A Wheel Selection Technique for Form Gear Grinding

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Abstract

Until recently, form gear grinding was conducted almost exclusively with dressable, conventional abrasive grinding wheels. In recent years, preformed, plated Cubic Boron Nitride (CBN) wheels have been introduced to this operation and a considerable amount of literature has been published that claim that conventional grinding wheels will be completely replaced in the future. The superior machining properties of the CBN wheel are not disputed in this paper. For what the conventional wheel suffers from in the way of inferior machining properties, it makes up for in its inherent flexibility, for unlike the CBN wheel, the dressable wheel is not limited to one gear tooth form. Consequently, it is a matter of economics dictated by costs and production size since the CBN wheel is also considerably more expensive than its conventional abrasive counterpart. In order to be able to evaluate the economics of using different types of grinding wheels, an analysis technique is presented in this paper.

Manufacturing economic equations are used which were specially adapted to the gear grinding process. Process parameters used in the equations include, in addition to feeds and tool life; machine and overhead costs, dressing time, diamond costs, and many other factors peculiar to gear grinding. Special case studies are also presented to illlustrate the use of the method and to show that CBN grinding is not limited only to large lot sizes nor is it a universal replacement for dressable wheel grinding.

The analysis has been written into a computer program which can run on most personal computers. This program is available from National Broach and Machine for use in process planning decision making.

Introduction

Currently, there are essentially two basic processes for finishing hardened gears to AGMA class 12 and better. They are generative grinding and form grinding. Lately, several new processes for high speed finishing of hard gears have been developed, however, they are still somewhat experimental and their use is not widespread. In the generative gear grinding process, the grinding wheel is in the form of an abrasive rack moving in mesh with the work gear. The relative motion between the wheel and the work gear, in combination with the rolling action, results in the abrasive generation of the teeth of the work gear. In the form gear grinding process, the grinding wheel has a profile representing the tooth space between two adjacent gear teeth. When this formed wheel is moved between the teeth of the work gear, it removes the excess stock resulting in the finished gear with improved accuracies. The generative grinding process is sometimes faster, if a continuous method (using a rotating, worm shaped wheel) is used, in comparison to form and non-continuous generative grinding where only a set of adjacent flanks are machined at a time. The generative process, however, is limited to involute forms with minor modifications while the form grinding process is virtually unlimited in terms of tooth profiles that can be produced. Form grinding also has the advantage of being able to grind specialized root profiles. This is generally not possible with generative grinding. For these reasons the use of the form gear grinding process is expected to increase, especially in the aerospace industry. This article will concern itself exclusively with the form gear grinding method.

In the past, form gear grinding was conducted almost en-

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Since joining National Broach and Machine in July, 1984 as a Product Development Engineer, **MR. RICHARD SCHWARTZ** *has been responsible for the research, development and testing effort that is involved in the development of new gear finishing processes and machines. Mr. Schwartz received a B.S. degree in Mechanical Engineering from the University of Wisconsin, after which he worked as a Manufacturing Engineer for Panduit Corp. Shortly thereafter, he went back to Wisconsin to earn a Master's degree - also in Mechanical Engineering. His thesis work involved computer control of processes and machines in a robotic work cell. Mr. Schwartz is currently the Supervisor of Product Development for National Broach. He is a member of ASME and SME.*

tirely with dressable conventional grinding wheels. The gear grinding machines were equipped with dressing mechanisms to accurately profile the grinding wheel to conform to the space between the flanks of two adjacent teeth. Dressing was also carried out when the wear on the wheel resulted in unacceptable deterioration of the profile or when a change was required in the tooth profile of the gear being processed. In recent years, wheels using the abrasive Cubic Boron Nitride (CBN) have been used in areas previously dominated by conventional wheels. In the form gear grinding area, direct plated, single-layer and reverse plated, multi-layer CBN wheels have been introduced with successful results.

