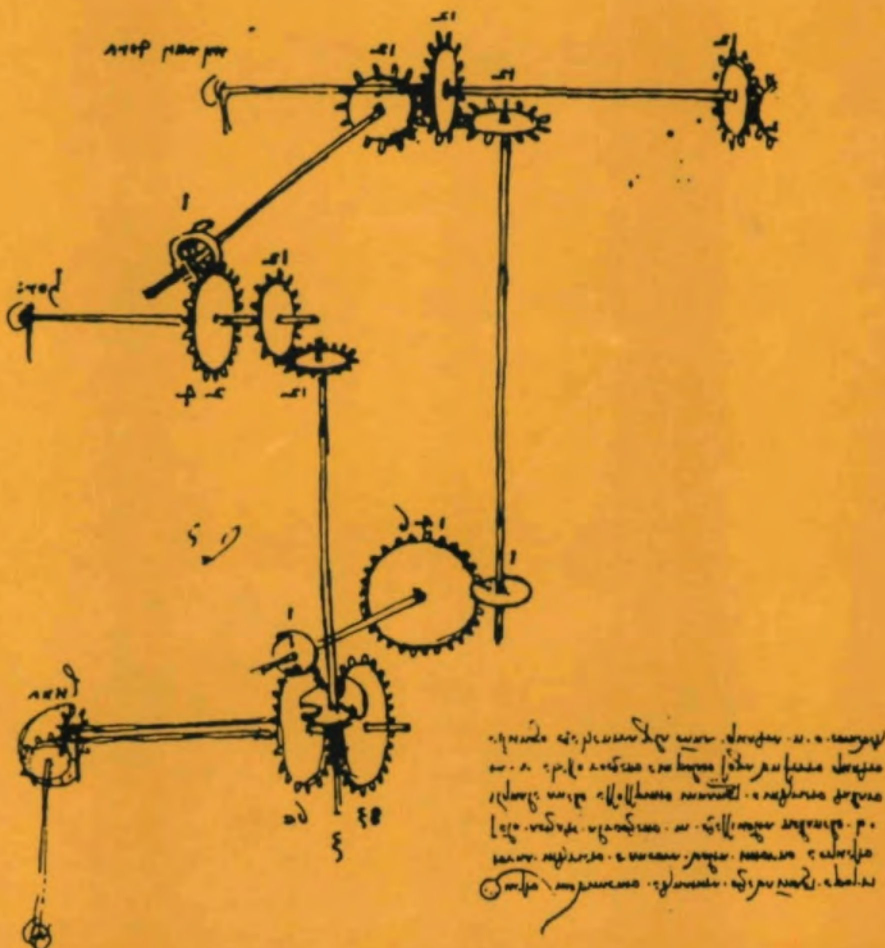
GEAR TECHNOLOGY

The Journal of Gear Manufacturing

MAY/JUNE 1986

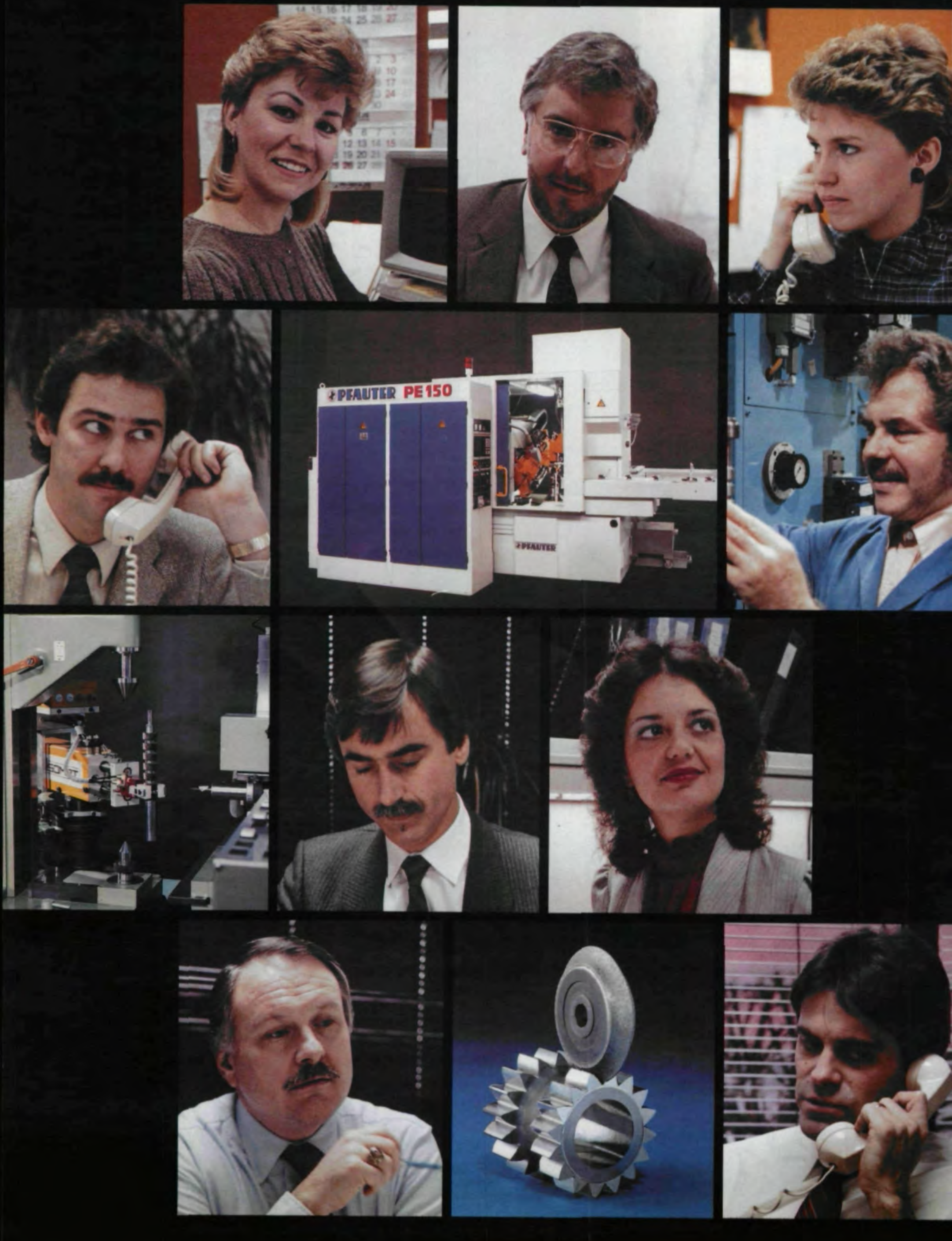


A Wheel Selection Technique for Form Gear Grinding

Identification of Gear Noise with Single Flank Composite Measurement

Selection of Material and Compatible Heat Treatments for Gearing

Generating and Checking Involute Gear Teeth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GEAR TECHNOLOGY

The Journal of Gear Manufacturing

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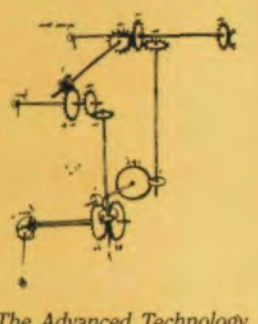

The Advanced Technology
of
Leonardo Da Vinci
1452-1519

COVER

Leonardo was very interested in clocks as evidenced by his many sketches of clock works.

The cover sketch depicts the geared mechanisms of an old monastery church clock. At the top of the sketch he notes "minutes of the hours." This was one of the first references to a minute hand, which was rare in Renaissance clocks. The reference below the mechanism is labeled "hours". The figures also indicate the number of teeth of each wheel.

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DEPARTMENTS

May/June 1986 — Vol. 3, No. 3

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MANUSCRIPTS: We are requesting technical papers of every sort from manufacturers of gear making machinery and related equipment, universities, and engineers. Articles should be of an educational and training nature with general appeal to anyone having anything to do with the purchase of materials or machinery, or the design, manufacture, testing or processing of gears. Subjects sought are solutions to specific problems, explanations of new: technology, techniques, designs, processes, and alternative manufacturing methods. These can range from the "How to . . ." of gear cutting (BACK TO BASICS) to the most advanced technology. All manuscripts submitted will be carefully considered. However, the Publisher assumes no responsibility for the safety or return of manuscripts. Manuscripts must be accompanied by a self-addressed, self-stamped envelope, and be sent to GEAR TECHNOLOGY, The Journal of Gear Manufacturing, P.O. Box 1426, Elk Grove, IL 60007, (312) 437-6604.

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CIRCLE A-8 ON READER REPLY CARD

VIEWPOINT

Dear Editor:

Sub: 'Finding Gear Tooth Ratios' article published in Nov/Dec 1985 issue

Let us congratulate you and Orthwein, W.C. for publishing this superb article in Gear Technology Journal. We liked the article very much and wish to impliment it in our regular practice.

During 'go-through' your article, we face two difficulties which are given below:

1. In the main program of GEAR RATIO (page 27) the 8th step is "Call GRATIO" (RB, EB). But we find nowhere the formula to find out RB.
2. In the 5th step of the same program (Call FACT (PC) and call FACT (PC), we think that second subroutine to be called in this step should be 'call FACT (QC)'

Thanking you and awaiting an early clarification.

HV Joshi
Manager: Gear Design
Elecon Engineering Co. Ltd.

Authors Note:
The author would like to thank Mr. Joshi for his interest in the article "Finding Gear Teeth Ratios" which appeared in GEAR TECHNOLOGY, Vol. 2, No. 6, November/December, 1985. He is correct in observing that the CALL statement in step 5 (Box 5) in Fig. 2, page 27, should read "Call FACT (PC) Call FACT (QC). RB and EB are used as augments of GRATIO in step 8 (Box 8) of the flow chart in Fig. 2 to emphasize that the remainder of the program is devoted to finding gear tooth ratios for the additional base points selected in the acceptable range from R − E/N to R + E/N. The FACTOR and ELIM routines may be applied to this ratio as it was applied to the central ratio R when the first permissable error was from R − E to R + E. That may have been clearer if rountines FACTOR and ELIM had both been included in the third block from the bottom of the flow chart. Finally, the number of teeth N_4 in Fig. 7, page 29 of the GEAR TECHNOLOGY article should refer to the larger of the two gears of shaft three.

Dr. William Orthwein

I have read the material presented in recent issues of your magazine GEAR Technology. I am impressed with the up-to-dateness of your editorial content; neither have you neglected the basics of the industry so important to newcomers.

The international aspect of modern manufacturing needs magazines of this caliber.

Best Regards
Henry H. Ryffel, Editor
MACHINERY'S Handbook

NOTES FROM THE EDITOR'S DESK

This issue of GEAR TECHNOLOGY, The Journal of Gear Manufacturing, marks the end of our second year of publication. As we approach our third year, it is time to review our statement of purpose. GEAR TECHNOLOGY'S primary goal was and is to be a reference source and a forum for the American Gear Industry, and to advance gear technology throughout the world.

We appreciate the cooperation and support that we have received from the many technical societies such as the American Gear Manufacturer's Association, Society of Manufacturing Engineers, American Society of Mechanical Engineers, ASME-Gear Research Institute and the Institute de L'engrenage et de Transmissions. We have had the opportunity to attend technical conferences and talk with readers and authors to get a feel for your problems and interests. As our publication has grown, it has been rewarding to see growth in attendance at these conferences as well.

We have seen our readership grow and extend to 33 countries. What is most gratifying is that this growth has come during one of the most difficult times for the American manufacturing industry and for Cadillac Machinery, my family's machine tool business. Yet, I look forward to the future with great anticipation. Some sectors of our industry are already very strong—others, are showing the first real signs of awakening. While the precipitous drop in oil prices will take its toll on those serving the energy sector, it should, along with decreasing interest rates and a falling dollar, provide higher levels of business and increased profits to those companies that continue to prepare and invest in the changing competitive climate.

Michael Goldstein
Editor/Publisher

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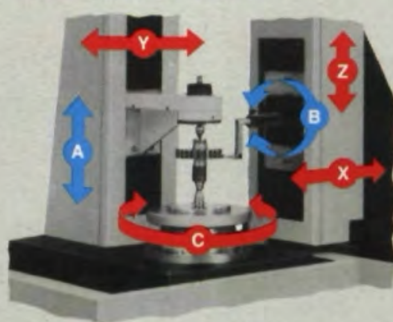

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Topological Map

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CIRCLE A-6 ON READER REPLY CARD

A Wheel Selection Technique for Form Gear Grinding

Richard W. Schwartz
Dr. Suren B. Rao

National Broach & Machine
A Division of Lear Siegler, Inc.
Mt. Clemens, Michigan

AUTHORS:

DR. SUREN RAO *is Vice President of Engineering at National Broach and Machine. He has been active in the field of machine tool research, design and development since 1970. He holds a Bachelor's Degree from India, and a Master's degree from McMaster University in Canada, and a Doctorate from the University of Wisconsin-Madison, all in mechanical engineering. He was employed at Central Machine Tool Institute in India and Battelle Columbus Laboratories in Columbus, Ohio before joining National Broach and Machine in 1983. He is a member of the ASME, SME and NAMRI.*

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.*

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 entirely 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.

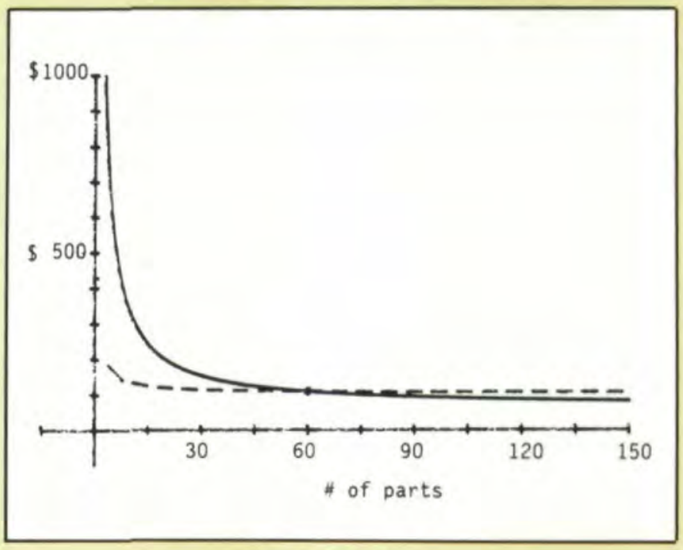

Fig. 1 – Example 1

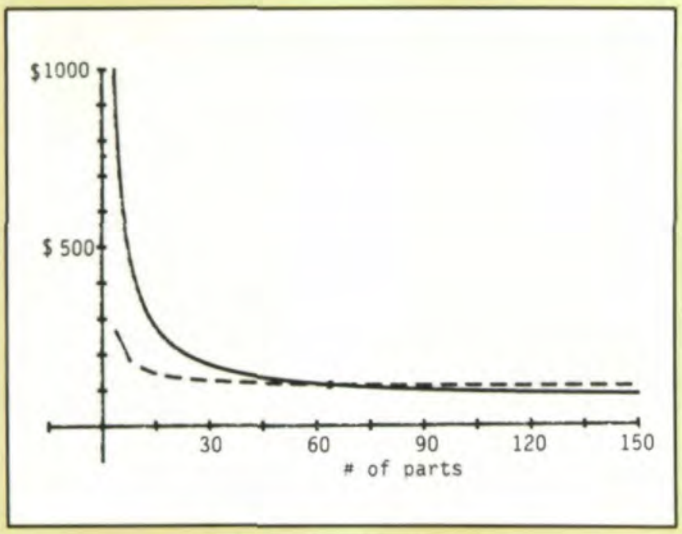

Fig. 2—Number of Batches = 10

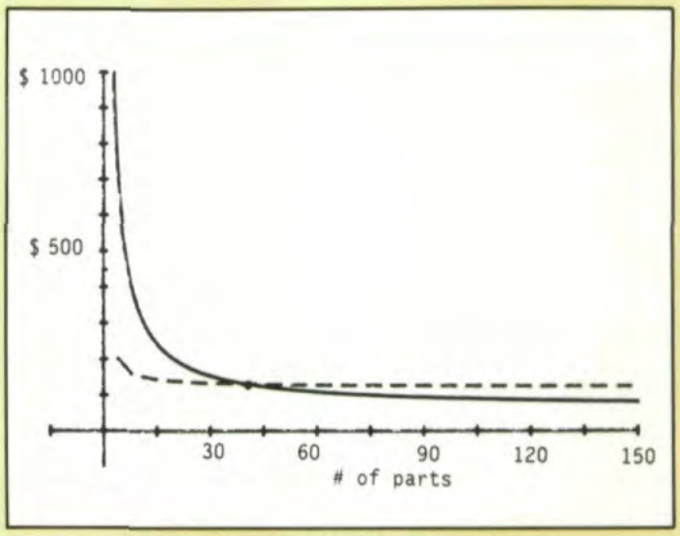

Fig. 4—Conventional Grinding Time = 90 Min.

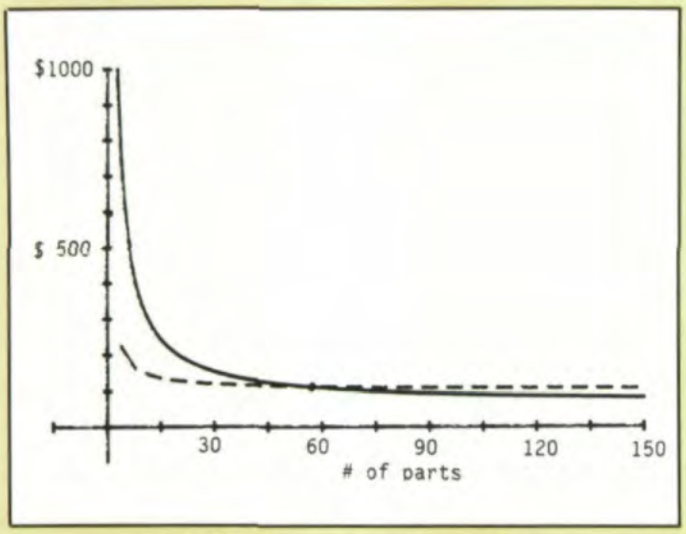

Fig. 3—Conventional Setup Time = 90 Min.

