Profile Grinding Gears From The Solid . . . Is It Practical?

Brian W. Cluff

Planetary Gear Set Data

Planet gear: Double helical, 28° HA, 37 teeth, 5.5 DP, 25° PA, 2.350 FW.

Ring gear: Double helical, 28° HA, 117 teeth, 5.5 DP, 25° PA, 2.350 FW.

Sun Gear: Double helical, 28° HA, 43 teeth, 5.5 DP, 25° PA, 2.590 FW.

Sun Gear Internal Spline: Spur, 48 teeth, 7.5 DP, 14.5° PA, 2.750 FW.

Ring Gear External Spline: Spur, 200 teeth, 7.5 DP, 22.5° PA, .5450 FW.

	Grinding Time From Solid in Soft State	Grinding Time After Heat Treatment
Planet Gear	330 min.	41 min.
Ring Gear	980 min.	156 min.
Sun Gear	380 min.	68 min.
Sun Gear Internal Spline	130 min.	82 min.
Ring Gear External Spline	80 min	22 min.

Fig. 1 — Planetary gear set, ground from the solid, using non-dressable CBN plated wheels.

Fig. 2 — Pfauter CNC profile grinding machine with internal grinding arm and 58 mm diameter CBN-plated grinding wheel for grinding 117-tooth, internal double helical gear described in Fig. 1.

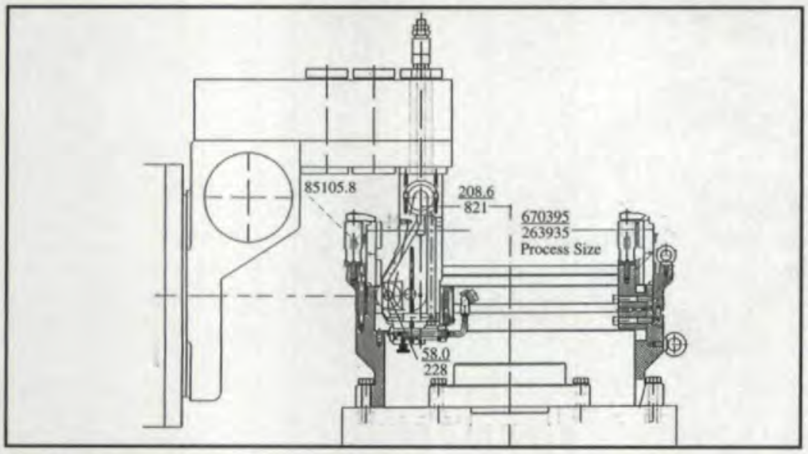

Fig. 3 — Layout of internal grinding setup for 117-tooth, internal double helical gear. Note the location of the grinding arm position on the grinding head. There are three possible positions to mount the arm, depending on the workpiece geometry.

It isn't for everyone, but . . .

Within the installed base of modern CNC gear profile grinding machines (approximately 542 machines worldwide), grinding from the solid isn't frequent, but a growing number of gear profile grinder users are applying it successfully using CBN-plated wheels.

One U.S. East Coast manufacturer of large gears disposed of 22 older wet and dry, single-index generating grinders (Höflers, Niles, and Maags) and replaced them with two new 100" CNC-controlled Pfauter profile grinders, which use plated, single-layer, nondressable CBN wheels. Part of the throughput increase enjoyed by this manufacturer came from processing all through-hardened parts by grinding from the solid.

Gears have been ground from the solid, either in the soft or hardened condition, for a variety of applications for over ten years. Most of these applications were developed through the efforts of Kapp, a manufacturer of CBN-plated wheels and CNC profile grinding machines up to 500 mm capacity, and of Pfauter, a manufacturer of CBN-plated wheels and CNC profile grinding machines up to 4000 mm or larger.

