Hard Gear Finishing

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Abstract:

Hard Gear Finishing (HGF), a relatively new technology, represents an advance in gear process engineering. The use of Computer Numerical Controlled (CNC) equipment ensures a high precision synchronous relationship between the tool spindle and the work spindle as well as other motions, thereby eliminating the need for gear trains. A hard gear finishing machine eliminates problems encountered in two conventional methods – gear shaving, which cannot completely correct gear errors in gear teeth, and gear rolling, which lacks the ability to remove stock and also drives the workpiece without a geared relationship to the master rolling gear. Such a machine provides greater accuracy, reducing the need for conventional gear crowning, which results in gears of greater face width than necessary.

Hard gear finishing offers many potential benefits, including elimination of heat-treat distortion, elimination of nicks and abrasions due to handling, greater load carrying ability through the use of highly accurate gears, the opportunity to design smaller, lighter gear boxes and reduction of gear noise caused by inaccuracies in gear teeth.

These benefits involve a minimal addition to direct labor costs because hobbing or shaping are done at higher production rates, while gear honing, gear shaving and de-nicking are eliminated. Furthermore, capital costs for gear cutting and material handling are reduced, less floor space is required and the overall operating costs of machines is lowered.

Background

Millions of gears in use today have teeth that are not finished after hardening, resulting in diminished accuracy of the gear. The reason for this is the difficulty and expense of finishing hardened gears. Methods of finishing in the soft also present certain problems to the manufacturer aiming for the most accurate gear mesh.

Gear shaving has been widely used for many years to finish gears before hardening. The shaving cutter works in tight mesh at crossed axes between the workpiece and the cutter. However, shaving fails to correct some errors between the cutter spindle and the work spindle.

In gear rolling, a method evolved from gear burnishing, the gear is rolled in tight mesh with a master gear or a master rack. Gear rolling lacks the ability to remove stock. It compresses or cold forms metal instead of shaving metal from the tooth flanks. Another drawback to gear rolling, as in gear shaving, is the inability to correct some errors in gear teeth because of the lack of synchronization between the cutter spindle and the work spindle.

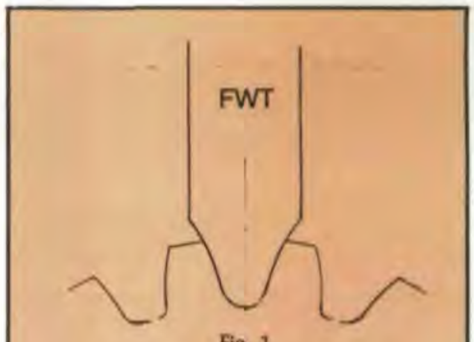

Fig. 1

Heat treating gears to reduce wear causes another set of problems. The helix angle of helical gears tends to unwind during heat-treat, and their profiles become distorted. To compensate for distortion, these gears are finished before hardening with a modified profile and a larger helix angle than the design specifies. This compensation is only partially successful because distortion caused by heat-treat is not always predictable; hence, the helix angle is crowned, and the profile is made full at the pitch line to overcome the effect of heat-treat distortion. A crowned gear reduces helical overlap, and a modified profile reduces involute overlap, both of which are necessary for quiet, efficient transmission of power.

Consequently, automobile transmission gears are made with a greater face width than would be required if they were made more accurately, for example, with the accuracy of aircraft gears that have their teeth ground after hardening. However, grinding gear teeth is a slow and expensive process and is not used for gears made in large quantities, such as those for automobiles, tractors and trucks.

Types of Hard Gear Finishing Machines

There are three types of hard gear finishing machines offered on the market today. In the following discussion these types are treated as CNC machines. These types, based on the cutters they use, are the Formed Wheel Type (FWT); the Gear Wheel Type (GWT); and the Worm Wheel Type (WWT).

The formed wheel type (Fig. 1) uses a machine that indexes the workpiece so as to grind one tooth at a time. A gear hob-

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bing machine with a suitable grinding head and a single index attachment is used for grinding large gears, while a hob sharpening machine has been developed to grind small gears.

The machines developed for this type of grinding use CBN coated or vitrified bond aluminum oxide wheels, depending on the size of machine used. However, it is generally accepted that when properly coated, a CBN wheel will give much greater tool life than an aluminum oxide one. One of the advantages of using a formed wheel is that it is easier to coat accurately with CBN than are either of the other two types.

Formed wheel type machines are used to grind either spur or helical gears and non-standard tooth forms. These wheels are used to grind the fillets as well as the root diameters of gears as required for pump gears or for aircraft gears. Each FWT hard gear finishing tool is designed for a gear of a given pitch, pressure angle, helix angle and number of teeth. It may not be used for other gears.

Continuous indexing on a FWT machine does not grind gears as rapidly as a worm wheel type machine. Index (spacing) accuracy of gears ground on a FWT are also a concern, but with the use of a CBN coated cutter, index accuracy is not a problem.

CBN coated wheels work best at higher surface speeds than are commonly used by hard gear finishing machines. The FWT machine, when using a 10" wheel, may run between 5,236 fpm and 16,439 fpm, while the developer of CBN recommends 20,000 fpm. At present, wheel speeds are limited by several factors, including spindle design and effective application of coolant to the workpiece. The formed wheel hard gear finishing machine uses creep feed to remove about 0.004" of stock from each tooth flank of the workpiece in one pass. The creep feed is approximately 23.6 fpm.

CBN coated wheels give 3,000 to 4,000 more times resistance to wear than aluminum oxide wheels. For formed wheel type grinding, tool life is estimated at 10,000 times the grinding wheel diameter for each pass across the face of a one inch gear (as advertised by the manufacturer). When estimating the tool cost for a given workpiece, it is probably best to include in the estimate the original cost of the tool plus the cost of three recoatings. For a formed wheel type hard gear finishing tool the cost of the wheel depends on its size. For instance, a 10" diameter wheel would probably cost $3,000.00, and recoating would cost $600.00.

If a 10" diameter wheel were used to grind a 30 tooth gear with a one inch face width, the cost per piece would be 36¢ as shown in Example 1.

Example 1.