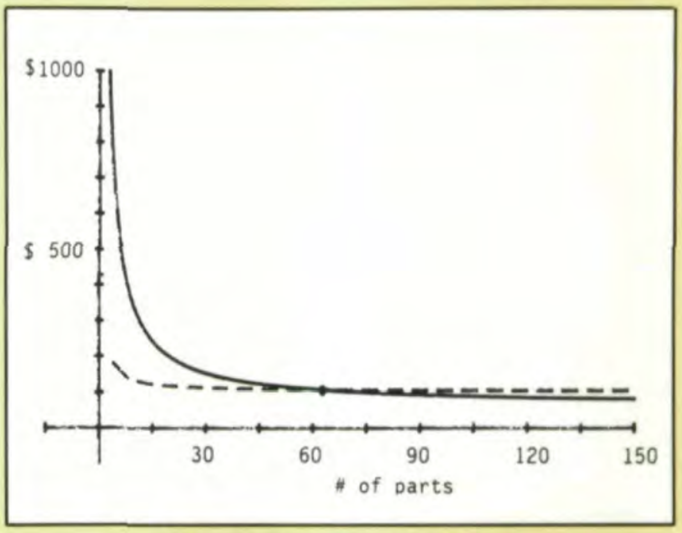

Fig. 5—Conventional Parts/Wheel = 20

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)

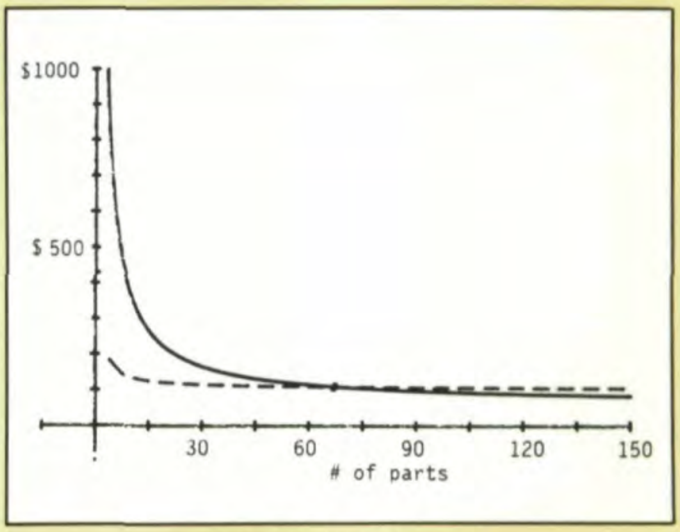

Fig. 6—Number of Years = 5

KEY: —— CBN

----- CONVENTIONAL

* BREAK EVEN POINT

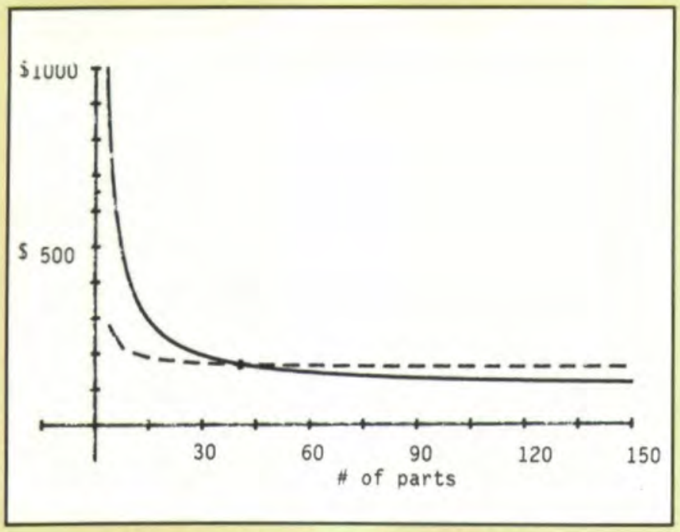

Fig. 7 – Machine/Operator Rate = 100 $/Hr.

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)

SELECTION OF MATERIAL . . .

(continued from page 37)

Nitriding — The process of adding nitrogen to the surface of a steel, usually from dissociated ammonia as the source. Nitriding develops a very hard case after a long time at comparatively low temperature, without quenching.

Normalizing — The process of heating steel to a temperature above its transformation range, followed by air cooling. The purpose of normalizing may be to refine grain structure prior to hardening the steel, to harden the steel slightly, or to reduce segregation in castings or forgings.

Quenching — Cooling from high temperature, usually at a fast rate.

Secondary Hardness — The higher hardness developed by certain alloy steels when they are cooled from a tempering operation. This should always be followed by a second tempering operation.

Solution Treatment — Heating an alloy to high temperature to form a solution from an aggregate.

Spheroidizing — A heat treating process used to change all of the carbides in steel to rounded particles, or spheroids. A completely spheroidized structure is the softest and most workable structure for any composition.

Tempering — Reheating quenched steel to a temperature below the critical range, followed by any desired rate of cooling. Tempering is done to relieve quenching stresses, or to develop desired strength characteristics.

Work Hardness — Hardness developed in metal resulting from cold working.

Series Designation	Types
10xx	Nonsulphurized carbon steels
11xx	Resulphurized carbon steels (free machining)
12xx	Rephosphorized and resulphurized carbon steels (free machining)
13xx	Manganese 1.75%
*23xx	Nickel 3.50%
*25xx	Nickel 5.00%
31xx	Nickel 1.25%, chromium 0.65%
33xx	Nickel 3.50%, chromium 1.55%
40xx	Molybdenum 0.20 or 0.25%
41xx	Chromium 0.50 or 0.95%, molybdenum 0.12 or 0.20%
43xx	Nickel 1.80%, chromium 0.50 or 0.80%, molybdenum 0.25%
44xx	Molybdenum 0.40%
45xx	Molybdenum 0.52%
46xx	Nickel 1.80%, molybdenum 0.25%
47xx	Nickel .05%, chromium 0.45%, molybdenum 0.20 or 0.35%
48xx	Nickel 3.50%, molybdenum 0.25%
50xx	Chromium 0.25, 0.40 or 0.50%
50xxx	Carbon 1.00%, chromium 0.50%
51xx	Chromium 0.80, 0.90, 0.95, or 1.00%
51xxx	Carbon 1.00%, chromium 1.05%
52xxx	Carbon 1.00%, chromium 1.45%
61xx	Chromium 0.60, 0.80, or 0.95%, vanadi 0.12%, 0.10% min., or 0.15% min.
81xx	Nickel 0.30%, chromium 0.40%, molybdenum 0.12%
86xx	Nickel 0.55%, chromium 0.50%, molybdenum 0.20%
87xx	Nickel 0.55%, chromium 0.05%, molybdenum 0.25%
88xx	Nickel 0.55%, chromium 0.50%, molybdenum 0.35%
92xx	Manganese 0.85%, silicon 2.00%, chromium 0 or 0.35%
93xx	Nickel 3.25%, chromium 1.20%, molybdenum 0.12%
94xx	Nickel 0.45%, chromium 0.40%, molybdenum 0.12%
98xx	Nickel 1.00%, chromium 0.80%, molybdenum 0.25%

*Not included in the current list of standard steels.

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Identification of Gear Noise with Single Flank Composite Measurement

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Abstract

This article was written to serve as a guide for the application of single flank composite inspection to the solution of gear noise problems. It includes a discussion of the relationship of transmission error to gear noise, housing dynamics, spectral analysis and how it is used in problem-solving situations. Several case histories are described.

Introduction

Anyone involved in the design, manufacture and use of gears is concerned with three general characteristics relative to their application: noise, accuracy, and strength or surface durability. In this article, we will be dealing with probably the most aggravating of the group, gear noise.

The use and analysis of single flank composite inspection of gears can result in the understanding and control of gear noise problems. This is achieved through the measurement of transmission error, which is the predominant cause of gear noise.

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ROBERT SMITH *Senior Manufacturing Technology Engineer at Gleason Machine Division, has over thirty years experience in the Gear Industry. Mr. Smith received his training from Rochester Institute of Technology. While at Gleason, Mr. Smith's engineering assignments have included gear methods, manufacturing, research and gear quality. These assignments involved the use and application of instrumentation for the study of noise, vibration, and structural dynamics. From these assignments, he expanded his ideas relating to gear metrology. Currently, Mr. Smith is chairman of the Measuring Methods and Practices and Master Gear Subcommittee in the American Gear Manufacturers Association, and is also a member of the Rochester Industrial Engineering Society and Society of Experimental Stress Analysis.*

Gear Noise

Gear noise comes in many types. The successful solution of gear noise problems first requires the determination of the type that is objectionable. What is perceived as "gear noise" depends to a great extent on the speed of operation.

The most typical type of gear noise occurs at tooth mesh frequency or harmonics, assuming that these frequencies are within the audible range.

Gear noise can also occur at once per revolution frequencies, or multiples of it. If the RPM is high enough, these frequencies will occur in the audible range. If the RPM is relatively low, this "noise" may be perceived as a low frequency vibration.

Noise can also occur as a low frequency modulation of the higher tooth mesh frequency noise. This results in a phenomenon called sidebands.

To properly define the type of noise that is of concern, it is usually necessary to apply some sound analysis measurements to the final application, whether it is a gear box, vehicle or some other structure.

Frequency is the key to understanding the type of gear noise, and ultimately to deciding what corrections must be made to the gears. Frequency analysis is done with equipment such as "tuneable narrow band pass filters" or "real time analyzers". The analysis of data from such instruments will be discussed in detail later.

Transmission Error

Transmission error is the parameter that is measured by single flank composite inspection. Transmission error is defined as the deviation of the position of the driven gear for a given angular position of the driving gear, from the position that the driven gear would occupy if the gears were geometrically perfect.[1]

It is measured on machines such as shown in Fig. 1. Generally, these machines use optical encoders such as the measuring transducer. (See Fig. 2) These encoders and associated electronics generate data as shown in Fig. 3.

Components of Transmission Error

Transmission error is normally observed in the form of a fairly regular once

Fig. 1—below

per tooth pattern, superimposed on large waves related to once per revolution type errors. Noise and vibration excitation is generally related to the once per tooth pattern, while accuracy problems are more generally related to the once per revolution type patterns. The curve can be generated by running a pair of work gears together, or by running a work gear with a master gear.

The total transmission error curve is made up of several components:

1. Total composite (F_i')
2. Tooth to tooth composite (f_i')
3. Long term component
4. Short term component (effective profile)

Total Composite (F_i')

The total composite error is read from the "raw" data as the difference between the highest and lowest points on the graph, within one revolution of the largest gear. If the gears are near a 1:1 ratio, several revolutions may be necessary for the errors of both gears to phase together and show the worst case.

This type of error is important for accuracy applications and includes the effect of accumulated pitch variation as well as a portion of profile or involute variation. (See Fig. 4A)

Tooth To Tooth Composite (f_i')

The tooth to tooth composite error is seen as the variation in transmission error at tooth mesh frequency. It is read as the highest to lowest point in any 360°/N (where N = number of teeth) or one angular pitch portion of the total transmission error curve. It results from a portion of the profile error plus the effect of individual pitch variations.

The resulting graph will be the short term component and is most generally related to errors in tooth form occurring at tooth mesh frequencies. (See Fig. 4C) In most gearing, long face helicals excluded, this relates primarily to a portion of the profile mismatch of the gear teeth or involute error. Both the amplitude and shape of this component are of concern relative to noise excitation.

This is the parameter that is most important for analysis of gear noise problems.

Development of the Short Term Component

When describing the relationship of tooth geometry to the transmission error curve, it is best to think in terms of involute spur teeth. However, the same principles apply to helical and bevel teeth when dealing in terms of short face widths.

This, also, is important for accuracy applications when small angle errors are of concern. (See Fig. 4A)

Long Term Component

The long term component results from drawing in the mean, or more properly, the upper envelope curve of the total transmission error. This can also be achieved by recording the output of a low pass filter with a cutoff frequency

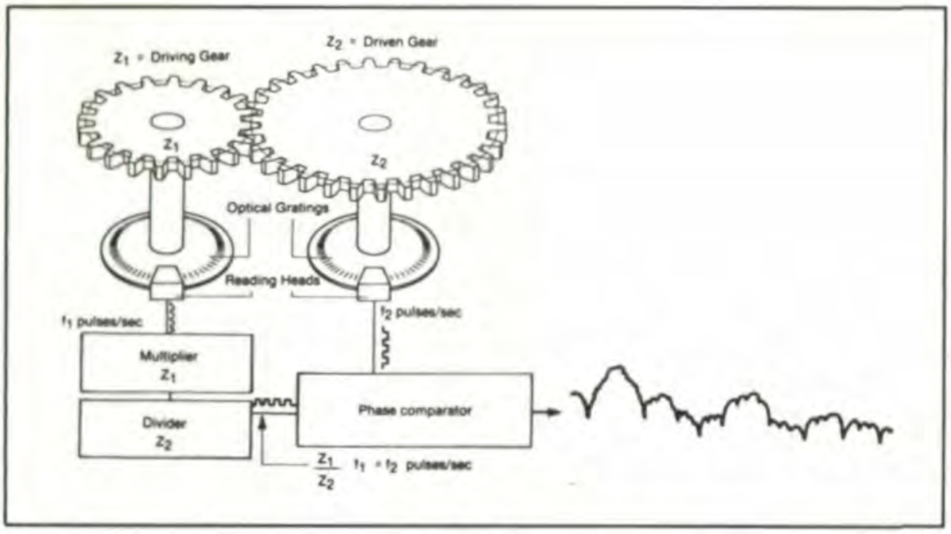

Fig. 2

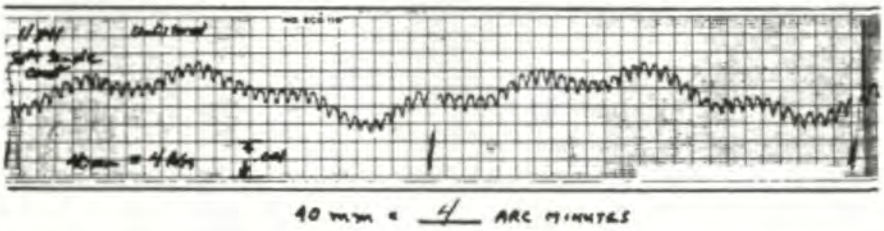

Fig. 3

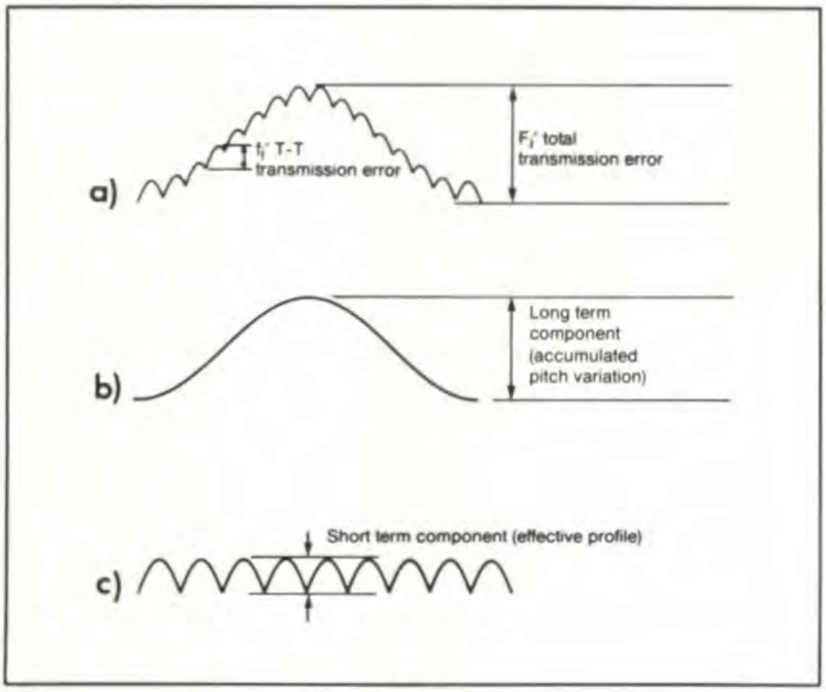

Fig. 4

properly selected to reject mesh and higher frequencies.

The resulting long term component, shown in Fig. 4B, is equivalent to accumulated pitch variation, assuming the gear was run with a perfect master. If a pair of work gears were run together, it would be necessary to use various cutoff frequencies to separate out the long term component of each individual gear.

Short Term Component

The short term component (effective profile) results from subtracting the long term component from total transmission error. This can also be accomplished by using a high pass filter with the cutoff frequency set just below the mesh frequency.

Profile[2]

Fig. 5 shows three typical tooth shapes and their resulting displacement motion curves. Each different tooth shape is shown rolling against a perfect master gear. Visualize the motion curve starting with the test gear tooth in contact near the root of the master tooth. The displacement curve generates as the teeth roll together and the point of contact moves toward the tip of the master tooth. This action repeats for each successive pair of teeth coming in contact or for each pitch. Fig. 5A shows the straight line generated by a perfect involute on the test gear, rolling with the perfect involute on a master gear. Fig. 5B shows the parabolic-like curve generated by a tooth modified with gradual tip and root relief. The zero displacement portion of the curve occurs when the teeth are meshing near the pitch line and the most negative portions occur when the teeth are in contact near tip and root. Fig. 5C shows the ramp shaped curve resulting from a pressure angle modification.

Influential Factors On Effective Profile (Short Term Component)

Helical or Bevels

Helical gears present a more complicated situation. In theory, the line of contact covers the entire face of the tooth as it rolls through mesh with the master so lead would have an influence on the motion curve. (See Fig. 6) However, from a practical standpoint, the tooth will generally have some lengthwise crowning. (See Fig. 7) This results in an instantaneous area of contact that will progress diagonally across the profile of the tooth. The motion curve is then dominated by the profile shape. This would not be true of long face helicals.