In Figs. 1–4, a double helical planetary set with 28° helix angle, 2.35" face width, 5.4978 DP and 25° PA gear elements was ground completely from the solid in the soft state, then finished on the same machine in the hardened state. In the mid-1980s, grinding from the solid was already a production process for the 9.6 DP, internal helical shown in Fig. 5. The internal/external set of high helix angle gears shown in Fig. 6 were ground from the solid in the soft state before finishing in the hardened state. In the aircraft industry a variety of gear forms, threads and splines have been ground from the solid since 1985, using non-dressable CBN-plated wheels.

What's The Appeal?

Gear profile grinding, particularly with plated CBN wheels on modern CNC form grinding machines, is about 30 times faster than Maag dry grinding, about 10-12 times faster than index generating grinding, competitive with threaded wheel grinding and on some medium pitch through-hardened gears, 2.5 times faster than hobbing and finish grinding.

The additional ability of the larger (above 400 mm) profile grinding machines to measure and document the stock envelope to be removed before grinding and to measure and evaluate the finished ground gear on the machine has significantly increased the productivity and efficiency of large grinders. On one-meter and larger profile gear grinders, the integrated measuring system feature can mean that the grinder enjoys 3-4 times more actual grinding hours than machines without the feature. This additional productivity depends on local plant off-machine measuring practices, queue times and re-setup times.

Some users state (and have closely held data to back up their statements) that the quality and the grinding signature of profile grinding with CBN-plated wheels provides them with the best performing, smoothest running, longest lived gears of all the grinding processes. One manufacturer of transmissions says profile grinding with CBN-plated wheels allows him to warranty the transmission longer than transmissions ground by other processes.

Some users who finish near-net forged gears have found the process of CBN-plated wheel profile grinding capable of removing large near-net stock envelopes faster than the two-step pregrind hobbing and finish grinding process. Fig. 7 shows a dual wheel setup for finishing a 3.5 DP gear with 4.0 mm of stock per flank in a single revolution of the gear.

When it comes down to purchasing an additional pregrind hobbing or shaping machine, many manufacturers who presently use modern CNC profile grinding machines are giving the alternative process of grinding from the solid a second look—particularly if it means saving on the purchase of capital equipment and the elimination of steps in the process which require additional direct labor.

Why Profile Grinding Instead of Generating Grinding?

Form grinding is a single index process where the grinding wheel has the form of the tooth space, or tooth flanks, and grinds the space in one operating step before indexing to the next tooth space. If single-layer, CBN-plated wheels are used, the profile is fixed on the wheel. If dressable media wheels are used, the profile is dressed onto and maintained on the wheel during the grinding cycle.

For large gears (800 mm and above in diameter), traditional index generating grinding is a single indexing, single flank generating process

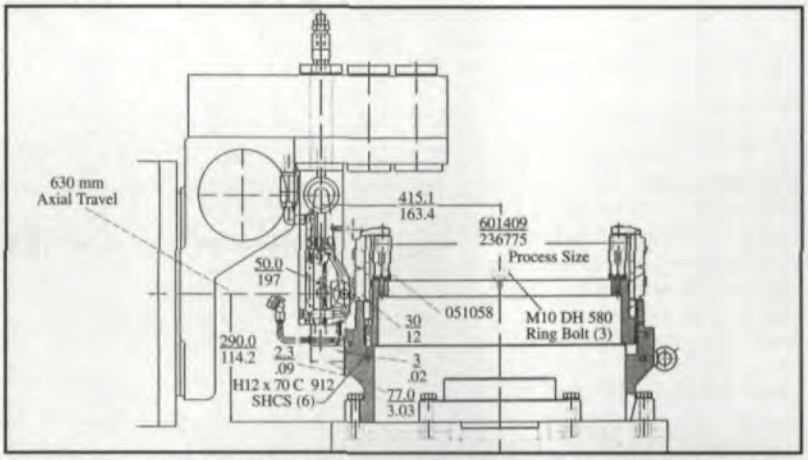

Fig. 4 — Layout of external grinding setup for 200-tooth, external ring gear spline shown in Fig. 1. Note the location of the grinding arm position on the grinding head relative to Fig. 3. The arm has been rotated for external grinding. The internal spur and helical grinding head can be used, with properly designed arms, for doing both internal and external work.