CBN is a man-made crystal surpassed in hardness only by the diamond. When used as an abrasive, it is extremely wear-resistant and able to retain its sharpness for a long time. Because of its cubic shape, it has pronounced cutting edges. CBN wheels are currently available in four bond types. They are resinoid, vitrified, metal and electroplated. Since form gear grinding requires extreme accuracy in the profile of the wheel and the former three bond types require occasional dressing (which is usually very difficult), electroplated wheels are generally considered the best wheel for the process.[1]* In this type, the exact form of the tooth space is represented by the wheel and dressing is not performed. When electroplated to a metal wheel (which provides the grains with a rigid support), CBN performs as a long lasting, efficient grinding wheel with some exceptional results. These results include more efficient material removal and the ability to take deeper cuts which lead to fewer passes and reduced cycle time. CBN grinding is also cooler than conventional grinding thereby causing less burning and distortion of the workpiece.[2] Because of the wear resistance, one wheel can last for hundreds of parts and dressing is never needed.

There are, however, several drawbacks to using a plated CBN grinding wheel. CBN wheels can cost over $2,000 compared with $15 or less for their Aluminum Oxide counterparts. Additionally, the delivery time for CBN can be several months. Many machine tools are not capable of utilizing CBN wheels effectively as they require increased stiffness and power with lower feed rates, higher coolant flows, and higher precision.[1, 3, 4] Another disadvantage is the inherent inflexibility of a CBN wheel. Since the form cannot be altered, a wheel can generally be used for only one specific part. If the profile specifications change even slightly, a new wheel must be made. A different wheel is required for every part. Clearly then there are some applications where CBN grinding is not economical. This article discusses the economic factors involved with form gear grinding and presents a mathematical formula specially adapted to gear grinding that incorporates these factors. Each term in the equation is examined and the effect of wheel selection is discussed. A computer program is presented which can be used to compare the costs of using CBN and conventional wheels. Example case studies are included to illustrate its use.

Economic Factors for Wheel Selection

The cost to produce a part is given by the general equation:

$$C_{PR} = C_S + C_L + C_M + C_T + C_{TC} \qquad (1)^{(5)}$$

where:
- C_{PR} = Production Cost ($/part)
- C_S = Setup Cost
- C_L = Load/Unload Cost
- C_M = Machining Cost
- C_T = Tool Cost
- C_{TC} = Tool Change Cost

To modify this general equation for gear grinding, the cost associated with dressing the wheel is added. The modified equation then becomes:

$$C_{PR} = C_S + C_L + C_M + C_T + C_{TC} + C_D + C_{DT} \qquad (2)$$

where:
- C_D = Dressing Cost
- C_{DT} = Dressing Tool Cost

The most predominant terms in equation (2) are tool cost and machining cost. Too often manufacturers look only at one or two terms and come up with a decision. For example, one manufacturer may consider tool cost and decide that because CBN wheels cost more than 100 times more than conventional wheels, grinding with CBN is too costly. Conversely, one may look at the machining and dressing cost and assume that because CBN requires no dressing and can grind a gear in a fraction of the time it takes for Aluminum Oxide, CBN is the only choice. The fact is that there is a tradeoff point. If production sizes are very small (such as in a job shop or R & D department) the high cost of CBN wheels makes that alternative an unwise decision. Where production volume is high and part specifications will not change over the life of the wheel, CBN will prove the more economical process. To compare gears ground with CBN and conventional wheels, all of these factors must be considered.

To compute the machine-related costs in the economic equation, the combined machine/operator rate must be accurately known. This rate translates into the actual cost of having a machine operator in the plant (whether the machine is producing or not). The formula is:

$$M = \frac{W_O}{Nm} * (1 + \text{operator wage}) + M_T * (1 + \text{machine overhead}) \qquad (3)$$

where:
- M = Machine/operator rate ($/hr.)
- W_O = Operator wage rate
- N_M = Number of machines per operator
- M_T = Depreciation rate of machine tool

The operator overhead includes benefits provided by the company, the cost of providing the working facilities and the cost of the administrators necessary to employ the worker. The machine overhead will include the cost of the power consumed by the machine, the cost of servicing the machine and the cost of providing the location for the machine. Machine and operator overheads are usually given in terms of percent of the respective rates.[5]

The first term in equation (2), setup cost, is the product of the combined machine/operator rate, the number of batches and the setup time divided by the number of parts made on that setup, i.e.:

$$C_S = M * T_S * NB / N \qquad (4)$$

where: T_S = Setup time
N_B = Number of batches
N = Number of parts

Setup time is sometimes slightly longer for dressable wheels due to the time required to dress the initial form onto the wheel but it can be shorter if the existing wheel can be dressed with the new form as the wheel need not be changed.