A	= DP	10
B	= PA	20°
C	= HA	0°
D	= No. of teeth	30
E	= PD	3.0"
F	= Face width	1.0"
G	= Circular pitch	0.314"
H	= Creep feed	23.6 fpm
I	= Cost of HGFT	$3000.00
J	= Cost of recoating	$600.00
K	= Dia. of HGFT	10"
N	= No. of recoats	3

Tool cost=

$$(I+3J) / [\{(1+N) \times (10{,}000) \times K\}/D \times F]$$

Tool cost = 36¢

Production estimate =

$$\{[(F/\cos C)+(G/2 \times \tan C)]/H\} \times D$$

Production estimate=88 seconds

The Gear Wheel Type HGF Machine I

From burnishing to shaving to rolling to hard gear finishing with a gear wheel type tool has been the empirical development history of the gear wheel type hard gear finishing machine. For many years, gears were burnished, shaved or rolled in an effort to machine the most accurate gears possible. In each of these processes, the cutter drives the workpiece at crossed axes without the two spindles being driven in a timed relationship.

The phrase, "You can make a good gear better, but you can't make a bad gear good," was coined to explain the limitations of these processes. Special steel treatment and the use of accurate gear blanks, protuberance hobs or shaper cutters and accurate gear cutting machines with reduced feeds and speeds before the shaving operation made an acceptable gear, but all these processes had to be performed before the gear was hardened.

The first gear wheel type hard gear finishing machine used techniques developed for plunge type shaving, but added a method of controlling the hard gear finishing tool spindle in timed relationship to the workpiece spindle with this basic change to the machine: Improvements were made to workpiece accuracy that could not be made by gear shaving. Errors in accumulative tooth spacing could be removed which would improve transmission error, as shown by single flank rolling tests. Moreover, this important improvement could be made after hardening the gear.

The gear wheel type tool emerges as a separate element,

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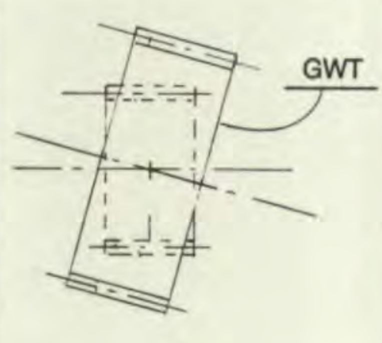


Fig. 2

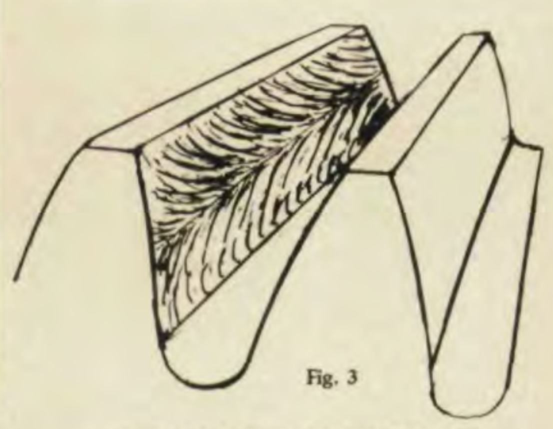


Fig. 3

FEED MARKS GWT/HGF

description of the worm wheel type hard gear finishing machine. Since no empirical data on tool life/cost is available for gear wheel type hard gear finishing machines, this data is used to estimate tool life/cost. The number of pieces that can be ground by the gear wheel type machine is found using the formula in Example 2. This *data is then divided into the cost* of the gear wheel type plus three recoatings to give tool cost per piece.

but one of equal importance with the machine. The shape of the teeth on the gear wheel type tool controls the accuracy of the tooth profile, as well as the accuracy of the lead trace, including the crown in the face width of the workpiece. The success of this operation is dependent on how well the cutter is made. (See Fig. 2.)

The gear wheel type hard gear finishing machine grinds one flank of the teeth on the workpiece while being fed to depth by closing the center distance between the cutter and the workpiece. The other flanks are finished by changing the direction of rotation of the cutter and its position so as to contact the opposite flanks. The gear wheel type tool is developed to the profile and amount of crown required. A resin bonded wheel is ground by the manufacturer, and test pieces are run by the user. This routine is repeated until the cutter has been developed to produce the required profile and crown. Then, the manufacturer makes a single layer CBN wheel. In this way the workpiece teeth are designed and redesigned until the part runs satisfactorily.

Tool life varies with the size of the cutter and of the workpiece, the surface speed used and the length of sliding action between the gear wheel type tool and the workpiece. The grinding action used by a gear wheel type hard gear finishing machine is a combination of specific sliding obtained from involute action, and crossed action sliding, which happens at the same time. This results in diagonal motion of the CBN crystals across the flanks of the workpiece teeth, which motion changes direction at the rolling diameter (pitch diameter) of the workpiece. (Fig. 3)

Tool life is established for a gear wheel type tool by comparing it to the tool life for a worm wheel type tool. A test while using a worm type cutter while grinding 40,000 16-tooth helical pinions developed satisfactory tool life/cost. While 3,092 pinions were ground, 1.45 sq. in. of crystals were worn 0.002". Full information is given for this test under the

Gear Wheel Type Hard Gear Finishing Machine II

A second gear wheel type hard gear finishing machine is being introduced with a development background similar to the one described above. Hard gear finishing machines developed from gear shaving are based on one or more of the gear shaving methods. These are conventional shaving, which moves the crossed axes contact point across the face width of the workpiece by feeding the workpiece along its axis; diagonal shaving, which moves the crossed axes contact across the face of the cutter by feeding the workpiece at an angle of 30° to 60° to its axis; and plunge shaving, which uses a cutter that envelopes the teeth of the workpiece and which eliminates all motion between the workpiece and the cutter, except infeed and rotation.

This second gear wheel type finishing machine is made to use all these methods, which are adapted to hard gear finishing. The machine may be used for gear shaving as well as hard gear finishing. The machine adds synchronization between the workpiece spindle and the cutter spindle, and controls this and the other required motions with CNC.