Fig. 5 — Pfauter CNC profile grinding machine with internal arm and single layer, non-dressable CBN wheel grinding a 124-tooth, 9.6 DP, 2.650 FW internal helical gear from the solid in 75 minutes.

Fig. 6 — High helix angle internal and external gears ground from the solid with single layer, non-dressable CBN plated wheels.

where the flank of the grinding wheel has only point contact on the flank of the workpiece tooth. To produce the final tooth profile, the grinding wheel must make several grinding strokes per tooth flank to create the enveloping cut which generates the profile.

Profile grinding efficiently creates a full line contact with the desired workpiece flank(s), providing

1. Higher metal removal rates than index generating grinding;

2. Simpler motion kinematics than index generating grinding;

3. A workpiece-dedicated wheel profile, repeatable from setup to setup.

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Fig. 7 — Near-net forged gear with 4.0 mm stock per flank, 43 teeth, 3.5 DP, 20° PA, 5.0" FW, being finished ground in the soft state using a dual set of CBN-plated grinding wheels. Time to complete, 21 minutes. One CBN wheel roughs the stock while the finer grit CBN wheel finishes the tooth. This same part can be finish ground from a pregrind hobbed state in 10 minutes (.15 mm stock per flank), but the combined pregrind hobbing and finish grinding process consumes 38 minutes of machine time, plus part handling and duplicate tooling.

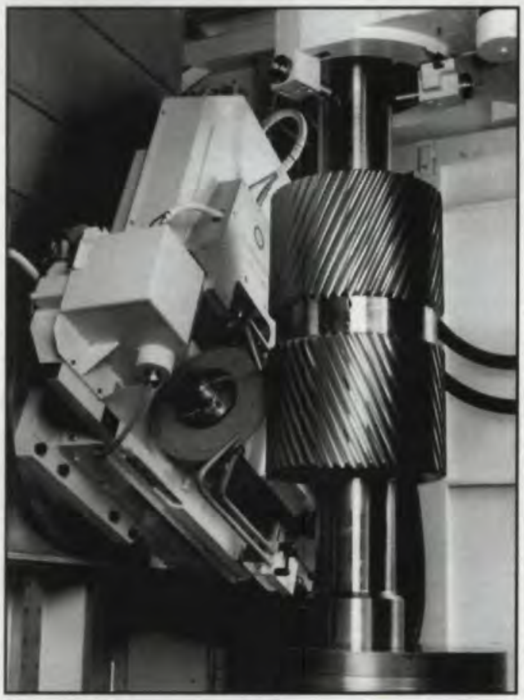

Fig. 8 — CNC 2-axis integrated dressing unit on a Pfauter 1600 mm profile grinding machine.

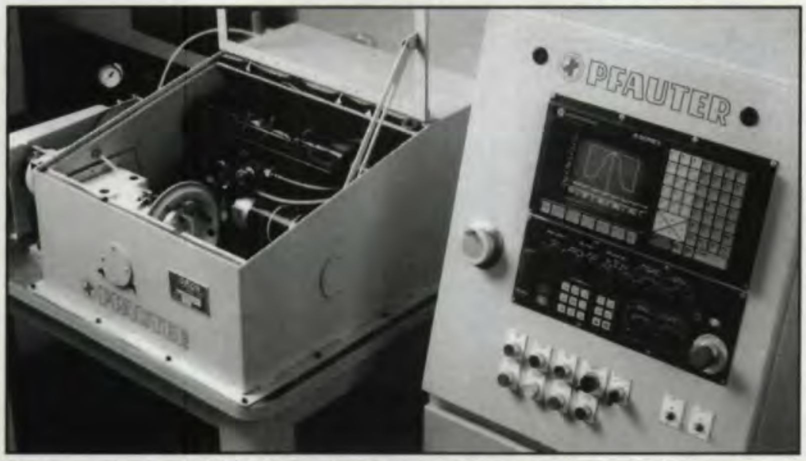

Fig. 9 — Orion 2-axis CNC dresser for dressing profile grinding wheels off the machine. Used commonly with dressable CBN media and SG media.