Load/unload cost is the machine/operator rate times the time required to unload a finished part and load a new workpiece, i.e.:

$$C_L = M * T_L \tag{5}$$

where: T_L = Load/unload time.

This cost is the same for both CBN and conventional wheels.

Machining cost is obtained by multiplying the machine/operator rate by the machining time, i.e.:

$$C_M = M * T_M \tag{6}$$

where: T_M = machining time

As indicated before, CBN grinding is faster than conventional grinding therefore, the cost is lower.

Tool cost is computed by dividing the cost of the grinding wheel by the number of parts produced by the wheel. Since a CBN wheel can only be used for a particular part, if the number of parts produced is less than the life of the wheel, the entire cost of the wheel must be amortized over this number of parts. Because of the high cost of a CBN wheel, the number of parts produced must be large enough to offset the wheel cost. On the other hand, conventional wheels can be redressed for different parts. An additional cost associated with CBN wheels, but not usually considered, is the cost associated with storing the wheel. Since CBN wheels last very long, it is possible that a wheel will be used for several years. The high cost of the wheel represents a considerable investment and the interest lost on that money must also be added to the cost of the wheel. Vitrified wheels on the other hand do not last nearly as long and can be purchased in small quantities as needed thus avoiding tying up capital over a long period of time. The equation for tool cost is:

$$C_T = C_W * (INT(N/P_W+1) + N_Y * I/2) / N \tag{7}$$

where: C_W = Cost of the wheel
P_W = Number of parts the wheel will produce
I = Interest rate
N_Y = Number of years the wheel is used

The second term in the equation (7) is the investment cost of the CBN wheel and becomes zero if conventional grinding is done (see appendix 1 for derivation).

Tool change cost is the product of the machine/operator rate and the total wheel change time divided by the number of parts made, i.e.:

$$C_{TC} = M * T_{TC} * (INT(N/P_W)) / N \quad (8)$$

where: T_C = Tool change time

Since CBN wheels last longer than conventional wheels, they do not require changing as often and the tool change cost is less.

The dressing cost is computed as the machine/operator rate times the time required to dress the wheel, i.e.:

$$C_D = M * T_D \quad (9)$$

where: T_D = Dressing time

Finally, the dressing tool cost is computed in the same manner as tool cost for conventional wheels except the cost is amortized over the life of the dressing tool since the same tool can be used on different parts.

It is given by:

$$C_{DT} = C_{DR} / P_{DR} \quad (10)$$

where: C_{DR} = Cost of dressing tool

P_{DR} = Number of parts per tool

CBN grinding can save on both dressing costs since an electroplated wheel is not dressed.

Software Description & Examples

A computer program was written in BASIC which incorporates the above equations. The program takes as inputs the machine/operator rate, setup time, load/unload time, grinding time, cost of the wheel, number of parts made per wheel and the wheel changing time. If a dressable wheel is indicated, the dressing time, tool cost and parts per dressing tool are asked for. If CBN grinding is indicated, the interest rate and number of years the wheel is used is asked for. If an input is unknown, such as machine/operator rate or grinding time, the program will prompt for additional information (machine cost, operator wage, number of passes and feedrate, etc.) and compute the term. Once all of the information is input, the program calculates the cost per part as a function of production size. The output of the program is the break-even point and a list of cost values suitable for plotting. The program's use is best illustrated by an example. It should be realized that the costs computed below are estimates for comparison only and may not reflect actual conditions. Often the only way to obtain true grinding times is to actually grind a gear.

Example 1.

A gear is to be ground having 125 teeth and a pitch diameter of 12.5 inches. It is in a hardened condition with stock to be removed requiring .020 inches infeed. The face width of the gear is 1.0 inch. The process plan for Aluminum Oxide grinding dictates 8 roughing passes with .001 inch infeed at 200 ipm and 10 dress cycles. The semi-finish cycle operates at .0075 in infeed for 2 passes at 100 ipm and 2 dresses. Two finish passes at .0025 inch infeed and 50 ipm with 1 dress followed by a sparkout pass at 50 ipm complete the gear. Adding the time required for indexing (1 second per tooth), the grinding time comes to 72.6 minutes. The 12 dress cycles at 1 minute each require 12 minutes.