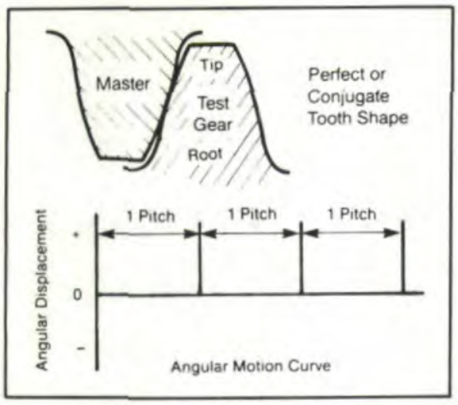

Fig. 5A – Angular Motion Curve

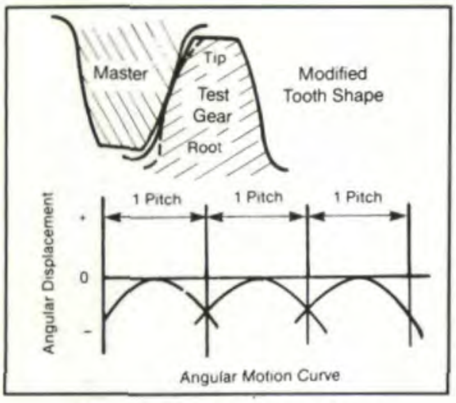

Fig. 5B – Angular Motion Curve

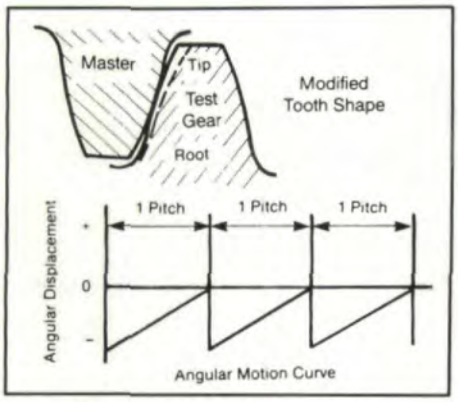

Fig. 5C – Angular Motion Curve

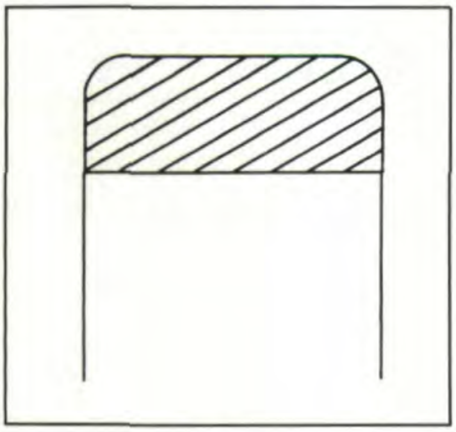

Fig. 6

Lead or Tooth Alignment[3]

Lead or tooth alignment, even on spur gears, is the one element least applicable to single flank measurement. It is impossible to look at a graph from a single flank test and quantify the amount of lead error in a gear. It can, however, have an influence on other elements of transmission error in a gear. Lead variation around a gear (wobble) will modulate the effective profile information. (See Fig. 8) Decreased contact ratio, due to high lead error will increase the effective profile or conjugacy error. However, it would be possible to have a large lead error, resulting in the tooth contact being at one end of the tooth. (See Fig. 9) If the tooth had good profile conjugacy, the resulting single flank graph would be a straight line. In this case, it would falsely indicate a good gear that might fail due

Fig. 7

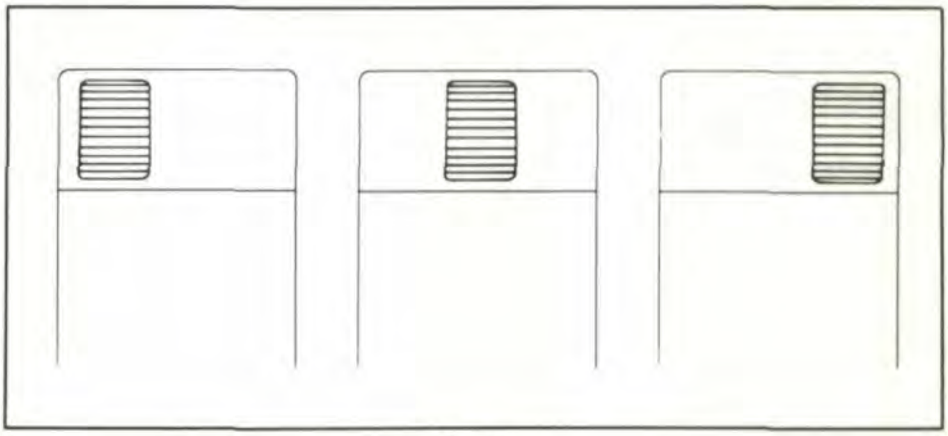

Fig. 8

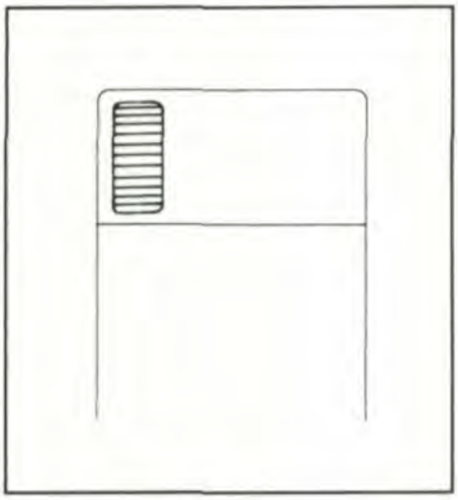

Fig. 9

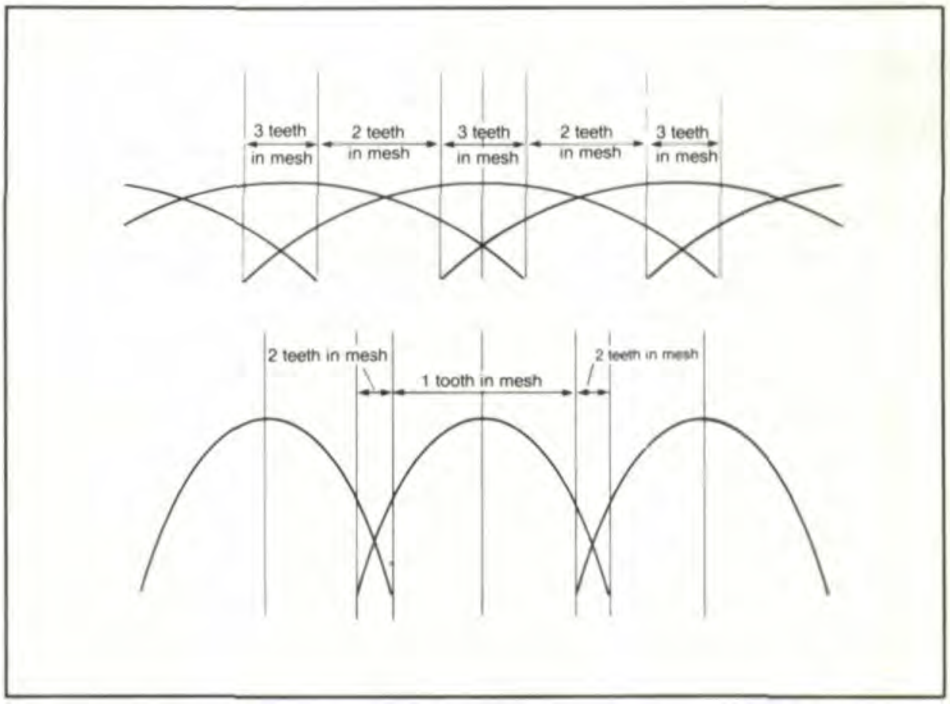

Fig. 10

to strength or surface durability considerations.

Contact Ratio

Consider a spur gear running with a perfect master gear. The gear is designed to have a contact ratio of exactly one and has curvature modification on the profile. The amplitude of the short term component of transmission error would be equal to the involute variation. If the gear was redesigned to increase contact ratio, the amplitude of the short term component would decrease and represent only a portion of the total involute variation.

If we considered a helical gear set, the total contact ratio (transverse plus face) would increase, and the effective profile error (short term component) would decrease even more.

However, there is a big difference between theoretical contact ratio and actual contact ratio. Contact ratio calculations are based upon full length and full profile contact. From a practical standpoint, most gears are designed with profile modifications and lengthwise crowning. This is to allow for housing errors and deflections, as well as tooth deformation under load. If, under load, contact is carried across the whole tooth, the contact ratio calculations are valid. However, in many instances, the contact is still localized even under operating conditions. In this case, the real contact ratio is much lower than the theoretical. In one helical design studied recently, the theoretical contact ratio was 3.4. Based on actual contact area, due to severe localization, the real contact ratio was 1.6. Fig. 10 shows the effect of different contact ratios on the effective profile amplitude shown in the single flank graph. There is a tendency to use too much localization on lightly loaded applications and, therefore, increase the possibilities of noise excitation.

Load Effects

Most single flank inspection is done at relatively low loads in typical test machines. To test at high loads, transducers must be attached to the housing used in the application. This is time consuming and expensive, but can be done in laboratory tests.

However, many applications such as vehicle drive gears usually have noise problems at light drive or float conditions. This correlates well to the lightly loaded single flank testers. In this case, a low effective profile error is a desirable condition. The gears can also be tested

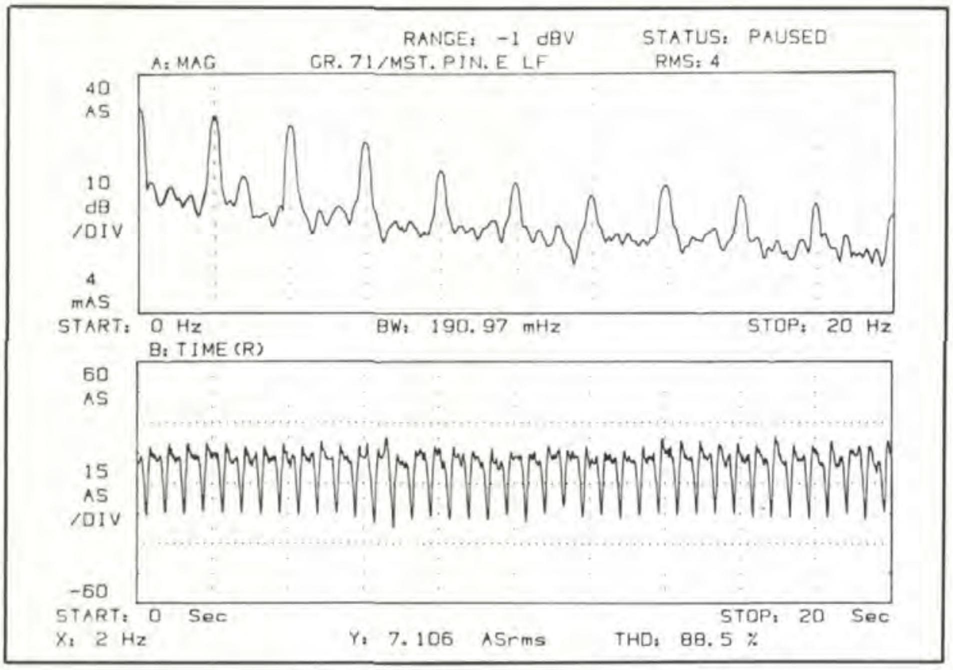

Fig. 11

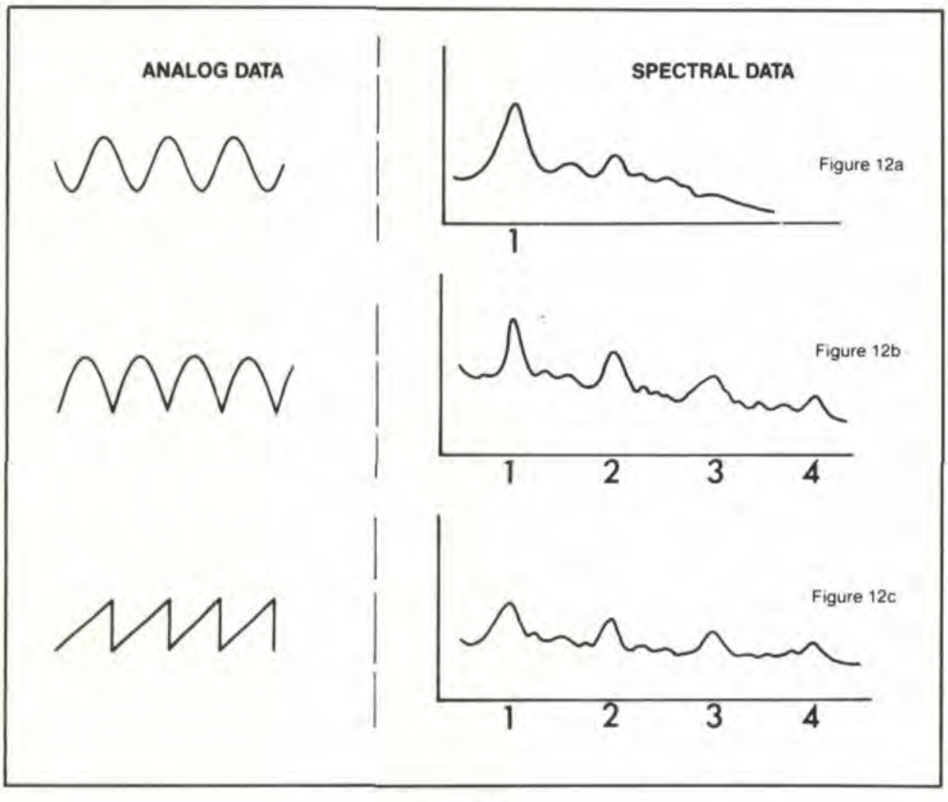

Fig. 12

at different positions to simulate load or thermal deflections of the housing.

If the gears are to be used in a heavily loaded application, then chances are that the tooth shapes have been modified, and that they won't run smoothly in a lightly loaded single flank test. In this case, the job must be investigated experimentally to decide what the desirable transmission error should look like under light loads.

Smith[4] and Mark[5] discuss the effects of tooth deflections, modification and transmission error to a greater extent.

Fig. 11 shows a highly loaded aircraft gear with tip relief running at low loads in a single flank tester. The large negative drop in the curve is the result of tip relief. If the amount of tip relief is correct, the curve would smooth out at operating loads.

Housing Dynamics

Gear noise is really a system problem, not just a gear problem. Most gearing used for power transmission is enclosed in a housing and, therefore, little or no audible sound is actually heard from the gear pair.[6] The minute vibrations created by the gears as they move through mesh are amplified by resonances of structural elements. This amplification occurs when the speed of the gear set is such that the meshing frequency, or a multiple of it, is equal to a natural frequency of the system the gears are mounted in.

Some structural systems are such good amplifiers that it is nearly impossible to make gears good enough to run quietly in them. When this happens, the gearing becomes unnecessarily expensive. At some point, it is more productive to modify the system and make it less critical to gear excitation.

This is done by making a modal study of the structure and then applying corrective measures. Modal studies can be done by actual vibration measurements, or theoretically, by the use of finite element techniques. Corrective measures may include a change in panel stiffness, ribbing in the housing, application of damping techniques or changing the path of transmitted excitation. In the case of vehicle noise, rubber isolaters or tuned absorbers are often used. It may also be possible to change the number of teeth in the gears, or the operating speed, in order to move the mesh frequency away from the resonant frequency. Smith[7] is a source of more information on this subject.

Spectral Analysis

As mentioned earlier, frequency is the key to understanding gear noise. Spectral analysis is really better described as frequency analysis. The analytical system takes a time varying signal and breaks it down into a spectrum of individual frequencies. The amplitude of any frequency of interest is actually the amplitude of a discrete sine wave contained in the more complex time domain waveform. This can be done with analog instrumentation, such as variable narrow band pass filters. Today, it is more often done digitally by the use of "real time analyzers" and a Fast Fourier Transform (FFT) algorithm. Most of these RTA's will display both the time domain data as well as, the frequency domain. (See Fig. 11)

Interpretation of Data
Analog Data
(Time Domain)

Analog data is useful for judging the actual shape or geometry of the tooth form. It is easy to look at the filtered short term component (effective profile error) and decide what corrective actions to take on tooth development. It is also useful, in the unfiltered state, for a quick judgement of accumulated pitch variation of each gear in the pair (long term component).

Spectral Data
(Frequency Domain)

The spectral data, on the other hand, is useful for identifying the characteristics of a transmission error curve that are the source of noise excitation. It takes a complex analog waveform and simplifies the analysis of it.

Relationship to Typical Motion Curve

A look at the relative amplitudes of the various harmonics in a spectrum can sometimes be useful in judging the characteristic wave shape. (See Fig. 12)

A lapped hypoid set of gears will often show an "almost sinusoidal" effective profile curve. The spectrum will show a discrete peak at the 1st harmonic of mesh, with the rest being white noise (all frequencies). (See Fig. 12A)

The most typical effective profile curve, for either spur and helicals or bevels, will be of the form that is nearly parabolic. This will generally show discrete peaks at 1st, 2nd, 3rd and possibly higher harmonics. The second harmonic will be approximately 12 Db lower than the 1st and the 3rd will be approximately 18 Db down. (See Fig. 12B)

The next most typical is the ramp shaped curve. In this case, the second will only be approximately 6 Db down and the 3rd approximately 10 Db down, from the first. This usually results from something like a pressure angle error and is easily recognized when the spectrum has excessive amounts of higher harmonic content. (See Fig. 12C)

These relationships can vary, depending upon how "pure" is the waveform.

Applying Spectral Analysis To Noise Problems

The characteristics of the dominant peaks displayed in any spectrum are very useful to the solution of gear noise problems. Different types of noise problems will relate to different characteristics. There isn't one simple piece of information that will relate to everyone's noise problem.

If one looks at the analog data of the filtered (long term component removed) effective profile error throughout one revolution of the largest gear, it will be observed that the shape and amplitude of each tooth mesh may vary. These geometric deviations, from that of conjugate gear teeth, are made up of two components; mean and random.[8] The mean geometric deviation component for a pinion or gear is defined as the tooth surface formed by taking the average of all tooth surfaces on the pinion or gear under consideration. The random component of the geometric deviation of a tooth surface is defined as the deviation of that tooth surface from the mean tooth surface. Thus, every tooth surface on a pinion or gear has the same mean deviation, but the random deviation generally will differ from one tooth to the next.

In the spectral data, the mean component relates to the mesh frequency and integer harmonics. The random component relates to sideband peaks. (See Fig. 13)

Mean component deviations of normal tooth shapes will create spectral patterns similar to those shown in Fig. 14. Extreme tip and root relief modifications will look like the data in Fig. 11.

