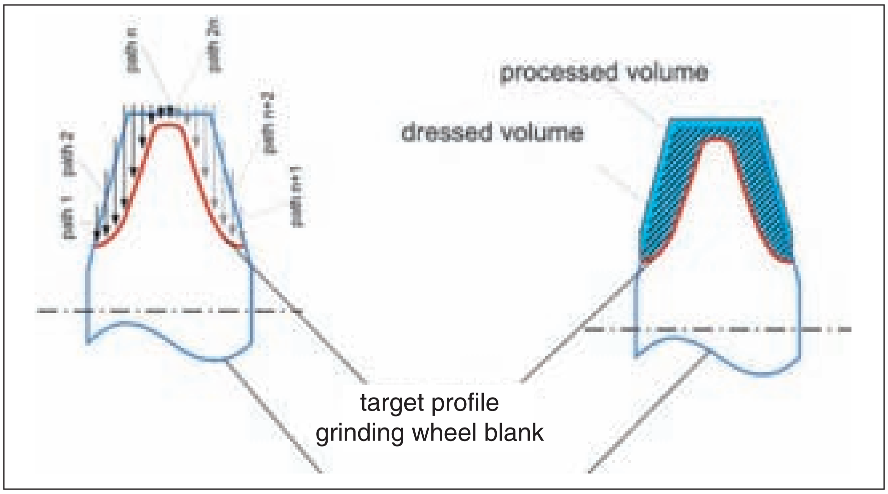
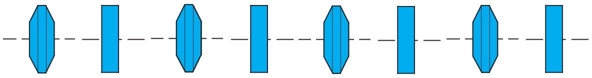


Figure 12—Power dressing.

there are four different possibilities to get these values.

The second possibility to avoid non-productive time for setting up the workpiece is the use of so- called "zero-point clamping systems." Instead of fixing the workpiece directly to the machine table, the workpiece is prepared outside the machine using a special-designed pallet. The workpiece still has to be aligned to this pallet, but this does not consume machining time since it can be done parallel to the grinding operation. When grinding a new gear, this pallet has to be loaded to the machine table, which has a special adaptor ensuring that the workpiece is centered correctly to the machine axis. Both systems help to reduce non-productive setup time tremendously.

Table 2—Performance Comparison of Power Dressing vs Conventional Dressing

Module	14		10		8		5	
No. of teeth	15		10		34		18	
Wheel width	50		40		30		20	
								
Convention (mm:ss)	20:27	55:37	k.A.	k.A.	9:47	31:30	4:48	13:12
Powerdressing (mm:ss)	4:40	6:16	3:10	4:30	3:48	3:55	2:11	2:48
Performance factor	4.4	8.9	k.A.	k.A.	2.6	8.0	2.2	4.7

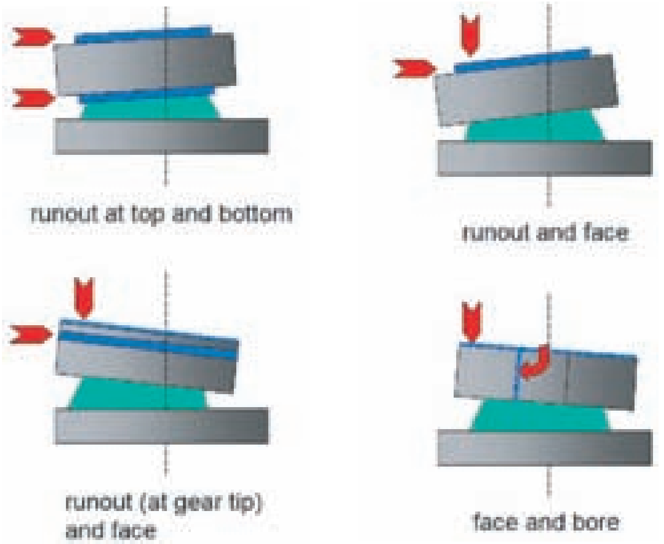


Figure 13—Possibilities to measure eccentricity and runout.

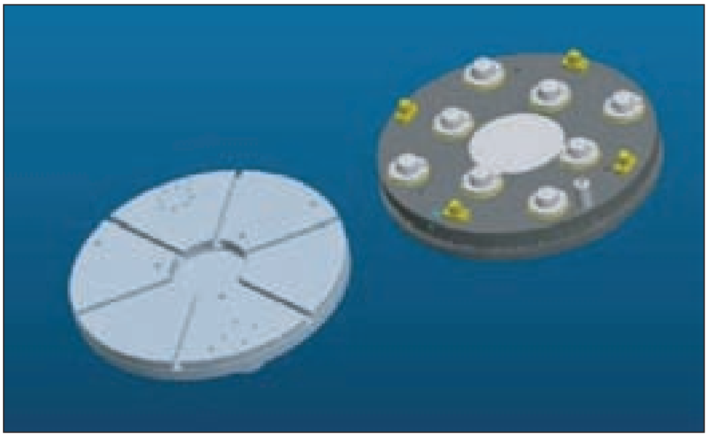


Figure 14—Zero-point clamping palette to reduce setup time in the machine.

Conclusion

Due to the boom in wind power energy, the request for ground gears has increased significantly. Those large-module gears are usually ground using profile grinding. But this process, which produces the highest possible quality, is not very productive compared to other processes such as threaded-wheel grinding. This paper provides an overview of the newest developments to reduce the overall cycle time, including aspects to reduce setup time, idle time and productive time, as well as dressing time.

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