For CBN grinding the entire gear is to be finished in one pass. To achieve this and also to obtain suitable surface finish, the feedrate will be 5 ipm. The gear will be ground unidirectionally requiring 1 second to return the wheel and index. The total time to finish the part then is 52.1 minutes which represents a decrease in cycle time of more than 41 percent compared to conventional grinding. The remaining parameters are as follows (for additional information see appendix 2):

Machine/operator rate = $65.5/hr. (See appendix 3)

Setup time conventional	= 60 minutes
Setup time CBN	= 90 minutes
Load/unload time	= 5 minutes
Parts per wheel conventional	= 10
Parts per wheel conventional	= 500
Wheel cost conventional	= $15
Wheel cost CBN	= $2000
Parts per dressing tool	= 500
Dressing tool cost	= $600
Wheel change time CBN	= 15 minutes
Wheel change time conventional	= 20 minutes
Interest rate	= 12 percent
Number of years	= 2
Number of batches	= 5

The setup time for the conventional wheel is less than that for CBN because it is assumed that the gear is being ground on a machine ordinarily used for this size gear and the existing wheel can be used. The wheel change time for conventional grinding is more than for CBN due to the time required to dress the initial form on the wheel.

The output indicates a break-even point of 60 parts (Figure 1). If the number of parts required is less than this, grinding should be done with a dressable wheel, above 60 parts, CBN. The break-even point is sensitive to many factors in the cost equation. To illustrate the effect, some of the parameters will be varied to show how they affect the break-even point.

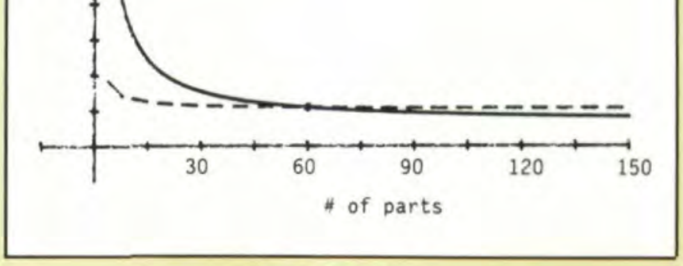

Fig. 1 – Example 1

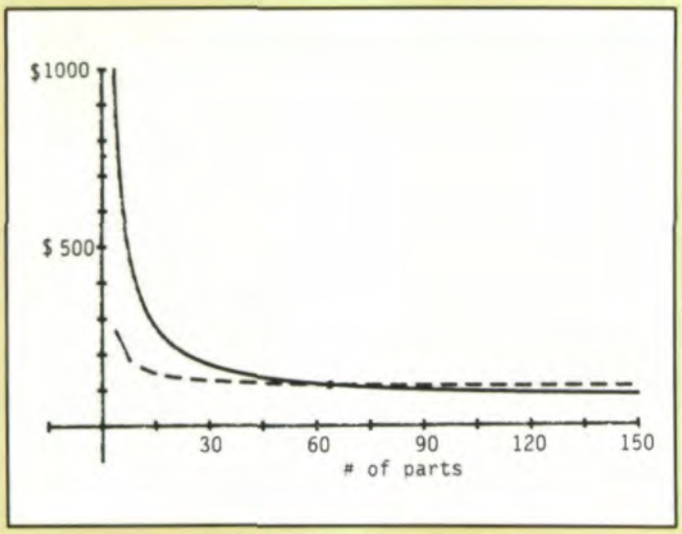

Fig. 2—Number of Batches = 10

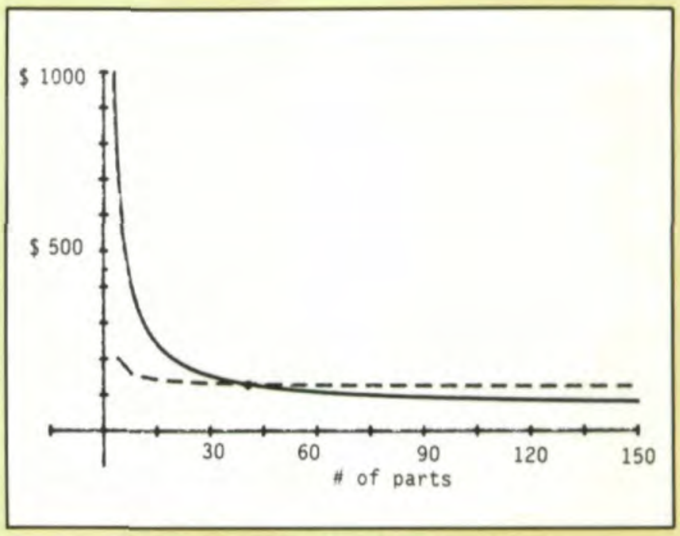

Fig. 4—Conventional Grinding Time = 90 Min.