While it is possible to use the "conventional" type gear shaving principle for hard gear finishing, its use is unlikely. (See Fig. 4.) With the generating action concentrated on the crossed axes point of the gear wheel type wheel, the area of CBN coating that does the grinding on the workpiece is greatly reduced. This results in a much greater tool cost, which makes a gear wheel type wheel expensive to use for

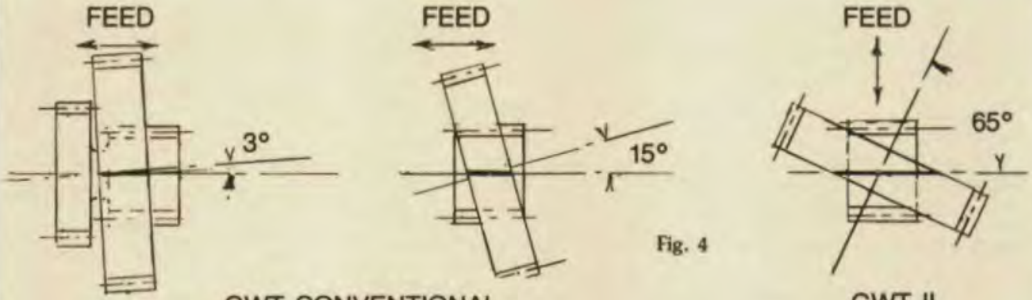


Fig. 4

GWT CONVENTIONAL

GWT II

Example 2 – Plunge Type GWT/HGFT.
Estimated tool life for other HGFTs compared to WWT/HGFT:

3092 (17.22/length of workpiece teeth) × (area of GWT/HGFT/1.45)

	Workpiece Data:		GWT Center		WWT Center*	
A	NDP	10	a	10	a	0.202"C.P.
B	NPA	20°		20°	b	20°
C	HA	20°	c	Spur	c	35' 45"
D	No. teeth	50	d	90	d	1 thd.
E	PD rad.	2.66"		4.5"	e	3.084"
F	Base rad.	2.4996"				
G	O.D. rad.	2.76"	g	4.635"	g	3.1496"
H	Add.	0.1"	h	0.135"	h	0.065"
I	Base pitch	.3141				
J	Face width	1.0"	j	1.064"		
K	R.P.M.	3721	k	2067	k	3300 RPM
L	Crossed Axes			20°		
M	Grinding time			80 sec.		
N	Contact area of by ctr.		n	21.15 sq. in.	n	1.45 sq. in.
P	No. pieces for one position for WWT ctr.					3092 pcs.
R	Total pcs. for original and 3 coatings WWT.					403,184
S	Cutter cost			\$3100.00		\$5250.00
T	Cost of recoating ctr.			\$1000.00		\$1800.00

*(Figures given for the WWT are used for 16 tooth pinion.)

Length of workpiece teeth = (J×D)/cos.C

Contact area for GTW/HGFT = d × (H + h) × J

Estimated tool life for GTW/HGFT compared to WWT/HGFT; 3092 (17.22/length workpiece teeth) × (area GTW/HGFT/1.45) Estimated tool life = 15,518 pcs.

Tool Cost = (S + 3T)/4 × Est. tool life
Tool cost for the gear data in the example equals 10¢ ea.

Example 3 – Conventional Type Gear Wheel Type Hard Gear Finishing Tool

Contact area of conventional gear wheel type = (d) × cross axes contact

Contact area = 90 × .08 sq. in. = 7.2 sq. in.

Estimated tool life = 3092 × (17.22/50) × (7.2/1.45) = 5,281 pcs.

Estimated tool cost = \$4800/21,145 = 23¢ ea.

conventional type grinding. As an example, when figures for the use of this wheel are entered in the formula used for plunge grinding, the cost per piece is shown. (See Example 3.)

The plunge type gear wheel type tool described for hard gear finishing machines may also be used by gear wheel type II. However, the wheel that will be used to the best advantage will have fewer teeth and have a larger crossed axes angle to provide more grinding action similar to a worm wheel type tool. For example a gear wheel type II/gear finishing tool with a 65° helix angle, grinding a spur gear would give the results shown in Example 4.

Internal Gear Wheel Type Hard Gear Finishing Machine

There has been a need for a hard gear finishing machine to grind internal gears. The configurations of internal gears used in automatic transmissions are sometimes designed so that machining causes stresses in the material that distorts the gear teeth. This condition is further aggravated by heat-treat distortion. Because of these conditions an unusually high scrap rate for some internal gear parts exists. There is also a need for hard gear finishing of internal gears to the same accuracy now available for external gears.

To meet this requirement two machines have been developed, both from gear shapers. These are vertical type

Example 4 — 65° Helix Angle GWTII/HGFT

		Workpiece		GWTII/HGFT		
A	=	Dia. pitch	10	Norm. DP		10
B	=	Pressure angle	20°	Norm. PA		20°
C	=	Helix angle	0		c	65 RH
D	=	No. teeth	50		d	37
E	=	Pitch dia.	5.0"			8.754"
F	=	Base dia.	4.698"			
G	=	O.D.	5.200"			
H	=	Add.	0.100"		h	0.135"
I	=	Base pitch	0.295"			
J	=	Face width	1.000"		j	2.366"
K	=	RPM	3,268			4,300
L	=	Crossed axes angle				65°
M	=	Cost of HGFT				$2,100.00
N	=	Cost of recoating				$ 650.00

Contact area for GWT/HGFT = d × (.08) × (j/cos c) = 16.57

Estimated tool life = 3,092[(17.22/(j×D))]×(area GWT/HGFT/1.45)

Estimated tool life = 12,158 pcs.

Estimated tool cost = (M + 3N)/4 × Est. tool life
Estimated tool cost = $0.083 ea.

Example 5 — GWT/HGFT for an internal gear.

		Workpiece		GWT/HGFT	
A	=	NDP	15.58	a	15.58
B	=	NPA	20°	b	20°
C	=	HA	18°LH	c	18°RH
D	=	No. teeth	70	d	51
E	=	Add.	0.064"	e	0.073"
F	=	Face width	1.22"	f	0.864"
G	=	Cost HGFT		g	$1,500.00
H	=	Cost recoat		h	$ 300.00
J	=	Strokes per tooth			5
K	=	No. infeeds			5
L	=	Strokes per minute			1200
M	=	Load/unload			30 sec.

Active area of internal HGFT = d × (E + e) × f = 6.037

Tool life:
3,092 × {[17.22/(D×F/cosC)]×(Active area/1.45)} × 0.4

Tool life = 1,092 pcs.

Estimated tool cost = (g+3h)/(4×tool life) = 55¢ ea

Estimated production = [(D × J × K)/(L)] + M = 118 sec.