Random component deviations can be caused by pinion runout, gear runout, and cyclic distortions of tooth profile forms due to heat treatment. The results of these deviations can be seen on the spectrum as sidebands. Sidebands will occur at the mesh frequency, plus and minus the frequency of the event passing through mesh. They could also occur at plus and minus the event frequency, from other harmonics of mesh. (See Fig. 13)

Other frequencies that are important are sometimes called "ghost" or phantom frequencies. These will be found in the spectrum between integer harmonics of mesh or runout frequencies. They also can occur as unusually high amplitudes of an individual integer harmonic. (See Fig. 13)

Ghost harmonics are generally due to flats or facets on the normal tooth form and are caused by such things as cutter runout or non-uniform motion of an element within the gear train of the machine that generated the tooth form. This could be caused by tooth to tooth transmission error of the "final drive gears" or runout

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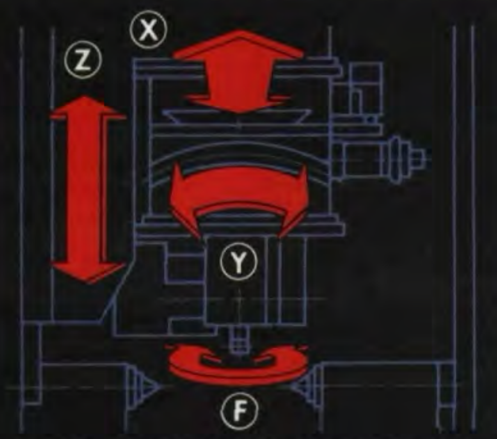

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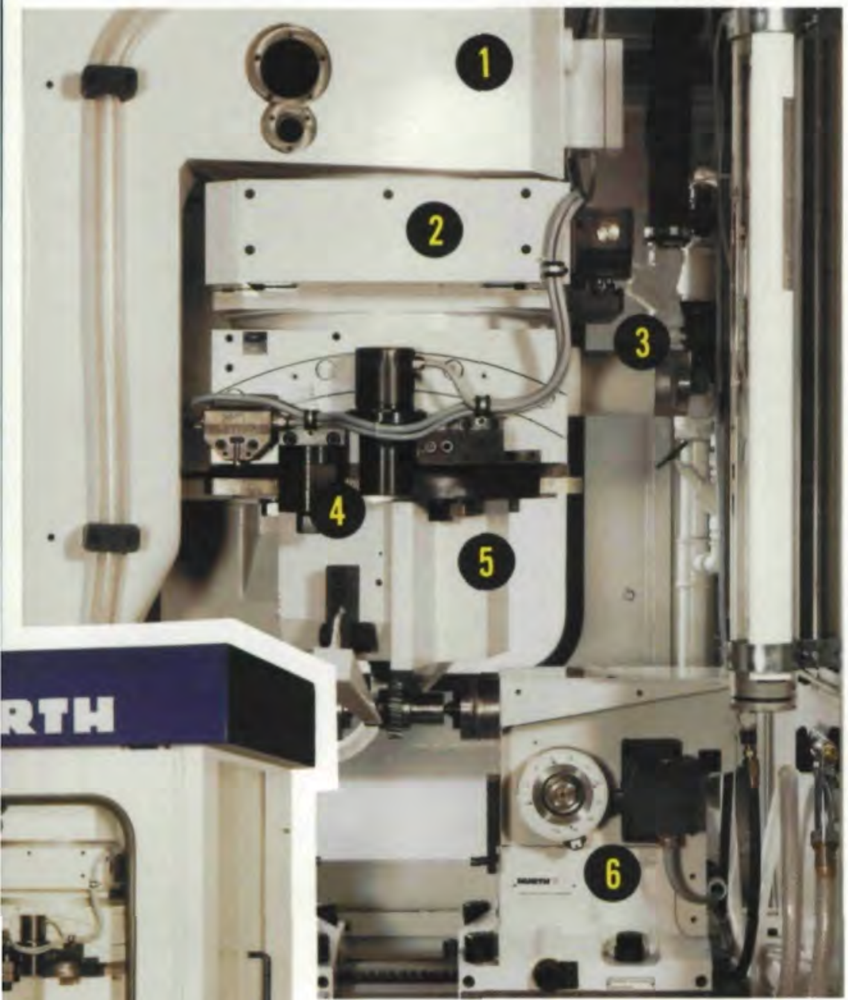

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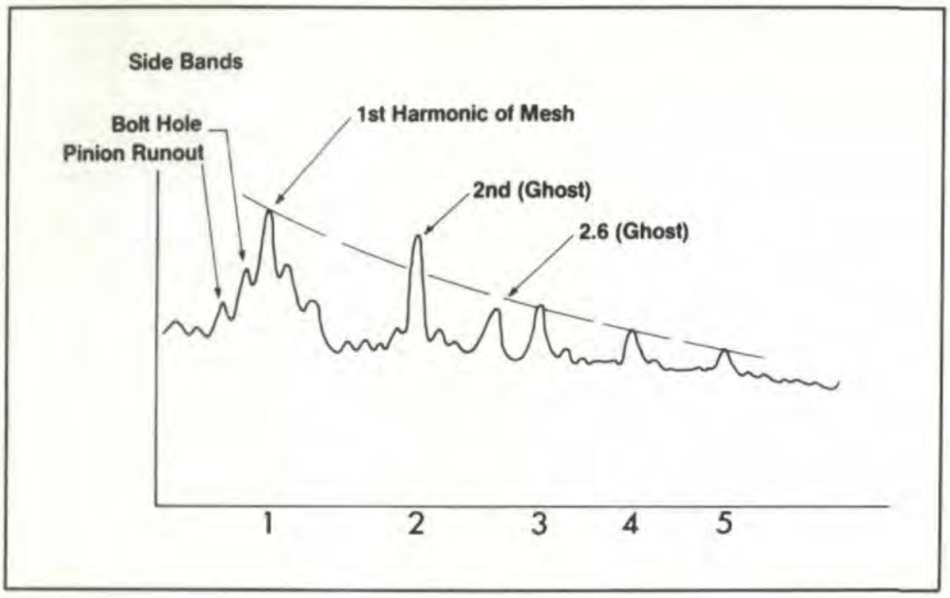


Fig. 13

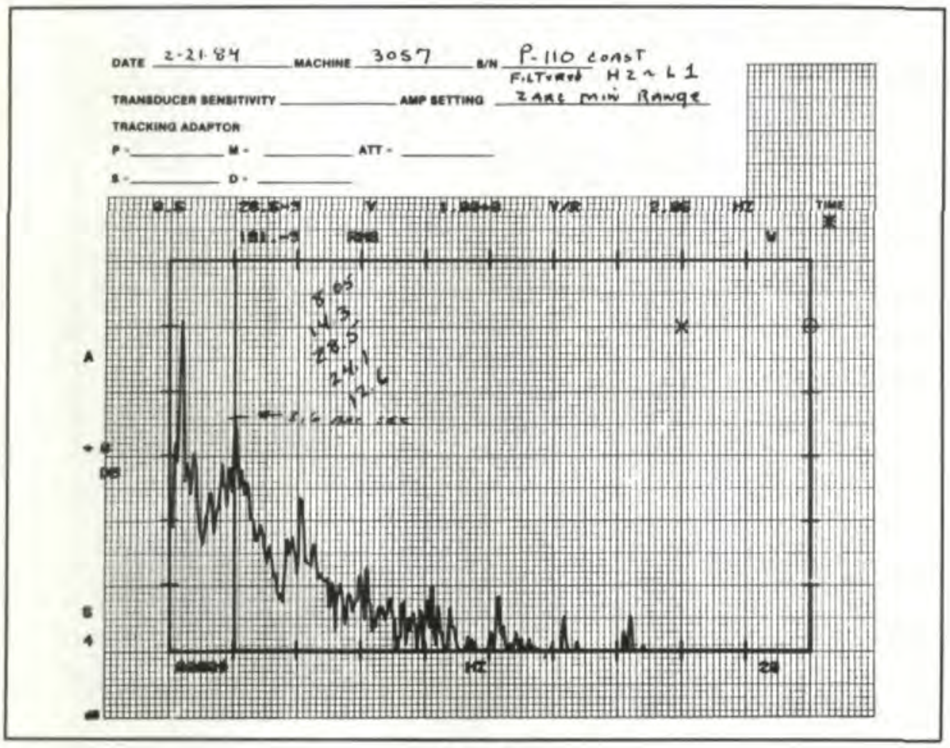


Fig. 14

of other gears or shafts within the drive train.

Case Histories

The following case histories are included to illustrate some of the points discussed above.

1. TYPICAL REAR AXLE NOISE. Fig. 15 shows a set of lapped hypoid rear axle gears. They show the typical parabolic shaped effective profile error, but of an excessive amplitude (.00035″). They were rejected in the vehicle for several "noise periods". This is evident from the content of higher harmonic amplitudes.
2. NOISE-THERMAL DEFLECTION. This case illustrates an unusual situation. They are hypoid gears used in a rear axle, but the housing is made of aluminum. Tests were run on a good set and a reject set. Both sets looked good at the build position. However, it had been previously determined that the pinion moved plus .004″ on pinion cone, at the elevated operating temperature. It was shown that the reject pair got worse at the thermally deflected position, but the good set actually improved. (See Fig. 16)
3. NOISE-CONJUGACY VS. ACCURACY. Fig. 17 is used to illustrate the fact that accuracy isn't necessary for noise control. It shows a lapped hypoid pair of gears with a relatively large total transmission error from accumulated pitch and bolt hole distortions, but with a very low tooth to tooth transmission error (less than .0001″). This was a quiet pair in the axle. The other pair was an experimental ground pair with very low total transmission error, but with a very regular high tooth to tooth error (.0002″). This pair was noisy in the vehicle at 1st and 4th harmonics of mesh frequency. It had a small amplitude of waviness superimposed on the tooth to tooth waveform that caused the 4th harmonic ghost noise. In this case, the vehicle was a van type, which is typically sensitive to excitation due to structural dynamics.
4. *PRECISION GROUND HELICAL* GEARS. A first look at the analog graphs (Fig. 18A and 18B) of these two sets might lead to the wrong conclusion. Spectral analysis, however, points out that the first set (Fig. 18A) is very conjugate (hardly any discernable peaks in the data). The spectrum of the second set (Fig. 18B) shows a high 2nd harmonic relative to the 1st. Remember, that these measurements are of angular displacement. If the data were double differentiated, it would represent angular acceleration which is proportional to force and would be more indicative of noise potential. The acceleration goes up by the square of the frequency. This high 2nd harmonic was difficult to identify by interpretation of the involute charts, but is easily discernable by single flank measurement.
5. GROUND AIRCRAFT SPUR GEARS-HIGH RPM. Although the major concern is not noise, because of high altitude operation, the gear producer was experiencing dynamic loading conditions that were excessive. Strain gaged data had shown this. The single flank tests, especially the spectral data, readily showed a high 2nd harmonic of mesh amplitude that coincided with their strain gage

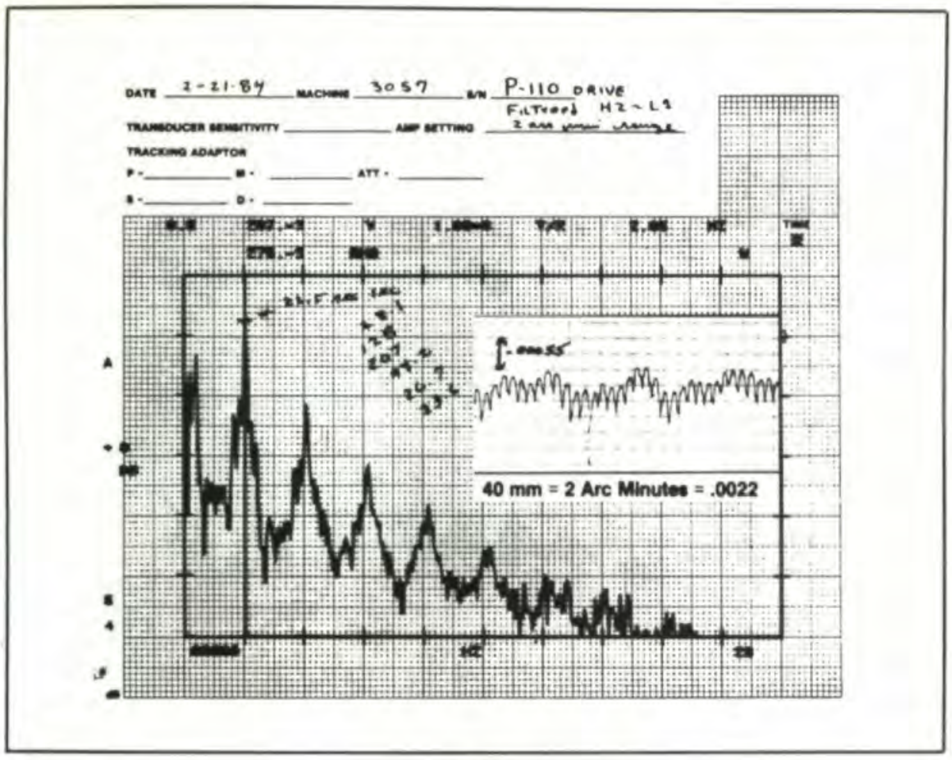
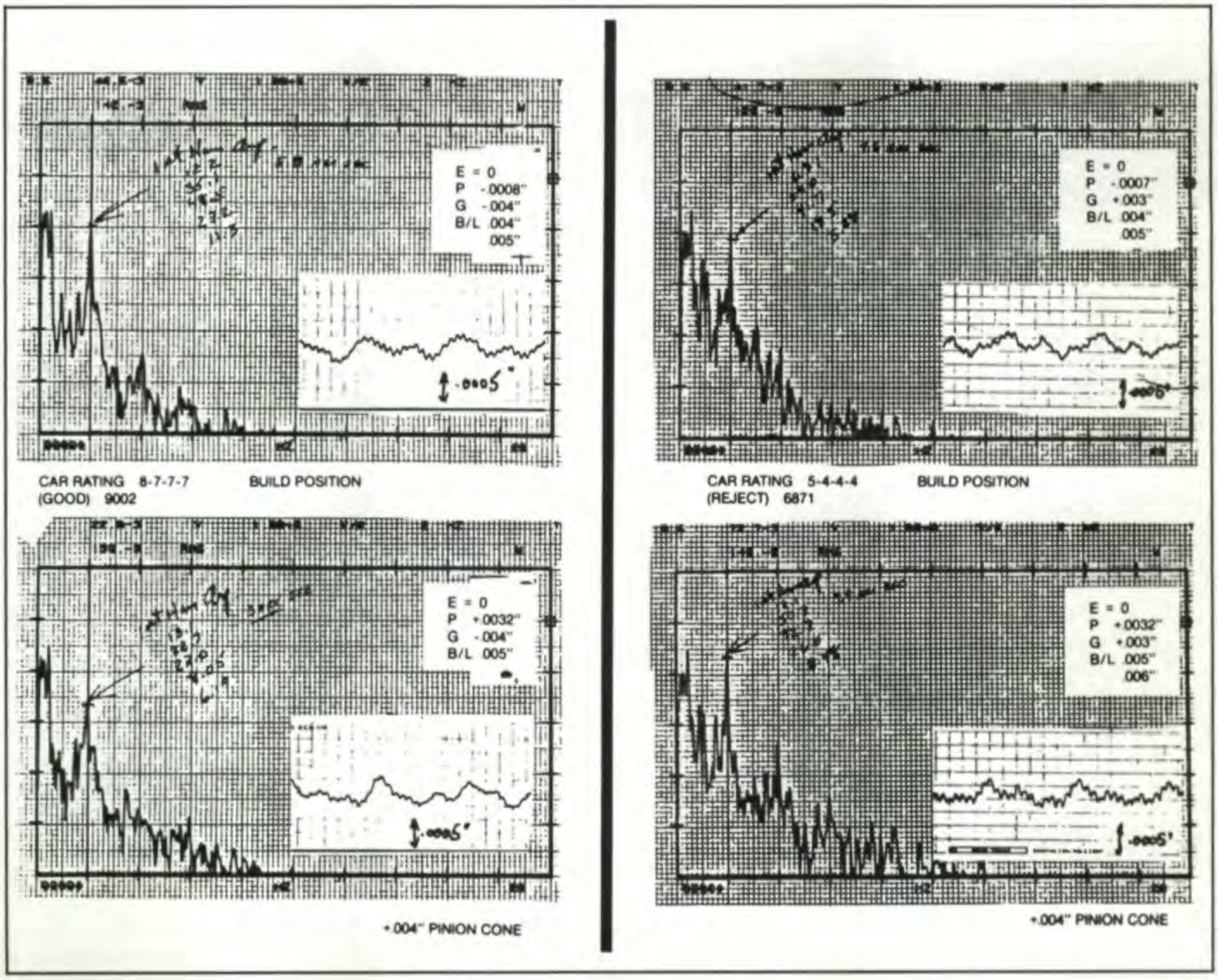


Fig. 15

data. Again, it had been difficult to find the problem with elemental tests such as involute checks (Fig. 19).