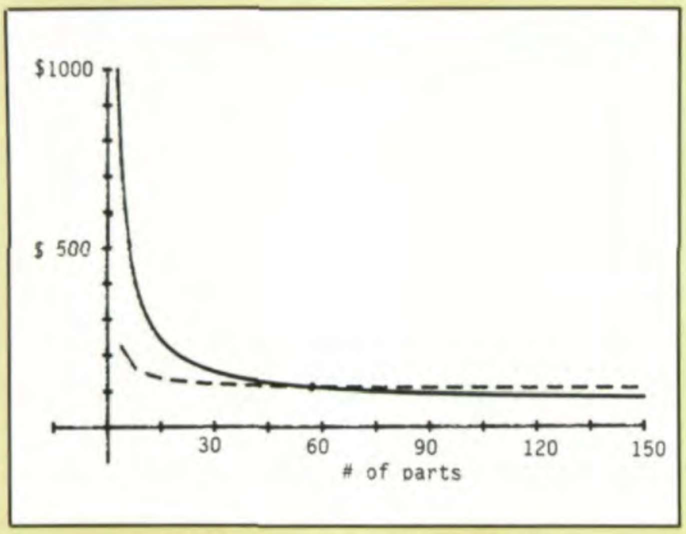

Fig. 3—Conventional Setup Time = 90 Min.

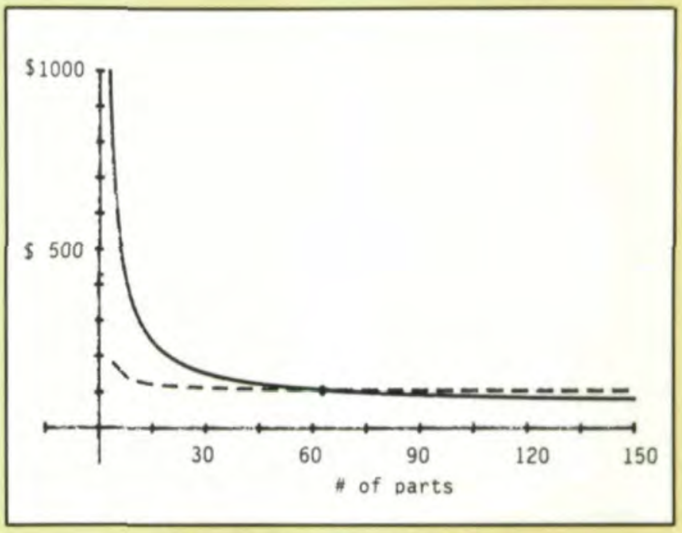

Fig. 5—Conventional Parts/Wheel = 20

If the number of batches is increased to 10, the break-even point moves up to 64 gears (Figure 2). This reflects the increased cost due to the increased setup time for CBN.

Increasing the setup time for conventional grinding to 90 minutes (the same as CBN) lowers the point to 56 gears (Figure 3).

Should the grinding time for conventional increase to 90 minutes, the break-even point shifts dramatically to 41 gears. The economic equation is extremely sensitive to grinding time (Figure 4).

If the conventional wheel will last for 20 gears, the break point shifts to 63 (Figure 5).

An important cost, that of storing the CBN wheel for a long time, can be examined by increasing the number of years. This part will be produced to five years. This causes the break point to move to 69 gears (Figure 6).