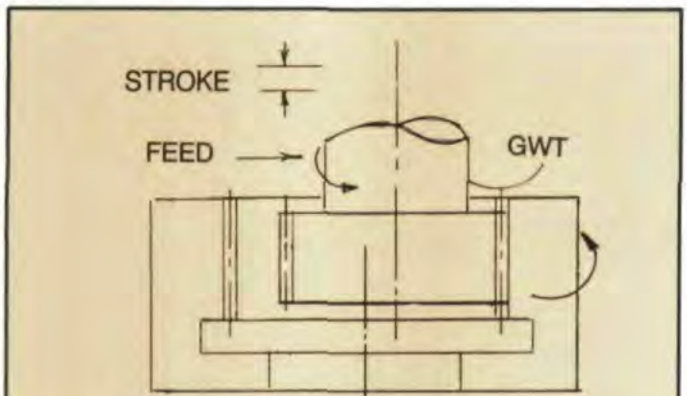


Fig. 5

machines which use state-of-the-art developments to reciprocate a gear wheel type hard gear finishing tool at 1,500 to 2,000 strokes per minute. The other motions required are controlled by CNC. (See Fig. 5.)

These machines produce very accurate gears at reasonable production rates. They are available not only for producing internal gears, but also for grinding close shoulder gears, such as those found in cluster gears used in transmissions.

When figuring tool life/cost, the efficiency of the gear wheel type tool used for grinding internal gears must be compared to that of a worm wheel type hard gear finishing tool. The gear wheel type tool used by this machine reciprocates at a speed of 100 surface fpm, while the worm wheel type rotates at a speed of at least 5,191 fpm. The expected 3,092 pieces produced by the worm wheel type have to be reduced by the efficiency of the slower moving gear wheel type. Arbitrarily, we have chosen a conservative 40% as an efficiency factor for the gear wheel type hard gear finishing tool used to grind internal gears. (See Example 5.)

The Worm Wheel Type Hard Gear Finishing Machine

Two manufacturers have developed the hobbing process as well as the threaded wheel grinding process into successful hard gear finishing machines. One of the makers has developed the process using as a basis a hobbing machine which was altered by replacing the hob head with a grinding head suitable for the speed and ridgity required for hard gear finishing, and using a six inch diameter hardened worm coated with CBN as a grinding wheel. The other manufacturer altered a gear grinding machine by using a 20" aluminum oxide wheel dressed to the required shape for plunge grinding.

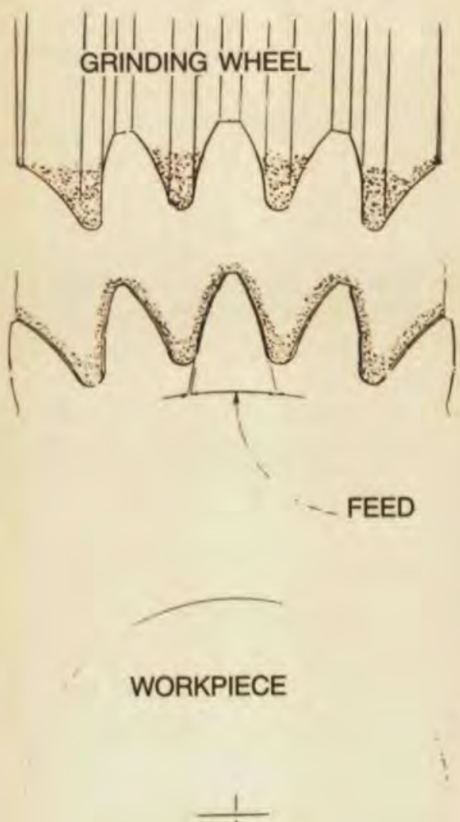


Fig. 6

Plunge Grinding With an Aluminum Oxide Wheel

Grinding in this manner makes it necessary to dress the wheel so that it will double-envelope the workpiece. This is done with a diamond coated gear which is equal to a perfect workpiece, with all the involute modifications as well as a lead trace crown, if required. The diamond coated dresser gear is plunge fed into the grinding wheel to full depth; then the synchronization between the grinding wheel and the dresser is changed to make the tooth space wider in the grinding wheel. This allows room for stock on the flanks of the workpiece and for the workpiece to be fed rapidly to the correct center distance before grinding.

First one side of each tooth is ground by a series of feeds moving the workpiece relative to the wheel in a side trimming motion. The other sides of the teeth are ground by reversing the direction of feeds. These motions are in sequence, resulting in a grinding rate of three to four seconds per tooth. (See Fig. 6.)

One of the advantages of this method of hard gear finishing is the short grinding and dressing times once every 30 to 40 pieces or as required. The grinding wheel may be dressed on the machine by feeding the dress gear through the automatic loader in place of one of the workpieces. The dress gear is moved into the wheel to dress each side of the teeth by the same sequence of motions used to grind a workpiece. Some accuracy may be sacrificed dressing in this way. However, to overcome any loss in accuracy the dress gear may be mounted behind the workpiece on the same spindle. When this is done, the machine is programmed to move into dress position and dress the wheel automatically after a preset number of pieces have been ground.

Using three to four seconds per tooth as a basis for production time and a 10 NDP, 20° NPA, 20° HA, 50 tooth, 1" face width gear, it takes approximately 200 seconds to grind this gear.

For tool life, both the vitrified grinding wheel and the diamond coated dress gear are considered. If the vitrified wheel is redressed for every thirtieth gear, its life is estimated at 7,000 pieces when a 20" diameter wheel is used. The estimated useful life of the diamond coated dress gear is estimated at 300 dressing cycles. The results are shown in Example 6.

Hard Gear Finishing With a CBN Coated Worm

Generating involute teeth with a modified worm as a tool is one of the oldest methods in use today. The accuracy of the machine and the tools used for this purpose have been improved since their invention 90 years ago; however, the basic machine and tool remain the same. It was, therefore, no surprise that this principle of gear generation was used as a basis for a worm wheel type hard gear finishing machine.