6. GHOST NOISE. Fig. 20 shows data taken from an internal helical used in the transaxle of a front wheel drive vehicle. Sound tests of an operating vehicle had detected "ghost" noise at the 1.7th harmonic of gear mesh. The gear had been marked with the number of the gear shaper that produced it. Further tests found other gears from the same shaper as well as others with the same problem. A series of gears were cut, one from each shaper using the same cutting tool and workholding equipment. They were all single flank tested with a master gear and the spectral data was checked for existence of this "ghost" harmonic. The offending machines were identified from the single flank data. A second "ghost"

Figure 16 – below



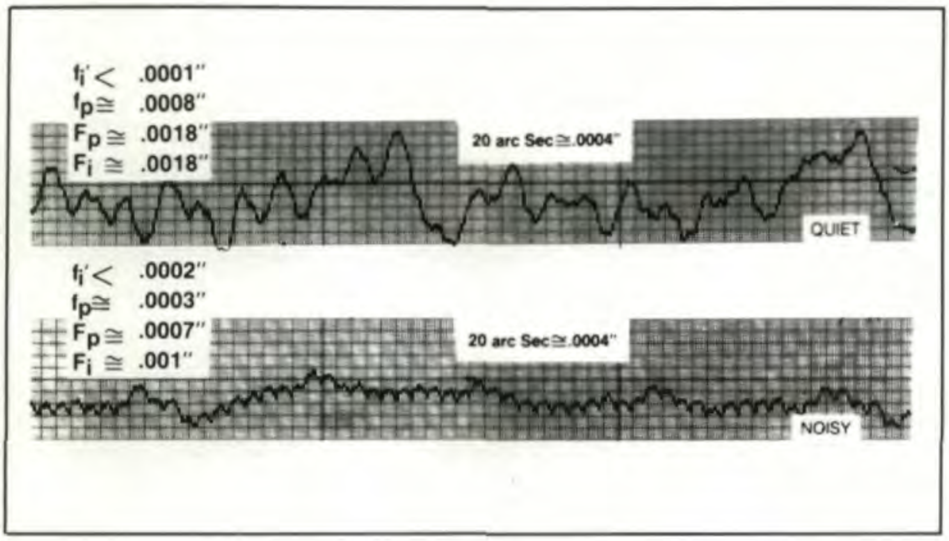


Fig. 17

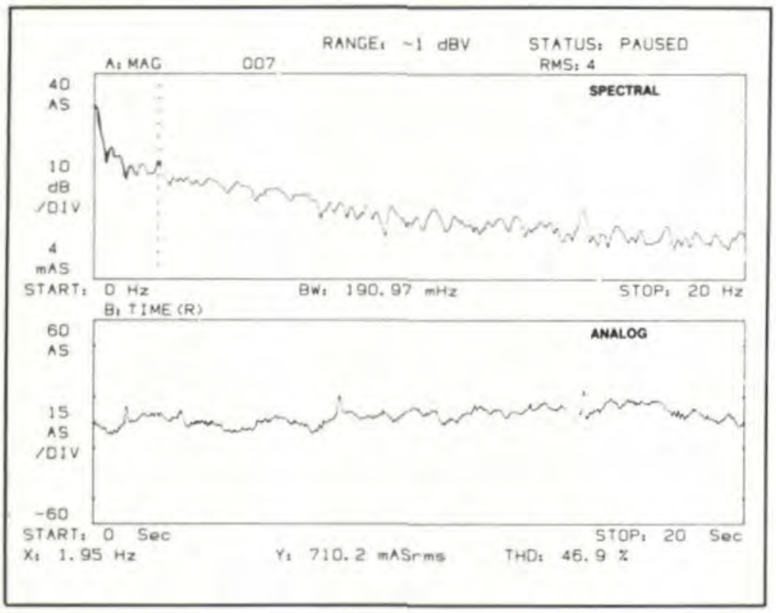


Fig. 18A

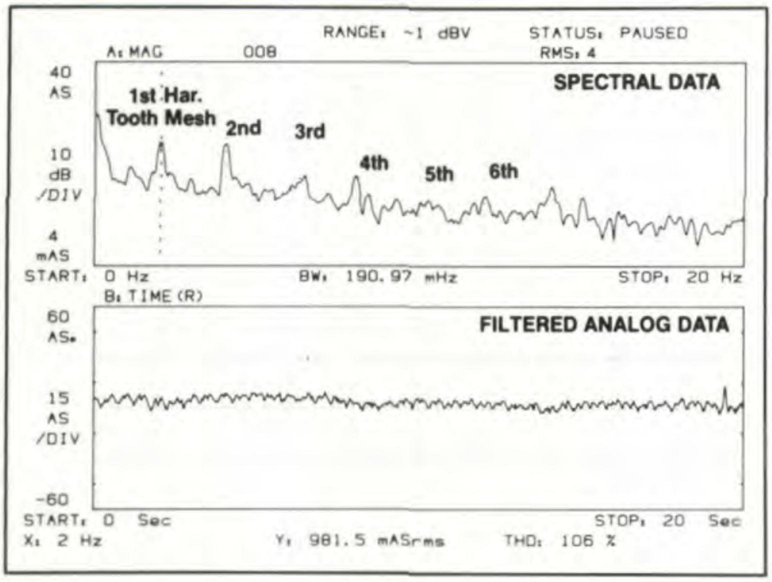


Fig. 18B

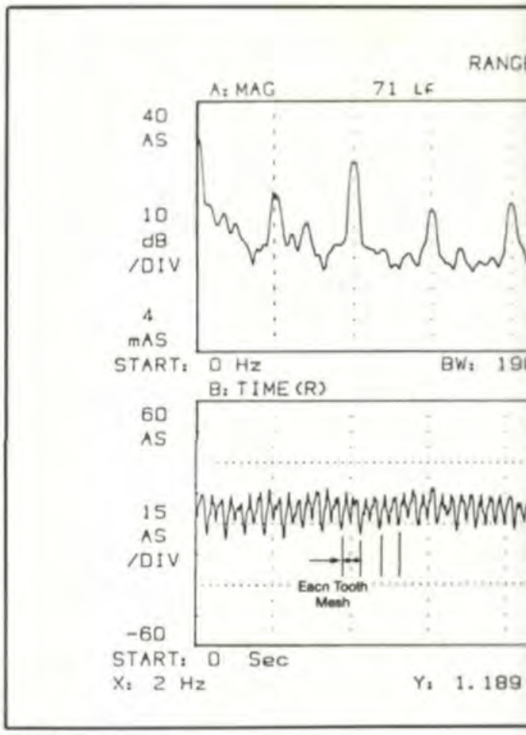
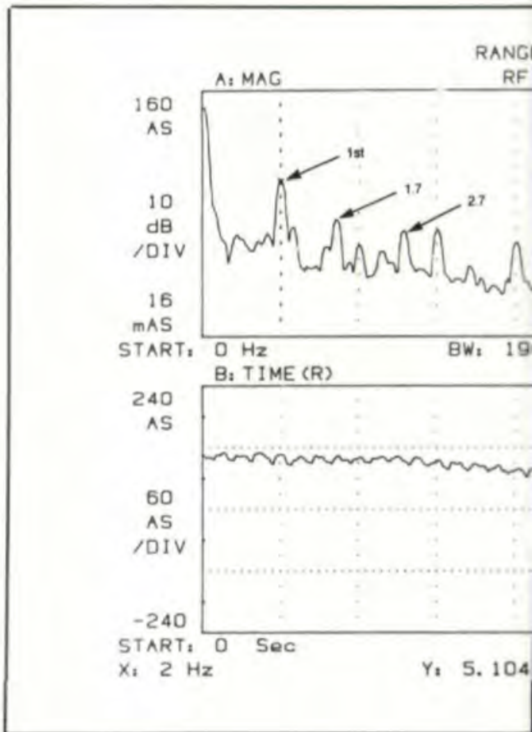


Fig. 19



harmonic was also found at the 2.7th harmonic.

An analysis of the gear train in the shaper showed that the 1.7th harmonic was from the tooth mesh frequency of the table drive worm and wheel, and the 2.7th harmonic was from the tooth mesh frequency of the cutter drive worm and wheel.

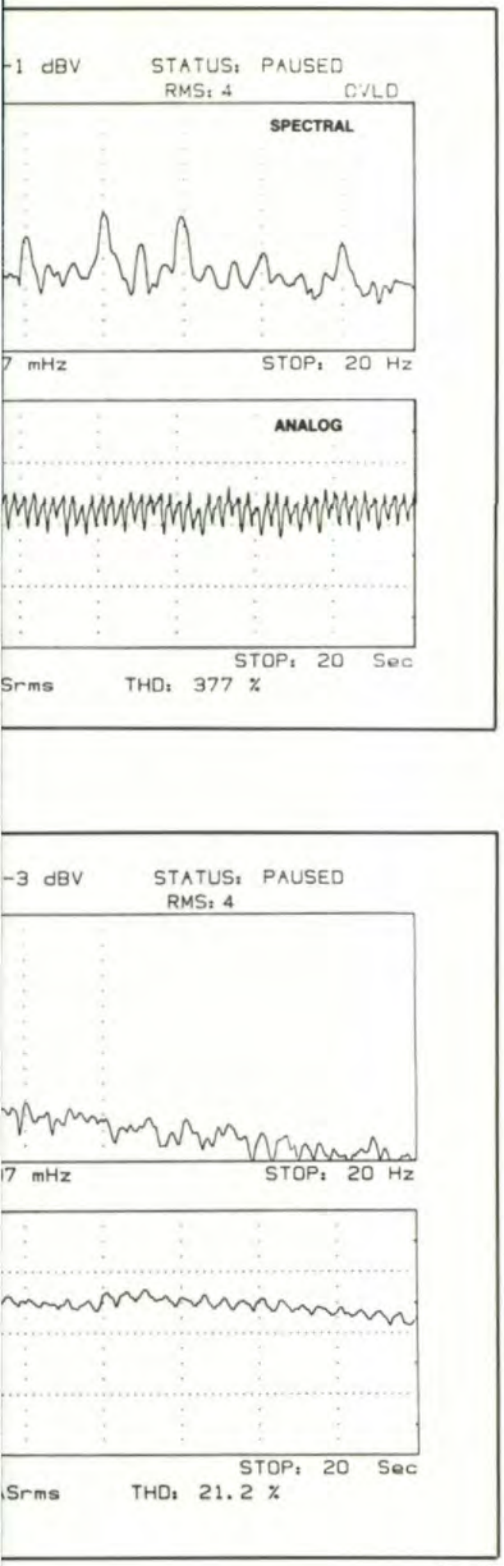


Fig. 20

Conclusions

Gear noise is a very complex subject, as can be seen in this information. This article does not pretend to cover all aspects of it. However, it is hoped that it will help the users of single flank equipment bring gear manufacturing out of the state of being a "black art."

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Selection of Material and Compatible Heat Treatments for Gearing

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Introduction

The manufacturing process to produce a gear essentially consists of; material selection, blank preshaping, tooth shaping, heat treatment, and final shaping. Only by carefully integrating of the various operations into a complete manufacturing system can an optimum gear be obtained. The final application of the gear will determine what strength characteristics will be required which subsequently determine the material and heat treatments. The following discussion will encompass the various heat treating procedures and will establish some basic guidelines for selection of the proper materials and process.

In general, the most common material used in gear manufacturing is steel. This type of gearing usually carries appreciable loads and the majority requires some type of subsequent heat treatment. Gears that are moderately loaded or where size and weight are of little consideration can be made of high quality cast iron. Gearing for special applications such as; corrosion resistance, electrical or magnetic properties, etc. will use a stainless steel, brass, bronze, plastic or phenolic materials.

Therefore, since the largest percentage of gears are made of steel, it seems applicable to concentrate this discussion on the selection of ferrous heat treatments and its application to gears.

The exploration of some definitions of heat treating processes from the fundamental and practical viewpoints will be expanded upon. Fundamentally, the phenomonen of heat treatment is the application of a controlled heating and cooling cycle to alter the material's physical properties to a desired characteristic. The material may be altered into a very soft, ductile state or on the other hand to a very hard, wear-resistance condition.

Selection Criteria

The choice of a proper material for a specific gear application is a very complex selection. The considerations of chemical composition, mechanical properties, processing attributes, and cost must all be included to make a final determination of the type of material to be used. To aid in this decision making process the final desired strength characteristics should be examined. Table I summarizes types of materials, various heat treatments, hardnesses rendered, and endurance limits as related to gear bending and contact stresses. As can be seen, case hardening heat treatments (carburizing, nitriding, or carbo-nitriding) render relatively high contract stresses and yield excellent bending strengths. This can be expanded upon if the geometry of a gear tooth is examined. Case hardening processes depend upon diffusion and therefore, where the high load bearing area or at the pitchline, the diffusion will go straight in. However, in the root area the diffusion will be outward and will result in somewhat less case than the pitchline thus increasing its bending capacity. It should be noted that the top of the tooth will have the heaviest case because the diffusion is inward.

In reviewing Table I, the harden and tempered materials, depending on the treatment, contact stresses in the range 95000 psi to 190000 psi and bending stresses of 13500 psi to 25000 psi, respectively can be obtained. It should be noted that the category of flame or induction hardening assumes the root area is not hardened for calculation and illustration purposes. However, in fact, these processes are selective hardening procedures and any desired hardness pattern can be achieved.

As pointed out earlier, there are many gears made of case iron, and heat treated to respected properties. In Table II the various types of cast irons, preliminary treatments, respected hardness ranges, types of applications, and secondary heat treatments are outlined. The important fact to remember is that the final hardnesses obtained are dependent on preliminary heat treatments and actual chemistries and resultant as-cast microstructures.

To further expand the selection criteria, it is important to have a perspective of what each type of treatment outlined in Table I costs. Because each gear design will require some type of special handling, and the fact of volume of produc-

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TABLE I

Steels, Heat Treatment, Endurance Limits

MATERIALS		HEAT TREATMENT	MINIMUM HARDNESS		ENDURANCE LIM.	
TYPE	AISI CODE		BHN	Rc	BEND psi.	CONTACT psi.
low—carbon steel .30%	10— 45— 11— 46— 15— 48— 25— 50— 33— 61— 41— 86— 43— 87— 44— 93—	carburized	614	60	30000	250000
			547	55	27500	200000
mild-carbon steel .3% .6%	11— 10— 41— 87— 43— 92— 46— 98— 61—	flame induction harden (unharden root fillet)	484	50	13500	190000
mild-carbon steel .3% .6%	(see above)	harden and temper	440	45	25000	190000
			300	33	19000	135000
			180	(8)	13500	95000
mild-carbon steel	41— 43— 46—	nitrided (300BHN core)	614	60	22000	160000
spec. nitride steel	64— nitralloy 125, 135, N, EZ					
stain-less steel	200 300 (malcolmize) 400	nitrided (250BHN core)	484	50	20500	130000
low-carbon steel	(carburizing grades)	carbo-nitride	614	60	26200	190000

tion will determine greatly on the actual cost, a rating system for basic cost understanding seems appropriate.

Table III, below, takes the five processes and rates each on a scale of 1 to 5, where 1 is less expensive and 5 is the most expensive.

It should be noted, Table III assumes that the processes class I-IV are a batch-type process and class V processes are labor intensive for low volume production.

To aid in the understanding of specific details of the various processes mentioned, the appendix includes a glossary of metallurgical terms and a summary of the series designations of the type of steels mentioned.

Hardening and Tempering

Gears made of steel can be hardened by the simple expedient of heating to above the critical temperature (Ac_3 transformation) holding long enough to insure the attainment of uniform temperature and solution of carbon in the austenite, and then cooling rapidly (quenching). Complete hardening depends on cooling so rapidly that the austenite, which otherwise would decompose on slow cooling, is maintained to relatively low temperatures. When this is accomplished, the austenite transforms to martensite on cooling through the Ms-Mf range. Rapid cooling is necessary only to the extent of lowering the temperature of the steel to well below any upper critical transformation points. Once this has been accomplished, slow cooling from then on can be employed to aid in avoiding excessive distortion or cracking. As quenched, the steel in a martensitic state is quite brittle and is rarely used without subsequent tempering. Tempering is the process of reheating hardened (martensitic) steels to some temperature below the lower critical. The tempering temperature depends upon the desired properties and the purpose for which the gear is to be used. If considerable hardness is necessary, the tempering temperature should be low;

TABLE II

CAST IRONS & RESPECTED HEAT TREATMENTS

TYPE	CLASS OR GRADE	HEAT TREATMENT	Hdn. (BHN)	APPLICATIONS	*SELECTIVE HEAT TREATMENT	Hdn. ( )
Malleable Iron	M3210 M4504 M5003	Air quench Temper	156 241	Transmission gears, Crank-shaft sections	Nitride Flame Induction	50 ↕ 60
	M5503 M7003 M8501	Liquid quench temper	187 302	High Strength wear resist Gears	Flame Induction	50 ↕ 60
Gray & White Iron	30 meehanite 40 Gunite 50 Ermalite 60 Ferro-steel Guniron	Normalized	Tube deter-mined by strength Proper-ties	Medium gear blanks - Large gear blanks	Flame Induction	50 ↕ 60
Duccile (Nodular) Iron DQ & T	80-55-06 120-90-02 D-7003 Quench &	Normalized Quench & Temper Normalized Specified Temper	As per TS Ys As per Ts Ys 241/302 Range	Gears, Pinions	Flame Induction	50 ↕ 60

* The surface hardness results obtained in selective hardening are dependent on preliminary heat treatments and actual chemistries of the castings.

if considerable toughness is required, the tempering temperature should be high.

TABLE III
PROCESS AND COST CLASS

Cost Class	Process
I	Harden & Temper (preliminary treatments included)
II	Carburizing
III	Carbo-nitriding
IV	Nitriding
V	Selective Hardening (Flame, Induction, Electron Beam, Laser)

The maximum hardness that can be obtained in completely hardened low alloy and plain carbon structural steels depends primarily on the carbon content. The relationship of maximum hardness to carbon content is shown in Fig. 1. As can be seen, the limitations of this process will restrict the final combination of physical properties that can be achieved (See Table I for steel designations and respective properties). Normally the hardening and tempering procedures are limited to steels with greater than .35% carbon contents for gearing applications.

Case-Hardening

Case hardening is a process of hardening a ferrous alloy so that the surface layer or case is made substantially harder than the interior or core. The chemical composition of the surface layer is altered during the treatment by the addition of carbon, nitrogen, or both. The case depths obtained can be designated in two distinctive ways; (1) Total Case Depth is the approximate total depth of carbon or nitrogen penetration, (2) Effective Case Depth relates to depth below the surface at which a specified hardness, or carbon, or nitrogen

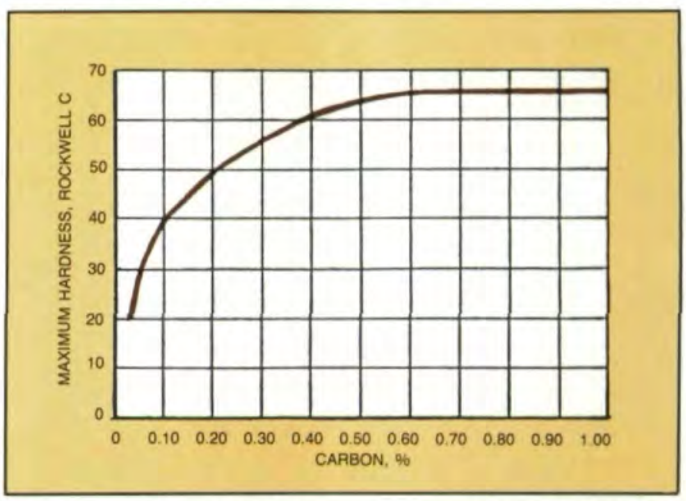


Fig. 1 – Burn, Moore, & Archer, Trans Am. Soc. Metal 3-26, 14 (1938)

content occurs (generally a specified effective hardness is 50 Rockwell "C").

a) Carburizing –

Carburizing is a process that introduces carbon into a solid ferrous alloy by heating the metal in contact with a carbonaceous atmosphere to a temperature above the Ac of the steel and holding at that temperature. The depth of penetration of carbon is dependent on temperature, time at temperature, and the composition of the carburizing agent. The operating temperatures range from 1500°F to 1800°F, and the time of the cycle range from minimum of 1 hour to 30 hours to develop .010" to .120" of total case depth. The actual cycle will depend on the parts characteristics and type of furnace equipment used. After carburizing, the steel will have a high carbon case (greater than .80% but less than 1.10%) graduating into the low-carbon core.