Modern CNC profile grinding machines for gears offer a variety of practical shop solutions for increasing productivity, reducing work in progress, increasing the number of inventory turns, reducing scrap and direct labor and improving overall quality. Many of the available CNC profile grinding machines offer

1. Integrated dressing units capable of dressing any of the available wheel media using diamond dressing wheels (see Fig. 8);

2. Stand-alone dressing units for dressing seeded gel (SG) wheels and CBN-dressable wheels off the machine (Fig. 9);

3. The capability of using any commercially available CBN-plated wheel;

4. Integrated stock envelope measuring and documentation (Fig. 10);

5. Final finished gear measuring and evaluation;

6. Internal and external gear and form grinding capability;

7. Grinding from the solid capability.

Profile grinding on modern CNC machines with the latest grinding media and techniques have elevated gear grinding to a new performance level. The gear industry worldwide, in general, has been slow to recognize the capabilities of this old, but very new method of processing gears. The installed base of new profile grinding machines has elevated the competitive level of play in the gear industry, and companies wishing to remain competitive are no longer ignoring the profile grinding process.

Why the Reluctance?

There is a worldwide gear manufacturing paradigm block when considering finish grinding gears 500 mm or larger. This paradigm is often expressed by repeating the following general misconceptions:

1. Gear grinding is too slow and expensive.

2. Because it is slow, grinding puts a bottleneck in production.

3. It requires comparably sized, expensive, stand-alone analytical gear inspection equipment.

4. It's inefficient. The grinder sits idle while the workpiece gets inspected.

5. It's labor intensive, requiring a high skill level among operators.

But the fact is, four key developments in grinding media, process technique, integrated measurement and software development have made profile grinding of gears of all sizes extremely efficient.

Grinding media. The pioneering efforts of the Kapp Company of Coburg, Germany, using CBN replatable, non-dressable profile grinding wheels have made profile grinding a productive, precise,

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Fig. 12 — Microphotography of a CBN-plated form wheel showing the nickel bonded CBN crystals and the degree of exposure of the CBN for cutting. Photo courtesy of Kapp.

Fig. 13 — Magnified view of chips produced by CBN micromachining. Photo courtesy of Kapp.

Fig. 14 — Magnified view of chips produced by an aluminum oxide wheel. Photo courtesy of Kapp.

Fig. 10 — Integrated measuring probe on a Pfauter 1200 mm profile grinding machine grinding head. The probe is used to establish the angular position of the gear relative to the stock envelope condition on the workpiece and to inspect the finish ground gear.

Fig. 11 — View of Pfauter-Winter CBN-plated wheels. The profile incorporated into the base body is defined by a CAD system which takes into consideration the quality of the profile to be achieved on the workpiece and the thickness of the layer of CBN crystal.

repeatable and economic process for finishing gears.

Process technique. What is unique about the Kapp process is that it uses a non-dressable, but replatable CBN wheel (Fig. 11). The wheel body is made from thermally stable ball bearing steel ground to a geometrically precise form on a 2-axis CBN grinder and then plated electrolytically with a single, uniform, preselected size CBN crystal layer. The bonding medium for the CBN is nickel. Roughly half the CBN particles are exposed for cutting (Fig. 12). No bond clearing is necessary. No wheel dressing is necessary. Wheel bodies can be stripped and replated indefinitely.

CBN, known by its trade name of Borazon®, has been applied to many types of grinding. As applied by Kapp, CBN is a micromachining process more akin to milling than grinding. The nickel bonded particles on the Kapp form wheel are like the cutting edges of microscopic milling cutter inserts. When magnified, chips produced by CBN form micromachining with a Kapp wheel look like milling cutter chips with a characteristic comma shape (Fig. 13). These chips dramatically differ from those produced by aluminum oxide wheel grinding, where the chips are non-uniform (Fig. 14). Single-layer CBN wheels are 3,000–4,000 times more wear resistant than aluminum oxide wheels.