The worm wheel type hard gear finishing tool is a hardened precision ground master worm made of tool steel with the

Example 6

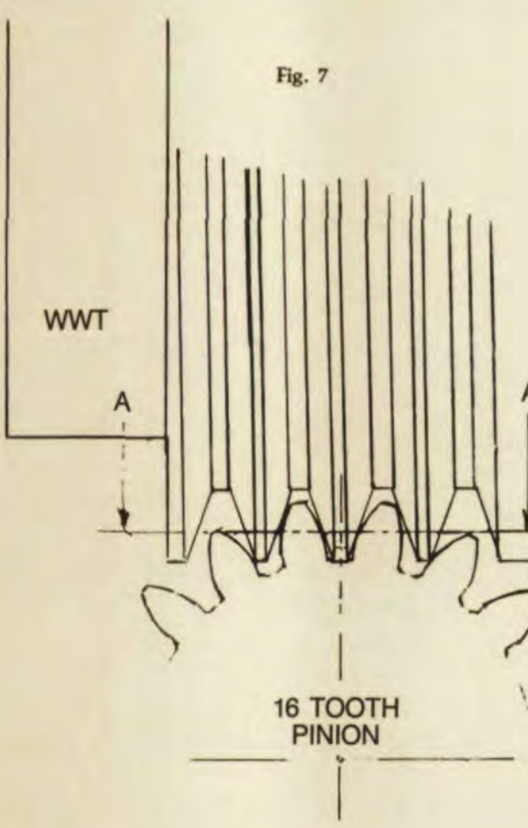
The tool cost is estimated to be

A	=	Cost of the vitrified grinding wheel	$ 300.00
B	=	Cost of the diamond coated dress gear	$3,000.00
C	=	Cost for recoating the dress gear	$1,600.00
D	=	No. of pieces per dressing cycle	30
E	=	No. of dressing cycles	300
F	=	No. of pieces for the grinding wheel	7,000

Tool cost = (A/F) + [(B+3C)/(D×E×4)] = 26¢ each required workpiece modifications ground into the tooth shape of the worm. (See Fig. 7.) A section through the pitch line of the cutter and the pinion shows the setting angle Φ, which is equal to the helix angle plus the thread angle. Also, the direction and length of feed of the workpiece across the hard gear finishing tool is shown. (See Fig. 8.) The tool is finished by coating its tooth flanks with CBN. Then it is carefully balanced to avoid chatter marks when the workpiece is ground. The size of the tool is 6.3" dia. by 3.54" long. Tools may have multiple threads, however, single thread tools are used most frequently. The tool rotates at 3,300 to 6,000 RPM. A feed parallel to the axis of the workpiece is equal to its face width plus a short overtravel. It is quite common to use feeds of 0.1" to 0.140" per revolution of the workpiece for roughing passes and 0.04" per revolution for a finishing pass. The tool feeds into the workpiece upon completion of each pass. Most gear teeth are cleaned up by removing 0.004" to 0.006" from the tooth thickness, which is done with three roughing passes and one finishing pass. Workpiece and tool data are shown in Example 7. Calculations are given in Example 8.

More than 45,000 pieces were ground to establish tool life. During these tests 6,000 workpieces were run in each of several positions along the hard gear finishing tool. Involute and lead tests were made on every hundredth part. (See Fig. 10.) These inspection charts show a slight improvement in surface finish between the first workpiece and the 6,000th workpiece ground.

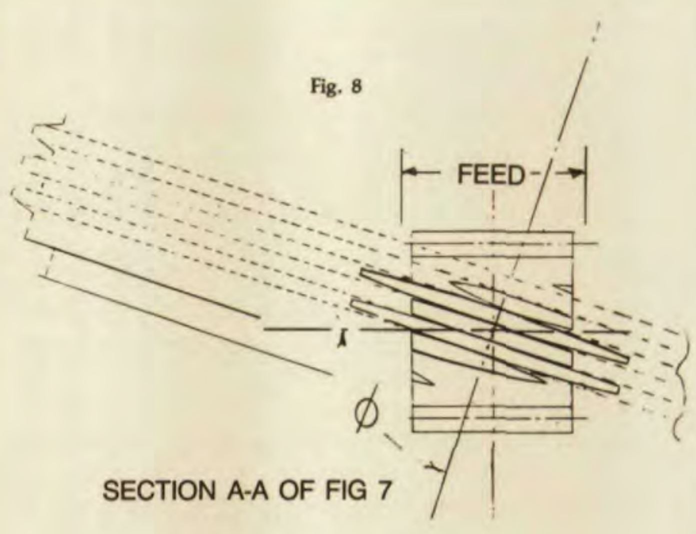
Fig. 7



Example 7 – WWT/HGFT.

Workpiece Data			
A	=	NDP	15.58
B	=	NPA	20°
C	=	HA (LH)	18°
D	=	No. teeth	16
E	=	PD (rad)	0.5399"
F	=	Base (rad)	0.507"
G	=	OD (rad)	0.62"
H	=	Add.	0.08"
I	=	Base pitch	0.1991"
J	=	Face width.	1.024"
K	=	Norm. circ. pitch	0.2017"
L	=	Full depth.	0.154"
WWT/HGFT Data			
a	=	NDP	15.58
b	=	NPA	20°
c	=	Thd. angle	35'45"
d	=	No. thds.	1
e	=	PD (rad)	3.0845"
f	=	Infeed (per pass)	0.0004"
g	=	OD (rad)	3.1495"
h	=	Add.	0.065"
i	=	Full depth	0.1756"
j	=	Length of HGFT	3.150"
k	=	RPM	3300
m	=	Circular pitch	0.20165"
s	=	HGFT cost	$5250.00
t	=	Recoating cost	$1800.00
u	=	Roughing feed	0.120"
v	=	Finishing feed	0.040"
w	=	Total no. of passes	4
x	=	HGFT set. angle	18.595°
y	=	Feed overtravel	0.07"

Fig. 8



Example 8 – Worm Wheel Type Tool
(See Fig. 9)

Active profile of WWT/HGFT:

$$\left[\left\{\sqrt{\frac{(G+F)\,(G-F)}{I}}\right\}/I\right] \times \left[\,(2e) \times \Phi\,\right] = 34.7363$$

Width of active profile:

$$2 \times \sqrt{E^2 - [E-(f \times w) \times \sin B]^2} = 0.049$$

Contact area of WWT/HGFT = active profile × width × 1.702

$$Le = J - [\,2(h/\tan.B) + (m/2)\,] = 2.5092$$

$$N = L/\text{width of active profile} = 4.181$$

$$T = \text{Active profile/Circum. at PL of WWT/HGFT} = 1.792$$

$$Pa = T \times L = 0.276$$

No. usable positions for WWT/HGFT:

$$Le/(pa/N) = 39$$

Tool life at one position

$$53{,}236/\{\,(D \times J)/\cos C\,\} = 3{,}092 \text{ pcs}$$

Total tool life:
Tool life at one position × No. of usable positions = 120,588 pcs.