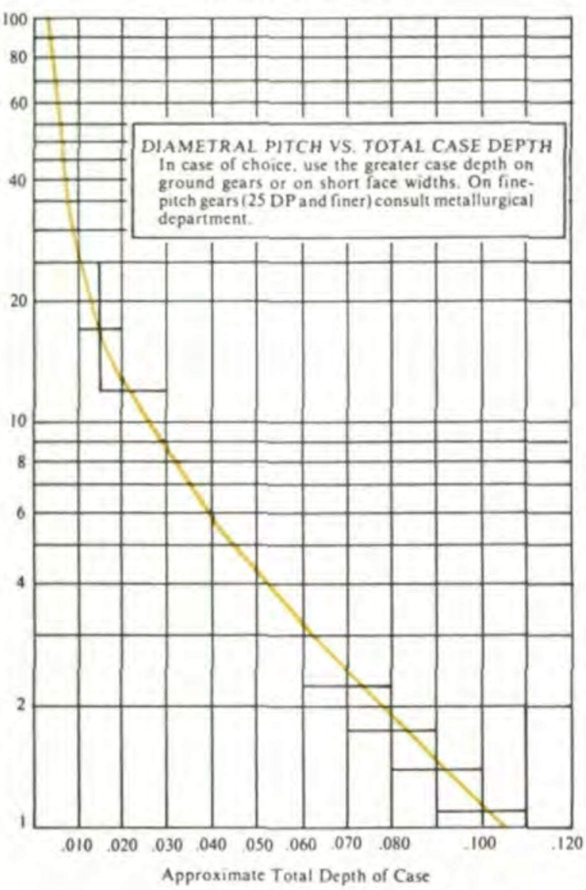
The graphs 1, 2, and 3 can be used for design aids when specifying a case depth for a specific gear. Note that Graph 1 references bevel gear diametral pitch versus total case depth to achieve overall strength characteristics. Whereas, Graphs 2 & 3 are more general for all types of gearing (both parallel axis and bevel) *referencing the effective case depth to* minimize case crushing and pitting.

A variety of heat treatments may be used subsequent to carburizing, but all of them involve quenching the gear to harden the carburized surface layer. The most simple treatment consists of quenching steel directly from the carburizing cycle; this treatment hardens both the case and core. Another simple treatment, and perhaps the one most frequently used, consists of slow cooling from the carburizing cycle, reheating to above the Ac_3 of the case and quenching; this treatment hardens the case only. A more complex treatment is to double quench first from above Ac_3 of the core and then from above the Ac_3 of case; this treatment refines the core and hardens the case. The plain carbon steels are almost always quenched in water or brine; the alloy steels are usually quenched in oil or equivalent synethic solutions. Although tempering, following hardening of carburized steel is sometimes omitted; a low-temperature tempering treatment at about 300°F is a good practice. Also is the dimensional stability, or a sub-zero exposure application is required, a cyrogenic cycle of 150°F should be implemented to assure full austenitic transformation, and a low temperature temper should follow.

Because of the complex design of gear, it may be desirable to carburize only certain areas. This can be accomplished by covering the surface with a media that prevents the passage of carburizing agent. This can be effectively done by copper

GRAPH 1

DESIGN CHART NO. 8

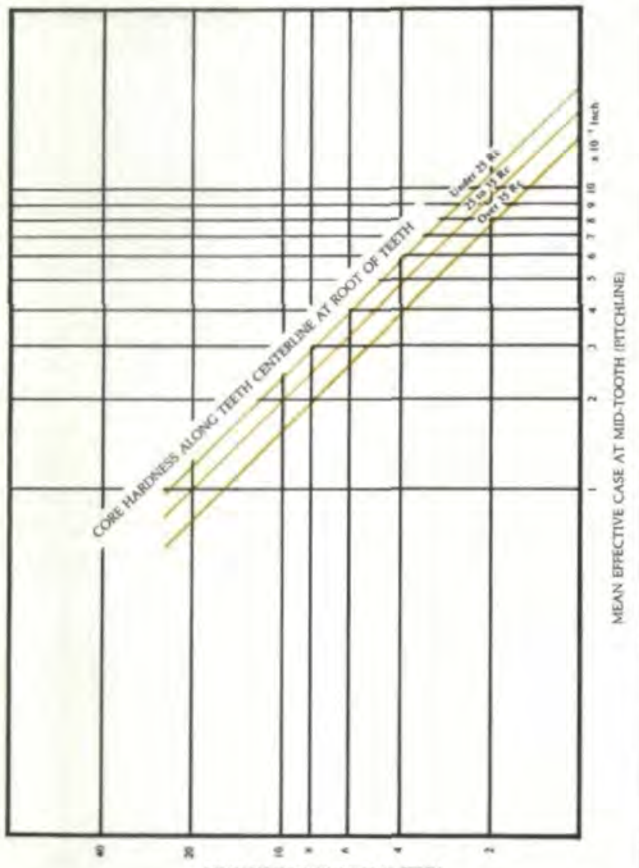


Approximate Total Depth of Case

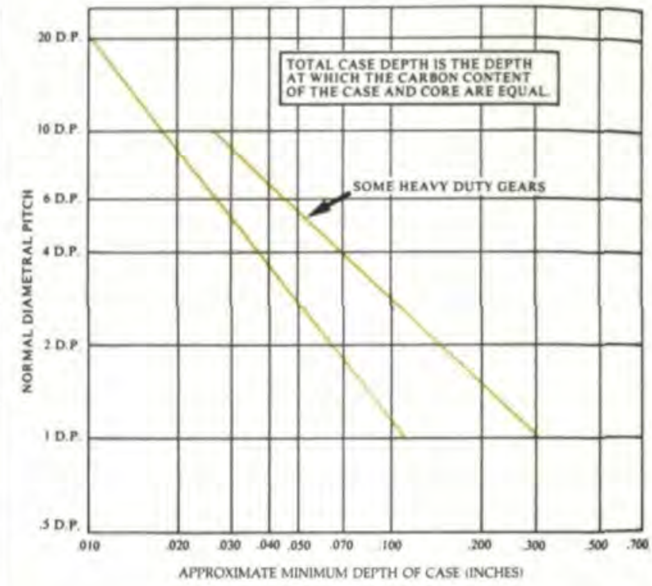
Diametral Pitch vs. Total Case Depth

*Data supplied by Gleason Works, Rochester, NY

GRAPH 2



GRAPH 3



plating, or there are several proprietary solutions or pastes that can cover the area to remain soft after carburizing and hardening. It is also possible to design the part with a false section thicker than the case depth and have it machined off before hardening, to guarantee an area to be soft. Table III summarizes the various carburizing grades of steels and their respected processing cycles.

b) Nitriding –

The nitriding process consists of the subjecting machined and preheat treated steel gears (core properties), to the action of a nitrogenous medium, usually ammonia gas, at a temperature of about 950°F to 1050°F to form a very hard surface. The surface-hardening effect is due to the absorption of nitrogen and subsequent heat treatment of the steel is unnecessary. The time required is relatively long, normally being one to two days. The case (total), even after two days of nitriding, is generally less than .020 inch and the highest hardness exists in surface layers to a depth of only a few thousandths of an inch.

Special low-alloy steels have been developed for nitriding. (See Table I) These steels contain elements that readily combine with nitrogen to form nitrides, the most favorable being aluminum, chromium, and vanadium. The carbon contents are usually between .20% to .50%, although in some instances higher carbon contents are used where higher core hardness are required. Stainless Steels also can be nitrided.

Because nitriding is carried out at a relatively low temperature, it is advantageous to use hardened, quenched and tempered steel as the vase material. Note, the steel should be tempered at a temperature higher than the nitriding temperature to assure no alteration of the established core properties. The resultant nitrided gear will have a strong, tough core with an intensely hard wear resisting case, usually much harder than what can be obtained by quench hardening carburize gears.

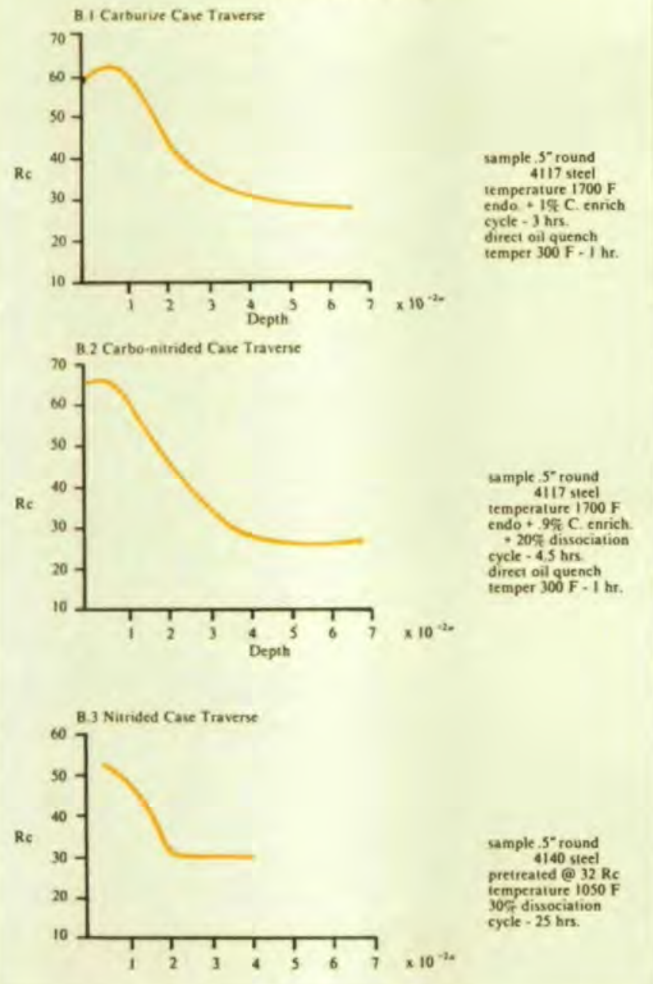
As in carburizing, selected areas can be stopped off to nitriding by tin, copper, bronze plating, or by the application of certain proprietary paints.

c) Carbonitriding –

Carbonitriding, also termed gas cyaniding, dry cyaniding, and nitrocarburizing is a process for case hardening a gear in a gas-carburizing atmosphere that contains ammonia in controlled percentages. A hard, superficial case can be obtained with introduction of nitrogen and carbon into the surface layers of the steel. The process is carried on above the Ac_1 temperature of the steel, and is practical up to 1700°F. The maximum case depth is rarely more than about .030 inch and the average depth is considerably less. Quenching in oil is sufficiently fast to attain maximum surface hardness; this moderate rate of cooling tend to minimize distortion. The process is applicable for plain carbon steels when higher hardness and distortion control is desirable. Also, for applications where the case is expected to highly abrasive wear conditions.

The same stop off procedures for selective carburizing or nitriding are applicable. In Schematic A, the graphs show the effect of carburizing, carbonitriding and nitriding of an 41xx series alloy steel and the comparable hardness gradients obtained.

SCHEMATIC A



d) Case Hardening Distortions –

Distortion is always a problem in all heat treating processes, and its reduction or elimination is a very important factor in the manufacture of precision gears. There are two types of distortions which occur in gears. One is body distortion, which for gears is gauged in terms of out of round, out of flat, or runout. The second is the change of tooth slope or contact pattern.

In carburizing the distortion is the greatest because of the high volumetric changes that occur and severity of the quenching media used. Part fixturing in the heating cycle, quenching media cooling rate control, and controlled reheating and quenching can be implemented to aid in control distortions. Another alternative is mechanical die quenching to round up and flatten the hot plastic gear. The change in tooth shape is minimized by control of the variables which cause these changes. These variables are grain directionally, pre-treatments prior to carburizing materials hardenability, case depth and carbon control. If all of these variables are closing controlled, uniform results can be obtained and minor manufacturing changes can compensate for what distortion that does occur.

Because nitriding is a relatively low temperature process and warpage is not a problem. However, the surface of the steel will increase slightly in size during this treatment. Allowance can be made for the growth in the finished gear.

In carbonitriding the distortions are less than carburizing because of the relatively somewhat less case depth and severity of the quench for equivalent hardnesses.

Selective Surface Hardening

It is frequently desirable to harden only the surface of ferrous alloys without altering the chemical composition of the surface layers. If a steel has sufficient carbon to respond to hardening, it is possible to harden the surface layers only by very rapid heating for a short period, thus conditioning the surface for hardening by quenching. The desirable characteristic is that the only distortion that is contended with, is within the hardened area. Any type of hardenable steel can be selectively surface hardened. For best results, the carbon content should be at least 0.35%, the usual range being 0.40% to 0.60%. Cast Irons also can be surface hardening. (See Tables I and II) Since selective surface hardening has no effect on the core, it is absolutely essential that required core strength be established and a desirable microstructure that will respond in the short time duration be obtained.

a) Induction Hardening –

In induction hardening, a high-frequency current is passed through a coil surrounding the gear, the mechanism of electromagnetic induction is used for heating the surface. The depth to which the heated zone extends depends on the frequency of the current, and on the duration of the heating cycle. The proper heating cycle is surprisingly brief, usually a matter of a few seconds or minutes. The selective hardness pattern is accomplished by suitable design of the coils or inductor blocks. The gear is immediately quenched either by inline spray systems, or submerged tanks. Precise methods for controlling the operation, that is, rate of energy input, duration of heating, and rate of cooling, are necessary. The macrograph, in Fig. 2, illustrates the hardening pattern of a fine pitch gear.

Induction hardening equipment usually incorporates all of the above controls into an automatic operation. That is why the process lends itself economically to high volume work instead of small piece lots.

b) Flame Hardening –

Gears in larger sizes are usually flame hardened. Flame hardening is a process of using gas flames to impinge directly on the selected surface and heat to a suitable temperature before direct quenching. The rate of heating is very rapid, although not as fast as induction hardening. The flame hardening of gears will require some special fixtures or equipment to hold the burners in the proper location and the control of the heat pattern may be somewhat variable. This process is labor intensive and is not practical for high volume production.

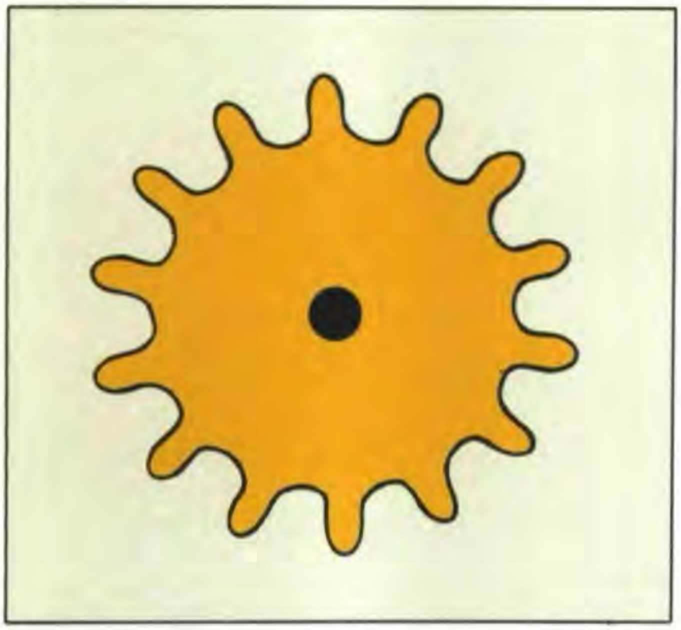


Fig. 2—(Photograph reduced, original size 4", diameter 4% Nital Etch.)

New Technology and Special-Purpose Treatments

a) Special-Purpose Treatments –

The use of low temperature carbo-nitriding processes (less than 1200°F) have proved beneficial to certain gear applications requiring high-cycle-low load fatigue characteristics. The processes commercially available are called Tufftride, Lindur, and Melonite. Each render a very shallow high wear resistant compound zone (less than .001") with a total diffusion of approximately .030". Because of the very low temperature the distortions become minimal.

b) New Technology –

In the field of selective gear hardening the use of electron beams and lasers have been successfully used to localize, heat the gear tooth in special applications. The state of the art has not rendered itself to the commercial field at the present time.

A relatively new technology, that used physical vapor deposition applied to a nitrided layer, termed ion-nitriding, has become commercially available. The advantages of this type of nitriding are; energy consumption, shortening of cycles as compared to conventional nitriding, and the ease of shielding for selective nitriding. The disadvantages are; relatively costly equipment, and very complex and integrated controls.

Summary

The background material covered here and the interactions described will hopefully allow the reader to do some of his own "gear manufacturing system analysis." For instance, the manufacturing engineer should be able to refer to Table I or II and pick a compatible heat treating process for desired strength characteristics. Then eliminate the processes that inter-relate from the standpoint of cost and distortion restrictions. With this information he should be able to pick a series of materials that are compatible to the heat teatment and further his analysis into other processing attributes for the most desirable material for the gear application.

Obviously, there are many combinations and permutations of the various components of gear manufacturing. Hopefully, it has been shown that the heat treatment process and material selection must be approached in its entirety in order to be optimized.

Appendix

Glossary of Metallurgical Terms

Aging—Aging is a structural change, usually by precipitation, that occurs in some alloys after a preliminary heat treatment or cold working operation. Aging may take place in some alloys at room temperature in moderate time (days) or in others, may be done in shorter time at furnace temperatures. Over-aging may be done at a temperature above normal to produce some desirable modification of physical properties.

Air Hardening Steel—An alloy steel which will form martensite and develop a high hardness when cooled in air from its proper hardening temperature.

Aluminizing—Forming a corrosion and oxidation-resistant coating on a metal by coating with aluminum and usually diffusing to form an aluminum-rich alloy.

Annealing—A very general term describing the heating of metal to a suitable temperature, holding for a suitable time, and cooling at a suitable rate to accomplish the objective of the treatment. Annealing may done to:

A. Relieve stresses
B. Induce softness
C. Improve physical, electrical, or magnetic properties
D. Improve machinability
E. Refine the crystalline structure
F. Remove gases
G. Produce a specific microstructure

Atmosphere—The gaseous environment in which the metal being treated is heated for processing. Atmospheres are used to protect from chemical change or to alter the surface chemistry of steel through the addition or removal of carbon, nitrogen, hydrogen, and oxygen and to add certain metallic elements as chromium, silicon, sulphur, etc.

Austempering—A heat treating operation in which austenite is quenched to and held at a constant temperature (usually between 450°F and 800°F) until transformation to bainite is complete. In some steels at certain hardness levels, bainite is tougher than quenched and tempered structures.

Austenite—Austenite is the name given any solid solution in which gamma iron is the solvent. Austenite is a structure name and means nothing as to composition. Austenite is the structure from which all quenching heat treatments must start.

Austenitizing Temperature—The temperature at which steel is substantially all austenite.

Bainite — The product formed when austenite transforms between 450°F and 900°F. Bainite is an acicular aggregate of ferrite and carbide and varies in hardness between Rc 30 and Rc 55.