CBN is free cutting. It does not cause burning, since the heat goes into the chip. The thermal conductivity of CBN compared to aluminum oxide is 46 to 1. Using CBN, about 4% of the heat generated goes into the workpiece. With aluminum oxide wheels, about 63% of the heat goes into the workpiece. The temperature of the chips as produced by CBN is typically 500–550°. Chip temperature as produced by aluminum oxide wheels is typically 800-950°. Several users have reported that it leaves significantly lower residual stresses than does vitrified wheel grinding.

Because the form of the profile to be ground is in the wheel, even after dozens of replatings, gear accuracies from lot size to lot size are significantly more repeatable than by dressable methods.

Integrated measurement. The integration of measuring into the gear grinding machine was inevitable. As CNC was applied to large, highly stable machine platforms for grinding applications, and with the accuracies demanded of grinding, it became apparent that the controls, axes resolutions and repeatabilities, feedback methods, machine kinematics and even some of the hardware was identical or very similar to the same devices used on stand-alone gear inspection equipment. It was logical to inspect on the machine because in large gear grinding, inspection and re-setup, which are often done 3 or 4 times, represent a large percentage of the time to produce the finished gear.

Software. Sophisticated software is now available that can align the heat treated teeth of the gear (including distortions) for uniform stock removal; measure and document the minimum and maximum amount of stock for removal; align, grind and measure double helicals in a single setup with precise apex alignment; determine cost-effective use of media though a combination of wheel inventory management programs and tool life programs; predetermine the grinding time based on wheel media and grinding method and store grinding programs on desktop or laptop computers. These programs have eliminated the variables that lead to cost overruns on large gear grinding. For example, the integrated measuring system feature for aligning the gear teeth allows the operator to measure before grinding several selectable teeth around the gear along the lead to determine the mean amount of stock and the minimum and the maximum amounts of stock. A screen display (see Fig. 15) shows the operator whether or not he will be able to grind the gear relative to the input size tolerance over pins dimension; that is to "clean up" to that pin dimension before he even starts to grind. Similarly, on double helicals, depending on the grinding stock left, the operator can determine before the start of grinding whether or not the apex lies within the allowed tolerance band for cleanup.

What these improvements have led to is a growing number of large gear producers who are applying the profile grinding method using:

a. Single layer, replatable CBN wheels roughing and finishing soft or hardened gears.

b. Single layer, replatable CBN wheels roughing and finishing soft and through-hardened gears from the solid.

c. Full form wheels for grinding full forms for better tooth strength.

d. CBN-plated grinding wheels for recurring small lot production and dressable wheels for low lot production.

e. Wheel saver programs to control wheel inventory and maximize wheel usage

f. Media selection programs to select the lowest cost option for production lot sizes on an annual basis. (See Fig. 16).

g. Special software for measuring before grinding to angularly position the gear to remove uniform stock.

h. Special software to determine apex alignment on double helical gears based on measured stock envelope.

The combination of these developments in a single profile grinding machine creates a powerful machine tool, compared to older processes and machines, that helps companies process high quality gears profitably, keep their competitive edge and achieve the advantages of innovation. ○

References:

Cluff, Brian W. *Gear Process Dynamics*. 1992, Chapter 13, pp. 219-221.