Tool cost per workpiece

$$(s + 3t)/4 \times \text{total tool life} = 2¢ \text{ ea. pc.}$$

Estimated production time (allows 10 sec. load/unload)

$$(D \times J \times \text{No.passes}/k \times d \times u) + (D \times J/k \times d \times v) + (w+9)/30 = 41 \text{ sec.}$$

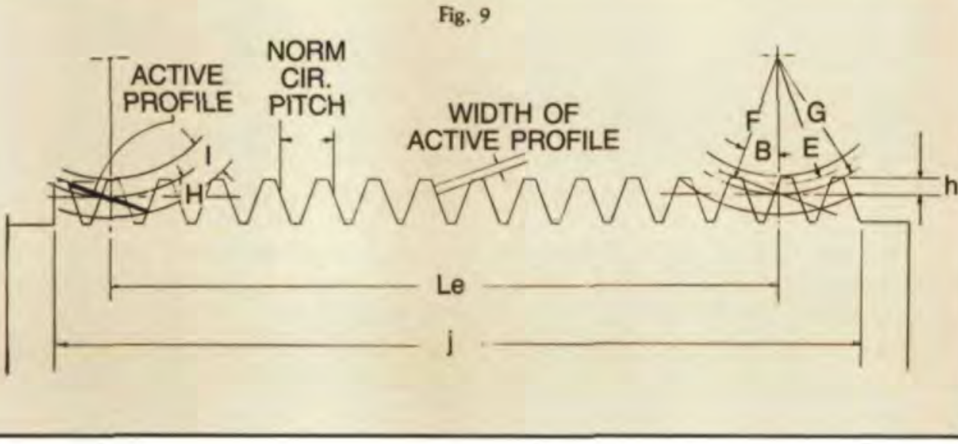
Feed overtravel (include in J above)

$$H \times \cos C \times \tan x/\tan B = 0.07''$$

Along with the inspection for accuracy, two other factors were considered. First, a torque meter was monitored to measure the power required to drive the hard gear finishing tool spindle to prevent reaching a predetermined torque, which would disturb the synchronization between the hard gear finishing tool spindle and the workpiece spindle. Second, every fifth workpiece was Nital etched to determine surface damage. This was necessary because there was no surface damage that could be seen with the naked eye.

The Nital etch process consists of dipping the workpiece into a solution of 5 parts nitric acid and 95 parts of ethyl alcohol for 5 minutes or until the workpiece turns black, followed by a second dip into 10% HCl mixed with water. This test does not determine whether or not the surface damage affects the life of the workpiece. For this reason, additional testing using X-ray diffraction and a goniometer were conducted in an effort to measure the extent of surface damage. However, several gears were given a "back to back" test which shows exceptionally good results. For the reasons given above, 3,092 workpieces were used for tool life when grinding a 16 tooth pinion instead of 6,000

Fig. 9



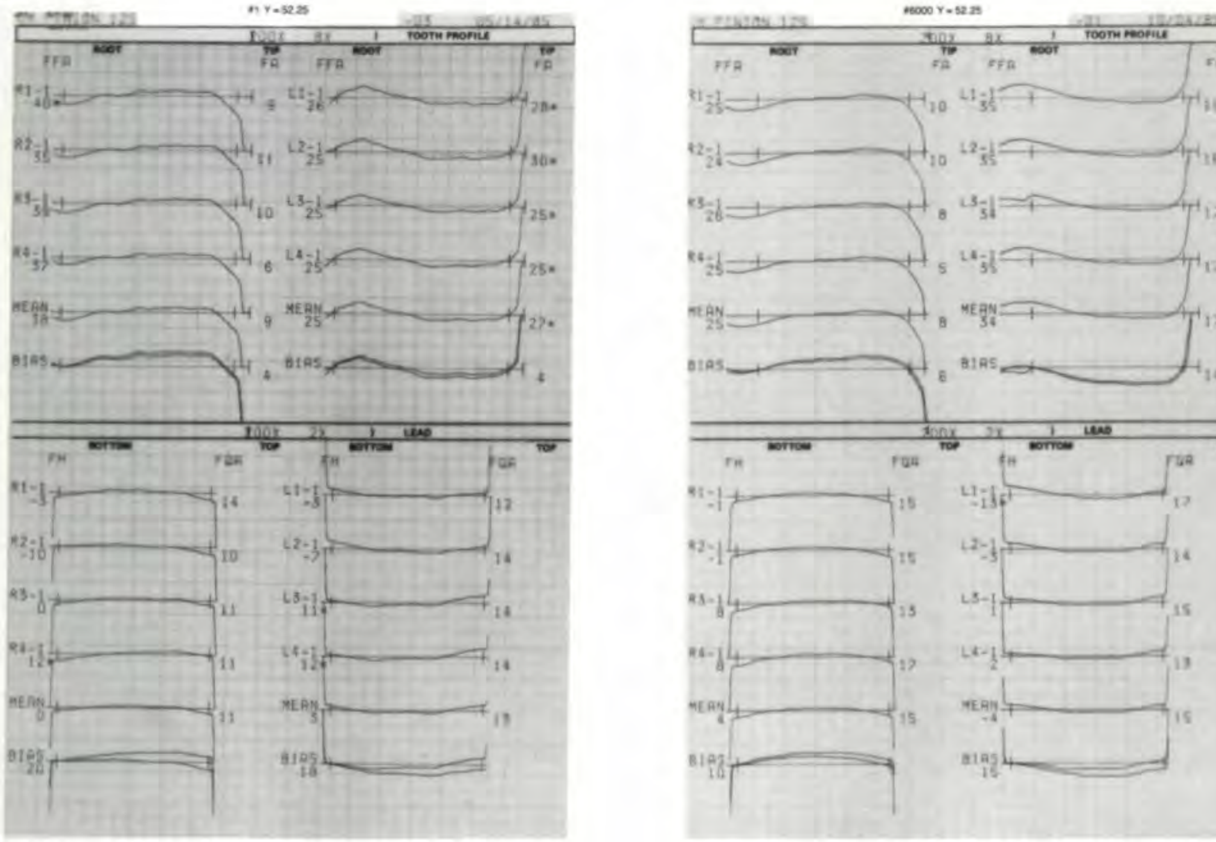


Fig. 10

pieces, which was established during accuracy tests.

This test was completed with the hard gear finishing tool rotating at 3,300 RPM. The drive motor used for the hard gear finishing tool spindle was a 3.75 HP DC servo motor, which was considered not to have enough horse power, but was the largest motor available. A later machine uses a system which provides for the use of a 5 HP DC servo motor that will drive the hard gear finishing tool up to 6,000 RPM.