Banded Structure — A layering effect that is sometimes developed during the hot rolling of steel.

Bark — An older term used to describe the decarburized skin that develops on steel bars heated in a non-protective atmosphere.

Bright Annealing — Annealing work in a protective atmosphere so that there is no discoloration as the result of heating. In some atmospheres oxides may be reduced.

Brittle Tempering Range — Some hardened steels show an increase in brittleness when tempered in the range of about 450°F to 700°F even though some tempering causes some softening.

Carbonitriding — A heat treatment for steel which adds carbon and nitrogen from an atmosphere rich in such elements.

Carbon Steel — Steel which is essentially iron plus carbon with no intentionally added alloy. Also known as ordinary steel, straight carbon steel, or plain carbon steel.

Carburizing — Adding carbon to the surface of steel by heating it in contact with carbon-rich solids, liquids or gases.

Case — The surface layer of a steel whose composition has been changed by the addition of carbon, nitrogen, chromium, or other material at high temperature.

Case Hardening — A heat treatment in which the surface layer of a steel is made substantially harder than the interior by altering its composition.

Cementite — The common name for iron carbide, Fe_3C, the chemical combination of iron and carbon.

Cold Working — Plastic deformation of a metal at a temperature low enough so that recrystallization does not occur during cooling.

Core — The interior part of a steel whose composition has not been changed in a case hardening operation.

Critical Point — A temperature point at which a structure change either starts, is completed, or both when a material is being heated or cooled.

Critical Range — The temperature range between an upper and lower critical point for given material.

Decarburizing — The process (usually unintentional) of removing carbon from the surface of a steel, usually at high temperature, when in contact with certain types of atmosphere.

Dissociation — The chemical breakdown of a compound into simpler compounds or elements. One of the most common examples is the dissociation of ammonia (NH_3) into nitrogen and hydrogen.

Draw — The common term used interchangeably with Tempering.

Fatigue — Failure by progressive fracture caused by repeated applications or reversals of stress.

Ferrite — Ferrite is the name given any solid solution in which alpha iron is the solvent. Ferrite is strictly a structure name and means nothing as to composition.

Flame Hardening — A process consisting of heating a desired area, usually localized, with an oxyacetylene torch or other type of high temperature flame and then quenching to produce a desired hardness.

Grain Growth — Growth of some grains at the expense of others, resulting in an overall increase in average grain size.

Hardenability — The fundamental characteristic of a steel which determines the ease or preventing the transformation of austenite to anything else but martensite during the quench.

Homogenizing — An annealing treatment at fairly high temperature designed to eliminate or reduce chemical segregation.

Hydrogen Embrittlement — The brittleness induced in steel by the absorption of hydrogen, most commonly from a pickling or plating operation.

Inclusions — Particles of impurities (usually oxides, sulphides, silicates and such) which separate from the liquid steel and are mechanically held during solidification. In some grades of steel, inclusions are made intentionally high to aid machinability.

Induction Hardening — A form of hardening in which the heating is done by induced electrical current.

Interrupted Quench — Stopping the cooling cycle at a predetermined temperature and holding at this temperature for a specific time before cooling to room temperature. Usually done to minimize the likelihood of cracking, or to produce a particular structure in the part.

Isothermal Treatment — A type of treatment in which a part is quenched rapidly down to a given temperature, then held at that temperature until all transformation is complete.

Martempering or Marquenching — Martempering is a form of interrupted quenching in which the steel is quenched rapidly from its hardening temperature to about 450°F, held at 450°F until the temperatuare is uniform, then cooled in air to room temperature. Actual hardening does not occur until the air cooling starts and is accomplished with a minimum temperature differential. Martempering is indicated for low to medium alloy steels when distortion may be a problem.

Martensite — The very hard transformation product which forms austenite when a steel is quenched and cooled below about 450°F. Technically, martensite can be considered to be a supersaturated solution of carbon in tetragonal (distorted cubic) iron. Under the microscope it appears as an acicular or needlelike structure. Hardness of martensite will vary from Rc 30 to Rc 68 depending on the carbon content.

Microstructure — The structure of a metal as revealed at high magnification, usually at 100x and higher.

(continued on page 16)

Generating and Checking Involute Gear Teeth

Fellows Corp.
Springfield, VT

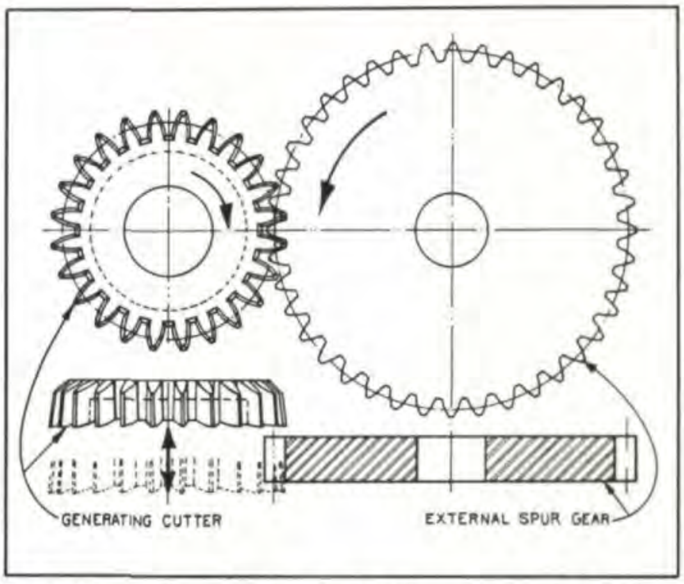


Fig. 1 – Diagram Illustrating That the Gear Shaper Employs the "Molding-Generating" Process for Cutting Gears.

It has previously been demonstrated that one gear of an interchangeable series will rotate with another gear of the same series with proper tooth action. It is, therefore, evident that a tooth curve driven in unison with a mating blank, will "generate" in the latter the proper tooth curve to mesh with itself. Similarly, a gear, which is made up of a series of tooth curves, is capable of "generating" in a blank a corresponding series of tooth curves, suitable for meshing with itself. This method of tooth "generation" is known as the "molding-generating" process, which will be more fully explained in the following pages.

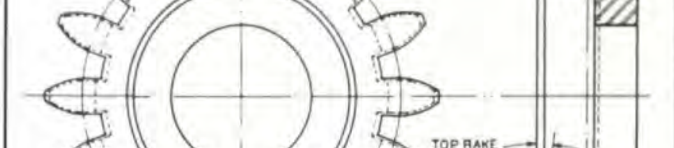
The "Molding-Generating" Process

It is, therefore, evident that if one gear is provided with suitable cutting clearances on the teeth and is hardened, it can be used as a generating tool. If this tool is rotated in the correct ratio with a gear blank, and at the same time is reciprocated, it will generate teeth in the blank suitable for meshing with itself, or with another gear of a corresponding series. This, basically, is the principle upon which the Gear Shaper operates, as is indicated diagrammatically in Fig. 1.

The Gear Shaper Cutter

Fig. 2 shows a Gear Shaper cutter designed for cutting spur gear teeth. It will be noted that cutting clearances are provided both on the ends and sides of the teeth. It has the appearance of, but is not a bevel gear; the reason being that the sides of the teeth are developed, or ground from a common base circle, so that the involute profile extends along the whole length of the tooth from the front face to the back of the cutter. The teeth are simply thinner at the back than at the front or cutting face. They are shortened to correspond with the reduction in thickness, by beveling the outside diameter of the cutter. This enables the cutter to cut the required width of tooth space as the cutter teeth are reduced in thickness by repeated resharpening. As the cutter is ground

Fig. 2 – The Gear Shaper Cutter for Cutting Spur Gears, Showing That It Has Cutting Clearances, but Does Not Change in Shape as It Is Ground Back by Re-sharpening.



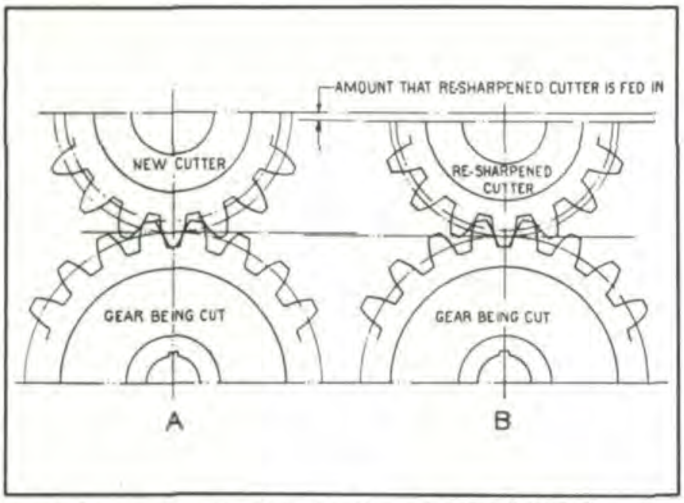


Fig. 3 – Diagram Showing a New Gear Shaper Cutter in Mesh with a Gear, and the Same Cutter after Repeated Re-sharpening in Correct Mesh with the Same Gear.

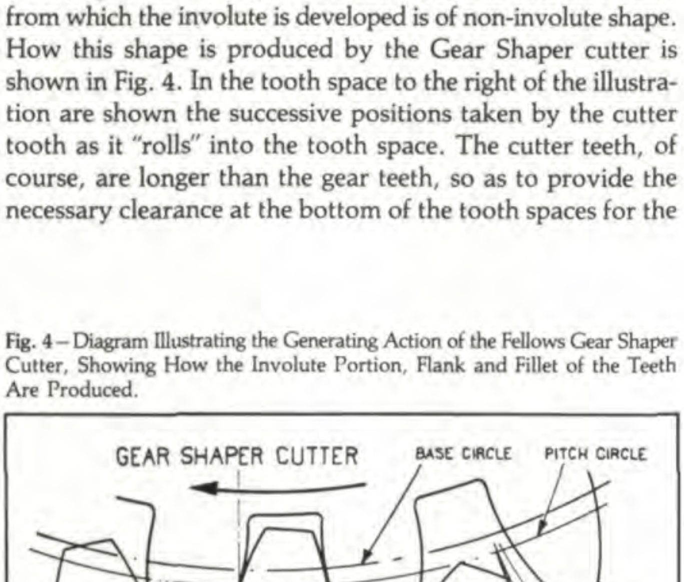
back, thus thinning the teeth, the center distance between cutter and work is decreased.

This condition is illustrated in Fig. 3. Here at *A* a "new" cutter is shown in mesh with a gear, the teeth of which have been generated by the cutter. At *B*, the same cutter, is shown in mesh with the same gear, but the teeth on the cutter have been reduced in thickness by repeated resharpening. The only change in these two illustrations is in the center distance of cutter and gear. Since the base circle of the cutter has not been changed by reducing the thickness of the teeth, it will, of course, produce teeth of the same shape as before.

Generating Flank and Fillet

That portion of a gear tooth lying inside the base circle from which the involute is developed is of non-involute shape. How this shape is produced by the Gear Shaper cutter is shown in Fig. 4. In the tooth space to the right of the illustration are shown the successive positions taken by the cutter tooth as it "rolls" into the tooth space. The cutter teeth, of course, are longer than the gear teeth, so as to provide the necessary clearance at the bottom of the tooth spaces for the

Fig. 4 – Diagram Illustrating the Generating Action of the Fellows Gear Shaper Cutter, Showing How the Involute Portion, Flank and Fillet of the Teeth Are Produced.



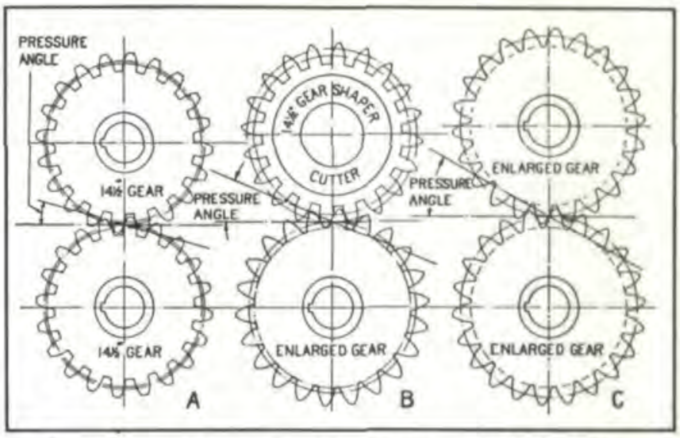


Fig. 5 – Diagram Illustrating Two "Standard" Gears in Mesh. A Cutter in Mesh with an Oversize Gear, and Two Oversize Gears in Mesh Which Have Been Cut with the Same Cutter.

mating gear. This illustration also indicates the nature of the chip taken by the Gear Shaper cutter, the heaviest portion of the chip, after reaching full depth, being in the flank and fillet, and the lightest chip on the involute portion of the tooth, thus assuring a fine finish.

Cutting Different Pressure Angles With the Same Cutter

The pitch circles and pressure angle are variable quantities depending on variations in the center distance. This is illustrated diagrammatically in Fig. 5. At *A* are shown two 20-tooth "standard" 14½° pressure angle gears, in mesh with each other at "standard" center distance. Both gears have been cut with the same Gear Shaper cutter, and, therefore, have the same tooth profiles.

At *B* is shown a 14½° pressure angle Gear Shaper cutter in mesh with a 20-tooth gear. The size of the blank, however, has been enlarged and is suitable for a 22, instead of a 20-tooth gear. It will be noted that there is no change in the base circle diameter of this gear, but the center distance between cutter and gear has been increased over that shown at *A*. Therefore, the generating pressure angle between gear and cutter has been increased, and a new pitch point has located the pitch circle of the gear farther out towards the ends of the cutter teeth.

At *C*, two of these enlarged gears are shown in mesh with each other. The base circles are the same as before, but the center distance has been increased, thus establishing a new and greater operating pressure angle. Now these two gears were cut with the same cutter and, hence, have the same tooth profiles. All of the other elements – pitch circles, pressure angle, etc., have changed due to the increase in the center distance.

Note, however, that the base circle once established never changes. The diameter of the base circle of the cutter is in the same ratio to the diameter of the base circle of the gear cut, as the number of teeth in the cutter is to the number of teeth in the gear. Hence, the base circle will remain fixed, no matter how the pitch diameter, pressure angle, outside diameter, etc., vary.

The Gear Shaper Cutter and Interference

Interference in involute gearing can be corrected, in cut-

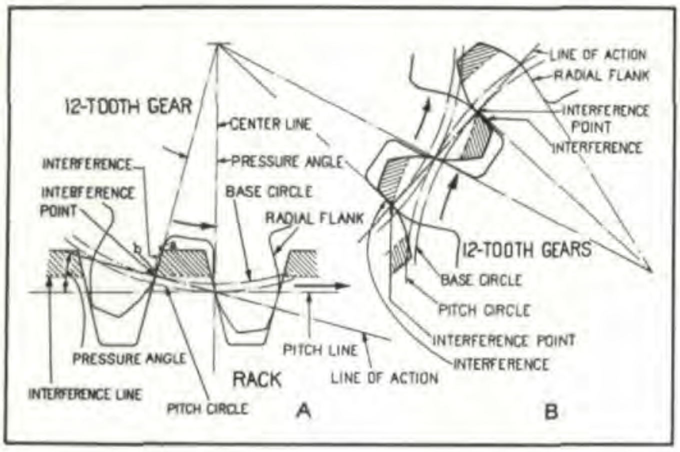


Fig. 6 – Diagram Showing How an Unmodified Rack Tooth Interferes with a 12-Tooth Pinion; Also Interference between Two Unmodified 12-Tooth Pinions.

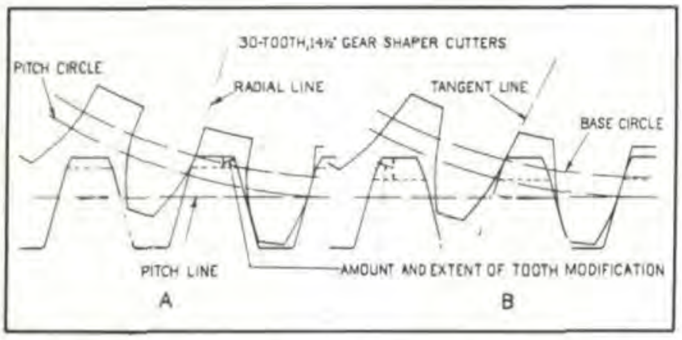


Fig. 7 – Diagram Illustrating How the Gear Shaper Cutter Can Be Made to Modify a Rack Tooth so as to Avoid Interference with a Mating Gear.

ting, by the Gear Shaper cutter. At *A* in Fig. 6 a 12-tooth 14½° degree pressure angle pinion is shown in mesh with a straight-sided rack tooth. It will be noted that the side of the rack tooth cuts into, or overlaps, the radial flank of the pinion tooth, at the point marked "interference." The "path" of the point of the rack tooth is indicated by the line *a-b*. In this particular case, the interference is so great that it extends almost to the pitch circle of the pinion. This interference condition can be avoided by modifying the rack tooth, or by undercutting the flank of the pinion tooth.

This interference is due to the fact that the teeth of a 14½° full-depth rack tooth are too long to permit proper conjugate action, without tooth modification, with a 12-tooth pinion of the same system. The line of contact on the pinion tooth terminates, of course, at the point where it is tangent to the base circle. This tangent point is the "natural" interference point, and no portion of the rack tooth, which extends beyond this point, unless modified, can have proper action with a radial flank 12-tooth pinion.

At *B*, in Fig. 6 two 12-tooth, 14½° full-depth radial-flank pinions are shown in mesh. Here it will be noted that the tooth profiles on both pinions would have to be modified, or the flanks of the pinion teeth undercut, in order to eliminate interference and provide proper tooth action. The extent of the interference in the illustrations at *A* and *B* is indicated by the cross-hatched portions of the teeth.