Should the machine be used during one shift instead of two, the machine/operator rate increases to about $100/hr. This increased expense makes the equation more sensitive to total production time with a decrease in the break-even point to 42. (Figure 7)

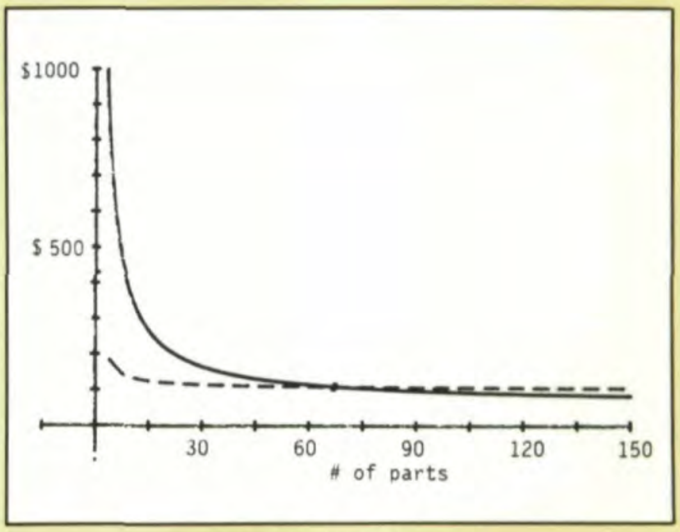

Fig. 6—Number of Years = 5

KEY: —— CBN
----- CONVENTIONAL
* BREAK EVEN POINT

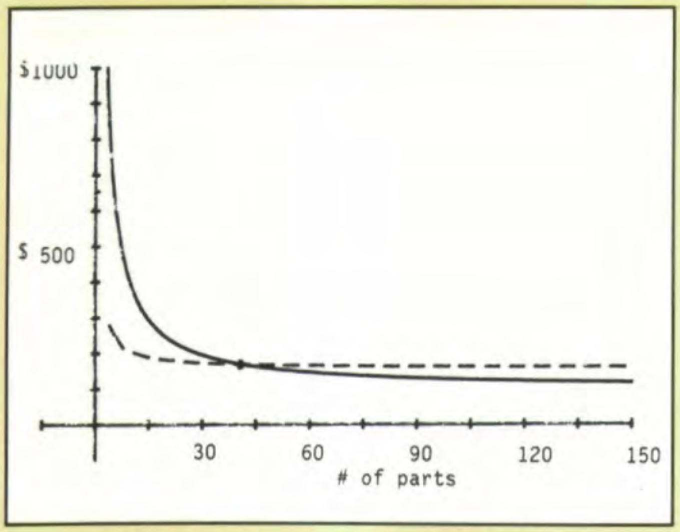

Fig. 7 – Machine/Operator Rate = 100 $/Hr.

Conclusion

As illustrated in this paper, the decision to grind gears with a conventional abrasive wheel or a plated CBN wheel should be based on the economics of the process which is dependent on several factors. Using dressable grinding wheels is less expensive at lower production sizes due to the lower cost of the wheel. At higher lot sizes, CBN grinding is lower in cost because of its shorter cycle times. This indicates the need for both CBN and conventional grinding processes on any machine tool used for gear grinding. However, when very high precision that can be achieved only through real time profile modifications and wheel truing on the grinding spindle is needed, conventional grinding with dressable grinding wheels still remains the only available process. When economics can dictate the choice, the technique presented in this article can be used to determine the more cost-effective process using established economic criteria. While originally developed for form gear grinding, the technique and program can be used equally well with other grinding and machining processes.

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Appendix 1 – Wheel Storage Cost Calculation

Initial cost of wheel = C_W Number of years = N_Y

After first year, wheel is worth $C_W - C_W / N_Y$

Average worth of wheel during year = $[C_W + (C_W - C_W / N_Y)]$ 12

Average worth of wheel during i^{th} year =

$$\frac{[(C_W - C_W (i-1) / N_Y) + (C_W - C_W / N_Y)]}{2}$$

Summing N_Y years, interest lost on wheel is

$$I \sum_{i=1}^{N_Y} \frac{(C_W - C_W (i-1) / N_Y + (C^W - C_W i/N_Y)}{2}$$

Collecting terms:

$$\frac{C_W I}{2} \sum_{i=1}^{N_Y} 2 - 2i + \frac{1}{N_Y}$$

The value of the algebraic series = N_Y

$$\text{Total Cost for wheel storage} = \frac{C_W I N_Y}{2}$$

Appendix 2 – Grinding Cycle Times

Example 1:

Conventional Wheel

Rough Cycle Time
= 125 teeth X 8 passes/tooth X 2 (bidir.) X 2 in. stroke/ 200 ipm

+125 indexes X $\frac{1}{60}$ min/index = 22.1 min.