Accuracy of Gears Ground by Hard Gear Finishing

It is generally accepted that all types of hard gear finishing machines are able to grind gears to AGMA Quality 13. To accomplish grinding gears to this accuracy, different types of hard gear finishing machines have various basics that must be held to close tolerances. The most difficult wheel to make is the gear wheel type used for plunge grinding. This is because the profile, the helix angle with a reverse crown, the tooth spacing and the concentricity must all meet master gear tolerances. In addition, the tool requires a wide face to envelop the workpiece.

The gear wheel type hard gear finishing tool made for conventional grinding or the wheel made to work at a large crossed axes angle do not envelop the workpiece. The workpiece lead trace is made tapered, crowned or true lead by the machine's CNC control. The gear wheel type hard gear finishing tool made to grind internal gears is made to master gear tolerances. Changes required from a true lead angle are made by tipping the machine column.

The worm wheel type finishing tool presents different problems. The teeth in cross section are modified rack teeth. The wheel must run true, and the thread angle must be held to close tolerance because runout or thread angle weave will cause errors in the workpiece teeth profiles. Electroplated CBN wheels used for grinding profiles are not easily dressed, and it is difficult to improve the wheel topography before use. Some worm wheel type finishing tools have been dressed using a diamond coated wheel or with a diamond coated duplicate of the workpiece. It is difficult to cut down the protruding crystals without disturbing the more deeply imbedded crystals using these methods. Every effort is made to coat the wheel with CBN crystals whose mesh size is uniform and to coat with uniform distribution.

The three involute/lead charts (Figs. 10 & 11) show external pinions ground with a worm wheel type finishing tool and an internal gear ground with a gear wheel type. None of these wheels were ground or dressed after they were CBN coated. The fact that it was not necessary to dress the crystals to obtain accuracy gave ultimate tool life. With sharp crystals, which are not partially blunted by dressing and which project from the bond material undamaged, the hard gear finishing tool is free cutting and permits grinding without surface damage due to heat. With sharp cutting edges, the involute chart of the first gear shows slightly rougher surface

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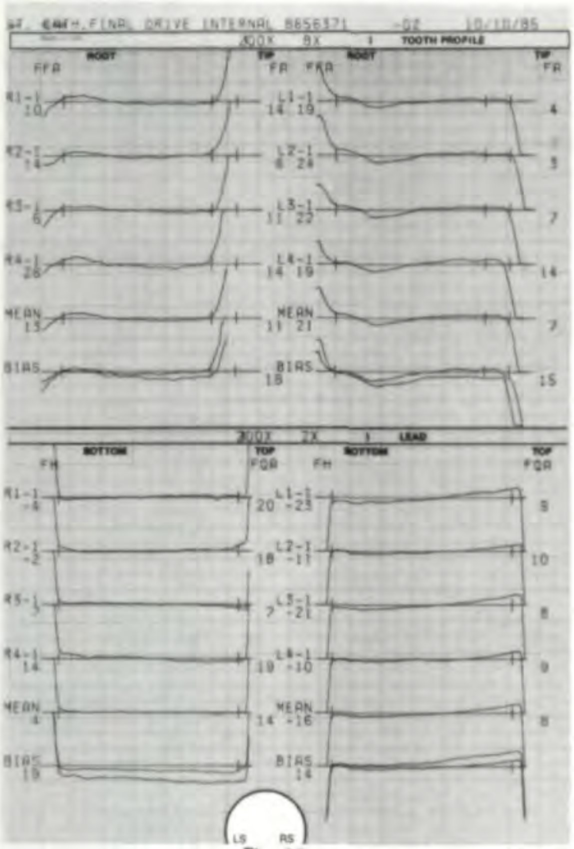

Fig. 11

finish. Now, as the crystals wear, the more deeply set crystals come into play increasing the number of cutting edges, which give a slightly smoother involute. These conditions are shown by the charts of the first and the 6,000th pinions. The difference in the progression of these conditions gradually increases the power required and the heat generated until it becomes necessary to change the hard gear finishing tool.

Hard gear finishing when using a worm type finishing tool is capable of finishes of two microns, peak to valley. The finish is determined by the grit size of the CBN crystals as well as the feed used for the finishing pass.

Surface Roughness vs. Durability

The surface durability of a pair of gears is affected by many factors, such as, roughness of the teeth, sliding speed on the tooth surfaces, hardness, material specification, accuracy of the gear teeth, loads applied, etc. One of the positive factors is that gears ground with CBN are left with compressive stresses. While there are different theories predicting the location of origin leading to tooth failures, experiments have shown that surface fatigue cracks are almost completely eliminated when metallic contact between meshing teeth is eliminated by reducing the roughness of the teeth. Table 1 lists the results of experiments which show reduced pitting of gear teeth when surface roughness of the teeth is reduced. However, surface durability cannot be increased by an improvement in surface finish alone. The accuracy of tooth profile and lead variation must be increased at the same time.

In these experiments, the theoretical oil film thickness (h min.) between meshing teeth was calculated using Dowson's equation. The D value was about 0.03 between a hobbed and a skived gear. When the driver and follower were ground, the value of D was 2, which suggests full separation of meshing teeth. D value = h min./(R max. driver + R max. follower).

Effect of Workpiece Hardness

From tests done on a 16 tooth pinion made of SAE 5140 steel drawn back to 35 Rc, it is apparent that wheel wear becomes greater while grinding low hardness steel gears. It *has been noted in a report by S. Tanaka, et. al. that wear* of the CBN coated wheel used for their tests increased appreaciably when they ground low hardness steel gears.[2]

This was attributed to higher plastic deformability which caused a difficulty in the production of chips. However, these tests were done while using wheel speeds of 3,700 to 7,400 fpm., and while using a very slow generating motion of 0.784 to 2.236" per min.

Worm wheel type hard gear finishing tool tests used a wheel speed of 5,190 fpm and a generating motion between the wheel and work of 21.2 fpm. The tests have shown the same surface texture and accuracy between gears of 35 Rc and 60 Rc. Fourteen hundred pieces were ground without shifting the hard gear finishing tool. This results in 44,240 pieces for one coating of the tool. (See Fig. 12.)