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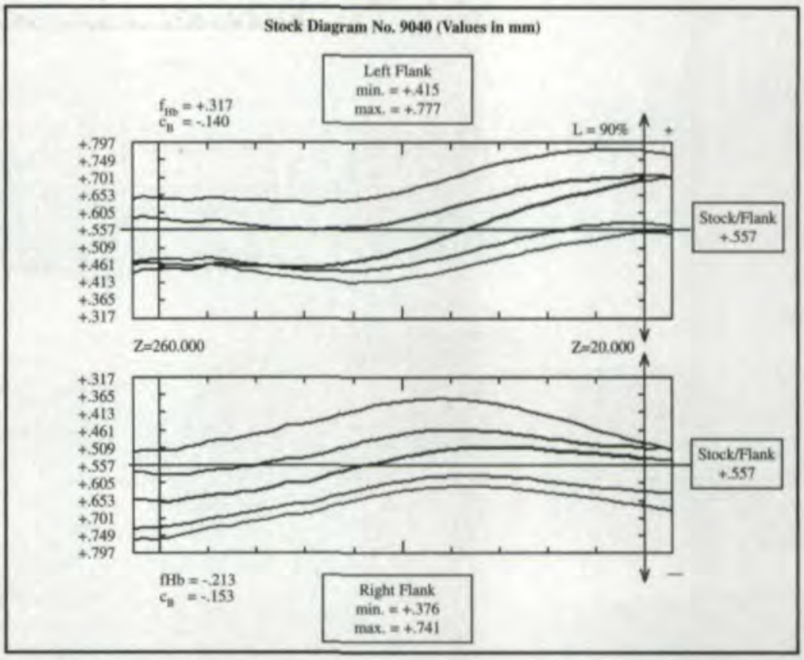

Fig. 15 — Graphic of the control screen display which an operator sees after measuring 5 leads, right and left flanks, on a heat treated, distorted workpiece to be finish ground. After the 5 leads on right and left flanks have been measured automatically, the angular position of the workpiece is positioned to a "best fit" condition relative to the desired finish size dimension and the stock envelope. The display shows the mean amount of stock (.557 mm in the example). The minimum amount of stock is displayed for each flank to verify that the part can be "cleaned up" all the way around the gear. The maximum amount of stock is displayed to allow the operator to select the most cost-effective grinding method. This prevents damage to the workpiece and to the grinding wheel.

COST ANALYSIS OF GRINDING A 3 DP GEAR, SPUR, 80 TEETH, 6" FACE WIDTH					
Hourly Rate		$120.00			
INPUT DATA IN CELLS COLORED					
Itemized Grinding Input		*Plated CBN*	*SG*	*AL Oxide*	*Vitrified CBN*
Wheel Cost	CBN Rgh+Fin	$6,000	$800	$300	$6,000
Dressing Disc Cost			$4,000	$4,000	$4,000
Setup Time of Dresser (min)			30	30	30
Setup Cost of Dresser			$60	$60	$60
Roughing Time Wheel Profile (min)			30	30	30
Roughing Cost Wheel Profile			$60	$60	$60
Finish Dressing Time of Wheel (min)			90	60	120
Finish Dressing Cost			$180	$120	$240
Inspection Time for 1st Pc (min)		120	120	120	120
Inspection Cost for 1st Pc		$240	$240	$240	$240
Redress Time for Final Dress			60	60	60
Redress Cost for Final Dress			$120	$120	$120
Inspection Time for Final Dress			60	60	60
Inspection Cost for Final Dress			$120	$120	$120
Machine Cycle Time for Dressing			18	12	0
Machine Cycle Cost for Dressing			$36	$24	$0
Parts/Wheel		50	10	2	1,500
Wheel Cost/Part		$120	$80	$150	$4
Parts/Dresser Disc			200	500	150
Dressing Disc Cost/Part			$4	$1	$40
Grinding Pc Cost per Lot Quantity					
	1	$6,240	$1,620	$1,045	$6,880
	25	$250	$230	$555	$314
Part Setup Time (min)		120	120	120	120
Machine Grind Time (min)		90	110	120	110
Machine Grind Costs (+ Setup)		$420	$460	$480	$460
Dress + Grinding Pc Costs/Quantity					
	1	$6,660	$2,080	$1,525	$7,340
	25	$670	$690	$1,035	$774
Note: Dresser Cost should be an average of new plus relap costs.					

Fig. 16 — Printout example of the wheel media selection decision matrix software. The software establishes the wheel cost/workpiece, the grinding cost/workpiece and total cost/workpiece based on the lot size of the gears to be processed.