Semi-finish Cycle Time
= 125 teeth X 2 passes X 2 X 2 inches/100 ipm
+ 250 indexes X $\frac{1}{60}$ min/index
= 14.2 min.

Finish + Sparkout Time
= 125 teeth X 3 passes X 2 X 2 inches/50 ipm + 375 indexes X $\frac{1}{60}$ min/index

(continued on page 48)

BACK TO BASICS . . .
(continued from page 46)

$$H = \frac{.47399}{.0174533 \times 1.4095} = 19° \; 16' \; 3''$$

$$F = 30° \; 46' \; 43'' - 19° \; 16' \; 3'' = 11° 39' \; 40''$$

$$BP = .3142 \times .93969 = .2952 \text{ inch}$$

$$\text{Percentage of overlap of contact} = \frac{.47399}{.2952} - 1 = .60 \text{ or } 60\%$$

It will be seen with this particular ratio, pressure angle and tooth length, that there is no involute or fillet interference, and that there is sufficient overlap of contact to provide continuous action. These conditions are verified by the charts presented in Figs. 10 and 11.

Charting Involute Gear Teeth

The gear teeth and the charts shown in Figs. 10, 11 and 12 presented a gear combination without any tooth modifications. Fig. 14 presents three charts illustrating high fillet, undercut, and involute modificiation at the tip of the tooth. Referring to the chart at *A*, Fig. 14, the tooth has a fillet which extends beyond the base circle, and if the angular height of this fillet is greater than the angle *C* in Fig. 9, the pinion tooth will interfere with the mating gear, and will prevent free rotation.

The diagram at *B*, Fig. 14, shows an undercut condition in which a portion of the involute profile above the base circle is removed. If the angular amount of undercut is greater than the angle *C*, Fig. 9, it will shorten the length of the line of contact, and may result in lack of continuous action with the mating gear.

The diagram at *C*, Fig. 14, shows a gear having tip relief or involute modification, necessary in some cases, and undesirable in others. It is important to know definitely the angular location and amount of this modification in order to determine if continuous action will be obtained when the gears are in mesh. When the tip of the tooth is modified the angle *F*, Fig. 9, is increased, because the "final" point of contact does not advance as far along the line of action, and thus shortens the length of contact. When this information is determined graphically or mathematically, the chart provides a means for accurately determining if such modifications exist and their angular location and amount.

Fig. 15 presents charts of an 8/10 pitch helical gear having 23 teeth, 20° pressure angle, and 23° helix angle. The involute profile of a helical gear is checked in the plane of rotation, the same as a spur gear. The chart at the top of the illustration is of the gear as cut prior to shaving. It will be noted that the flank of the tooth is undercut 0.0038 inch covering 16 degrees of involute, which extends to a point halfway between the base circle an pitch circle. When this gear is shaved the undercut is reduced to 0.0026 inch and covers only 13, instead of 16 degrees. This chart, as previously explained, when compared with a similar chart of the mating gear can be used to determine the usable portions of the profiles on both gears, and the actual length of the line of contact can be determined from the preceeding formulas.

A WHEEL SELECTION TECHNIQUE . . .
(continued from page 14)

= 36.2

Total Machining Time
= 22.1 + 14.2 + 36.2 = 72.6 min.

CBN Wheel

Machining Time

$$= 125 \text{ teeth} \times 2 \text{ in. stroke/5 ipm} + 125 \text{ indexes} \times \frac{1}{60}$$

= 52.1 min.

Appendix 3 – Machine/Operator Rate

$$M = \frac{Wo}{Nm}(1 + \text{worker overhead}) + M_T(1 + \text{machine overhead})$$

$$M_T = \frac{\text{cost of machine}}{(\text{hours/year}) \times (\text{depreciation years})} = \frac{\$750{,}000}{(4000)\ (10)} = \$18.75 \text{ hr.}$$

assume: $Wo = \$14/\text{hr.}$, $Nm = 1$

$$M = \frac{14}{1}(1 + 100\%) + 18.75\ (1 + 100\%) = \$65.5/\text{hr.}$$

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