Coolant and Filtration

Wheel wear is closely related to the temperature of the

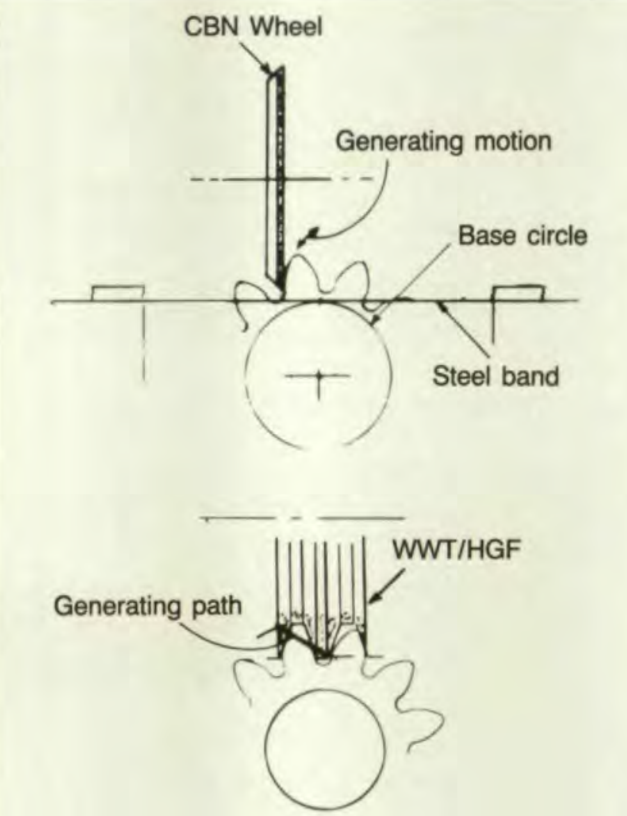

Fig. 12

TABLE 1

	Driver*			Follower**					
	Kind of Material	Hardness BHN Rc.	Surface Roughness R_{max}um	Kind of Material	Hardness BHN Rc.	Surface Roughness R_{max}um	Hertzian Pressure MPa***	Revolutions of Follower	Pitting Area Ratio (%)
HOBBED 9 AGMA 9	AISI 5135	300 BHN	10	AISI 5135	300 BHN	10	780	6.9×10^6	2.69
SKIVED AGMA 8	AISI 5135	64 Rc	2	AISI 5135	41 Rc	3	1180	10×10^6	3.3
GROUND AGMA 12	AISI 5135	64 Rc	0.1	AISI 5135	185 BHN	0.1	1180	31×10^6	0.58

*Driver - 8.466 Pitch, 20 P.A., 25 teeth, 590 face **Follower - 27 teeth ***780 = 53.5 Kg/mm², 1180 = 120 Kg/mm²

TABLE 2

TYPICAL PHYSICAL PROPERTIES OF OIL USED AS COOLANT

Appearance	Color	ASTM L2.5
Specific Gravity @	60°F	0.87
Flash Point	C.O.C.	388°F
Viscosity @	100°F	118 SUS
Copper Corrosion @	210°F x 1 hr.	1 (a)
Total Acid Number	Milligrams K.O.H./gm	0.86

wheel matrix. As the temperature increases, the wear of the wheel increases. The best results are obtained by grinding with oil as a coolant. The properties of such a coolant oil are shown in Table 2.

While grinding with a worm wheel type finishing tool, two coolant nozzles are used, one pointing toward the arc of cut from each side of the axis of the wheel. Each nozzle is supplied with coolant by its own pump. The pump used is driven by a one-half HP 1,200 RPM motor and delivers 16 GPM.

Coolant Filtration

The level of coolant filtration has an important effect on the power required for grinding and the quality of surface finish, as well as on wheel wear. The system used should remove particles larger than five microns.

Discussion

Some information has been given above on currently available machines that use CBN coated wheels with brief mention of a machine which uses an aluminum oxide wheel. Research and development is a slow, painstaking process. The machines developed will serve as a corner stone for a process that is exciting and useful. Other machines will be developed that will improve on the basic process.

Further development is needed in the following areas:

- More even coating of wheels and distribution of CBN
- More exact control of grit size for CBN distribution
- Closed circuit TV monitors to check CBN coatings
- CNC controls providing for use of bigger, faster motors
- Multi-thread worm wheel type finishing machines to increase production
- Means of eliminating surface damage
- A program to determine surface damage by test rather than by Nital etching.

There are other means of manufacturing hard finished gears; i.e., the use of a carbide tool by the skiving hobbing principle and by the skive shaving principle. Skiving hobbing is slow and not competitive with the use of CBN wheels. Skive shaving shows few demonstrable production results. Therefore, these methods of hard gear finishing are not described above.

A major U.S. corporation has hosted an informal meeting to exchange views on the development of hard gear finishing using CBN coated tools. This meeting was attended by representatives from automotive and tractor companies, as well as many others interested in hard gear finishing. The meeting disclosed that Japan's consumption of CBN is well ahead of the USA's and Europe's. Further, because higher accuracy of gears was required and conventional grinding of gears was too expensive, a Japanese car manufacturer designed and built ten hard gear finishing machines. These machines are reported to use 12" diameter electroplated CBN wheels that run at 15,700 sfm. The configuration of these machines was based on existing "threaded wheel" gear grinding machines. Because of the close correlation between surface speed, production rates and tool life for hard gear finishing, it will be of interest to learn more about these machines.

Conclusions

(a) From data obtained through tests and production runs on existing machines, it is clear that higher surface speeds should be used for hard gear finishing tools. This would increase tool life as well as production rates.

(b) Higher surface speed and more powerful stepping motors must wait for new developments in CNC control equipment. Meanwhile, it is possible and desirable to design a machine with a single drive motor to drive the hard gear finishing tool spindle and the workpiece spindle through change gears.

(c) Grinding the roots and fillets of teeth by hard gear finishing will strengthen gears by a smooth blend of the fillet with the profile, which will leave tensile stresses in compression.

(d) Hard gear finishing should be used to finish internal gears. With the use of machines now available on the market this is possible.

(e) Accuracy after hardening is equal to AGMA 13. This means accuracies of AGMA 9 or 10 are easily available with the use of these production methods.

(f) Oil as a coolant supplied with medium pressure at high volume will increase wheel life and improve surface finish.

(g) Chip separation is important. A filtration system to remove particles larger than 5 microns will improve tool life and lower the power required to drive the wheel.

(h) Up time is important because it affects both direct labor cost and production rates. Different types of hard gear finishing tools should be considered with this factor in mind.

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