How the Gear Shaper Cutter Removes Interference

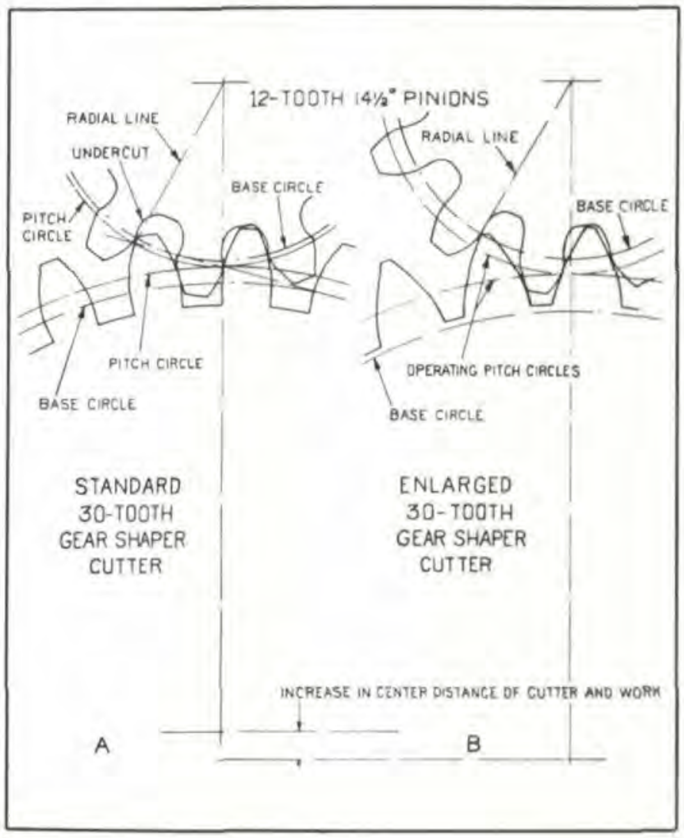
The Gear Shaper cutter, being a cutting tool in the form of a gear, can be so made that it will remove those portions of the gear or rack teeth that interfere with each other. At *A* in Fig. 7 is shown a 30-tooth 14½° Gear Shaper cutter in contact with a rack tooth. The flank of this cutter is made radial, and as indicated modifies a portion of the rack tooth above the pitch line. At *B* the flank of the Gear Shaper cutter is "filled in" still more than at *A* and consequently the amount and extent of modification is greater. Gear teeth can be modified in a similar manner.

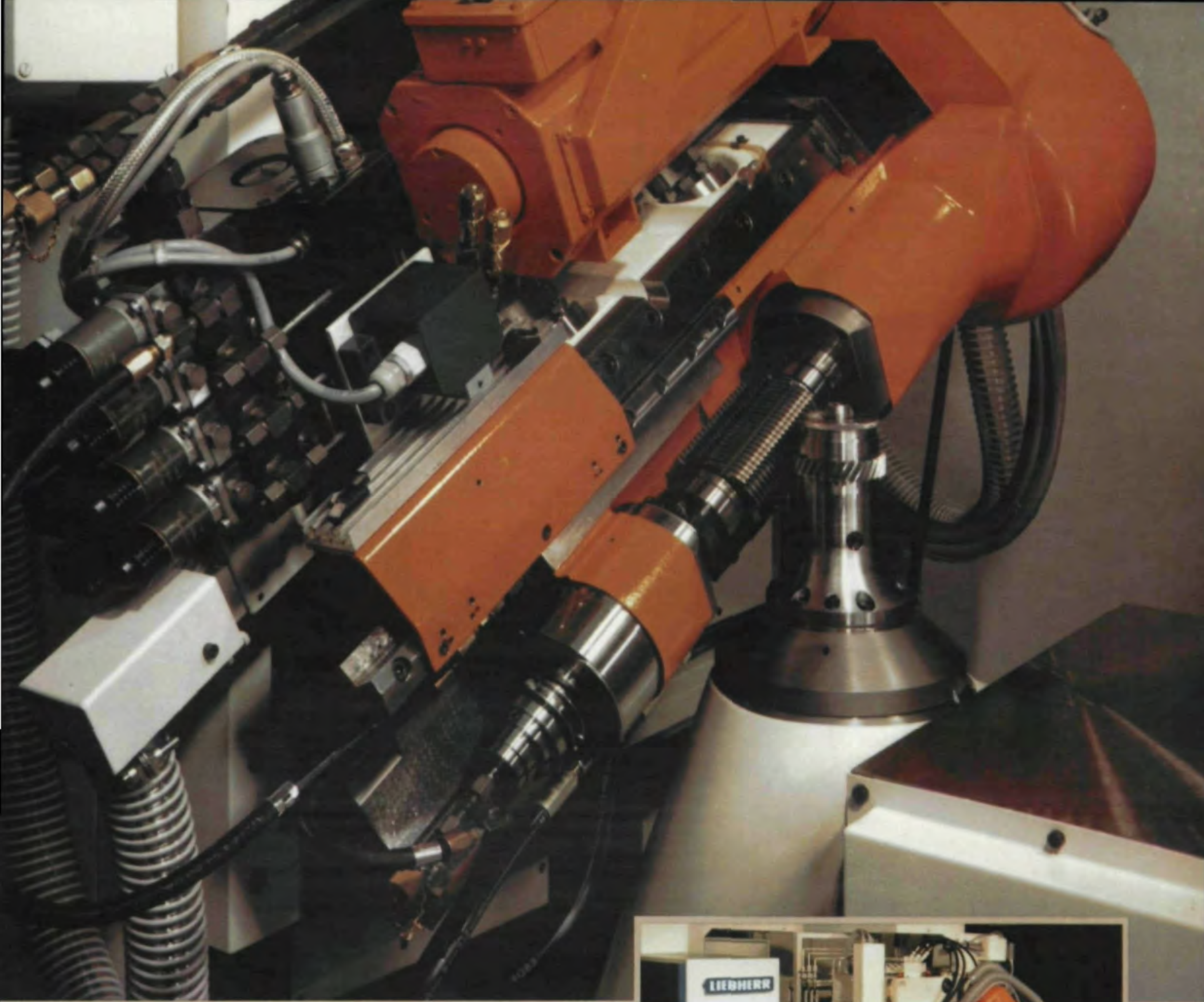
At *A* in Fig. 8A a 30-tooth 14½° Gear Shaper cutter is shown in mesh with a 12-tooth pinion. Here it will be noticed in generating the flank and fillet that the ends of the cutter teeth "sweep" inside the radial line, and, hence, undercut the flanks of the pinion. As the gear or the rack is generally stronger than a pinion having a small number of teeth, the gear or rack teeth are generally modified where a severe interference condition exists. This is also the practice where the teeth have to be modified to provide for tooth deflection under heavy loading conditions.

When undercutting of the flank of a pinion having a small number of teeth is to be avoided, several methods can be employed:

1. The blank diameter of the pinion can be enlarged, as shown at *B* in Fig. 5 and the outside diameter of the mating gear reduced a similar amount. This results in long and short addendum teeth.

Fig. 8A – Diagram Illustrating How the Gear Shaper Cutter Can Be Made so as to Avoid Undercutting the Flank of a 12-Tooth Pinion.



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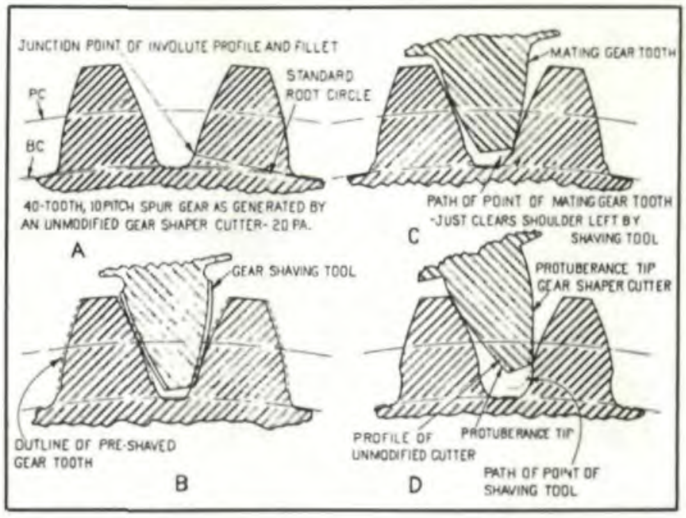


Fig. 8B – Diagram Illustrating Type of Gear Shaper Cutter Used When Gears Are to Be Finished by a Shaving Tool, and Where Flank of Gear Tooth Must Be Undercut.

2. An increased pressure angle can be used.
3. An increased pressure angle combined with shorter addendums.
4. An enlarged Gear Shaper cutter can be used, as shown in *B* in Fig. 8A.

Here, it will be noticed that the ends of the cutter teeth do not "sweep" inside the radial line. Enlarging the cutter has the effect of increasing the generating pressure angle, and, hence, changes the pitch circle or "rolling circle," and in effect withdraws the cutter from the gear, thus preventing the cutter teeth from undercutting the flanks of the teeth. This, of course, does not avoid interference with the mating member, which would have to be modified, as indicated in Fig 7. It does, however, provide a stronger tooth shape in the pinion, as undercutting the flank naturally weakens the tooth, all other factors remaining the same.

Pre-Shaving Gear Shaper Cutters

When finishing gears by means of a shaving tool, it is sometimes necessary to undercut the flank of the gear tooth to prevent contact of the shaving tool inside the base circle. Contact with the flank of the gear tooth by the shaving tool can produce two undesirable results. One is that it causes deflections that result in modifications near the top of the gear tooth; the other is that a ridge may be formed in the fillet of the gear tooth which might interfere with the proper operation of the mating gear.

Pre-shaving cutters are, therefore, made with a protuberance, or what might be called a plus involute on the tips of the teeth. This protuberance tip "sweeps" out the flank of the gear tooth and prevents the shaving tool from contacting the non-involute portion of the gear tooth. It also avoids the formation of a ridge in the fillet of the gear tooth.

These conditions are illustrated diagrammatically in Fig. 8A. At *A* is shown a 40-tooth, 20° full-length gear tooth as cut with an unmodified Gear Shaper cutter. At *B* this pre-

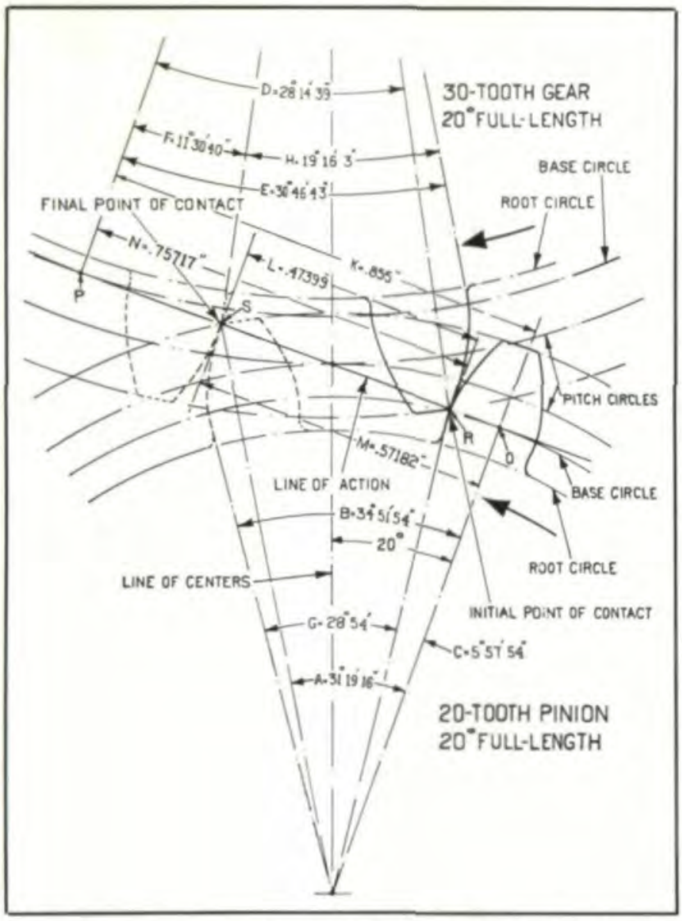


Fig. 9 – Diagram Illustrating Gear Tooth Action, Active Length of Involute Profile, and Length of Contact.

shaved tooth is shown as finished with a shaving tool. Note that the shaving tool leaves a ridge in the fillet of the tooth, which is liable to interfere with the proper operation of the mating gear, as shown at *C*. If this gear had been cut with a cutter having a protuberance tip, as shown at *D*, contact of the shaving tool with the flank of the gear tooth would have been avoided, and no ridge left to interfere with the proper operation of the mating gear.

This type of cutter is usually recommended for gears 16 pitch and coarser. For finer pitches where an undercutting of the flank is necessary prior to shaving, the pressure angle on the cutter is made less than the specified pressure angle, and by "feeding" this cutter in farther than "standard" depth, it "sweeps" out the non-involute portion of the tooth to provide "clearance" for the shaving tool.

Analyzing and Checking Involute Tooth Profiles

With the exception of the circle, the involute is one of the easiest curves to reproduce and check accurately. It is possible to chart and measure the shape of involute tooth profiles, and to accurately determine the angular location and amount of any deviation of the tooth profile from the "true" involute shape. The angular location of the "initial" and "final" points of contact between two mating gears can be calculated, but it is also possible to determine these points diagrammatically, and to correlate the diagram with charts made on Involute Measuring Instruments, as will be subsequently explained.

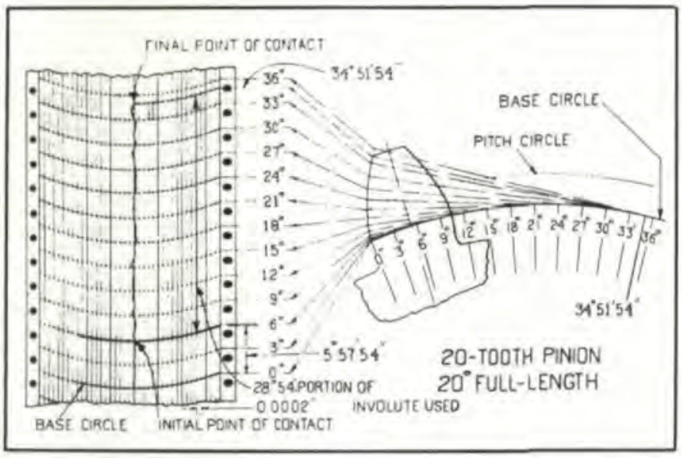


Fig. 10 – Chart of 20-Tooth Pinion in Fig. 9 as Produced on Fellows Involute Measuring Instrument.

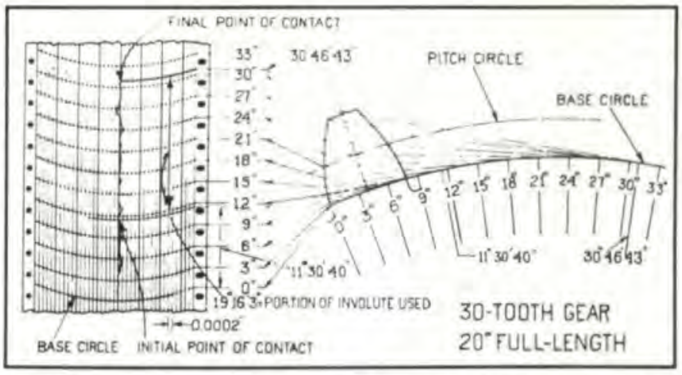


Fig. 11 – Chart of 30-Tooth Gear in Fig. 9 as Produced on Fellows Involute Measuring Instrument.

Checking Involute Tooth Profiles

An analysis of gear tooth action, as represented in Fig. 9, will help to explain the application of the diagrammatic and charting method for determining the actual length of contact of mating gears, and the angle of involute used.

In general, the involute profile of a gear tooth is checked from its origin, or base circle, to the outside circle, or top of the tooth. Fig. 9 shows a pair of involute gears in mesh for the purpose of illustrating the "initial" and "final" points of tooth contact, and the active portions of the tooth profiles. Points *O* and *P* are the "natural" interference points, and indicate the maximum permissible length of the line of action, provided that the outside circles of gear and pinion, respectively, were extended to the interference points.

Assuming that the pinion is the driver, the point *R* where the outside circle of the gear cuts the line of action is the "initial" point of contact; and point *S* where the outside circle of the pinion cuts the line of action is the "final" point of contact. On the 20-tooth pinion, angle *B* represents the total angle of involute; and, on the 30-tooth gear, *E* represents the total angle of involute. The active angles of involute are *G* on the pinion and *H* on the gear.

Deviations in the profiles within the spaces confined by angles *C* and *F* can be neglected, as far as any involute action is concerned for this particular gear ratio, tooth length, etc., as shown in Fig. 9. Angles *G* and *H*, and the length of the line of contact can be calculated, as will be explained later. They also can be determined approximately from this diagram.

It is also possible to approximately determine the location of the "initial" and "final" points of contact by placing two mating gears on pins spaced at the correct center distance, "rolling" the gears, and marking the points on the tooth profiles where contact starts at *R* and finishes at *S*, as shown in Fig. 9.

It is evident from a study of this diagram that only a portion of the involute on both the pinion and gear is used. Hence, the angles of involute of both members charted in Figs. 10 and 11, as produced on the Involute Measuring Instrument, are greater than those portions of the involutes that are used. It will be noticed in Fig. 10 that the used portion of the involute on the chart is the same as the angle of involute *G* in Fig. 9. The same applies to the chart in Fig. 11 for the gear, where *H* is the angle of involute used.

The "initial" point of contact on the pinion is *5° 57' 54"* from the origin or base circle, which is equal to angle *C* in Fig. 9, and on the gear, the final point of contact is 11° 30' 40" from the origin or base circle and is equal to the angle *F*.

On the charts in Figs. 10 and 11, the involute "reading" is recorded with reference to a straight line, and any departure from this straight line represents the amount of deviation from the "true" involute shape. The angular location of deviation in the tooth profile is indicated by the position of the charted line relative to the accurately spaced curved lines. The space between the vertical lines on the chart represents a deviation of 0.0002 inch. The measuring instrument is provided with a ratio mechanism, so that the space between the curved lines can represent either 3 degrees or ½ degree of involute "roll."

For the benefit of those who are interested in determining these angles, etc. mathematically, the formulas and methods of procedure are presented in the following pages.

Calculating Involute Angles

The angular position of any point on an involute with respect to its origin on the base circle can be determined in degrees of rotation of the base circle necessary to develop the involute to that particular point. This value is known as the angle of involute. On a gear, the total angle of involute is the number of degrees of rotation of the base circle from the origin at the base circle to the top of the tooth, or outside circle.

Fig. 12 is a schematic diagram of an involute profile developed by rolling a base cylinder along a base line in which a tracing point is located. The full lines show this cylinder tangent to the base line at the tracing point, which is the origin of the involute. As the base cylinder is rolled counterclockwise along the base line, the involute is developed by the tracing point, as shown in the illustration.

When the base cylinder has rolled along the base line to the position indicated by the dotted outline, *B* is the angle of involute "roll," *M* is the linear distance traveled, and *OR* is the radial distance from the center of the cylinder to the tracing point, or end of the involute. Angle *B* and distance

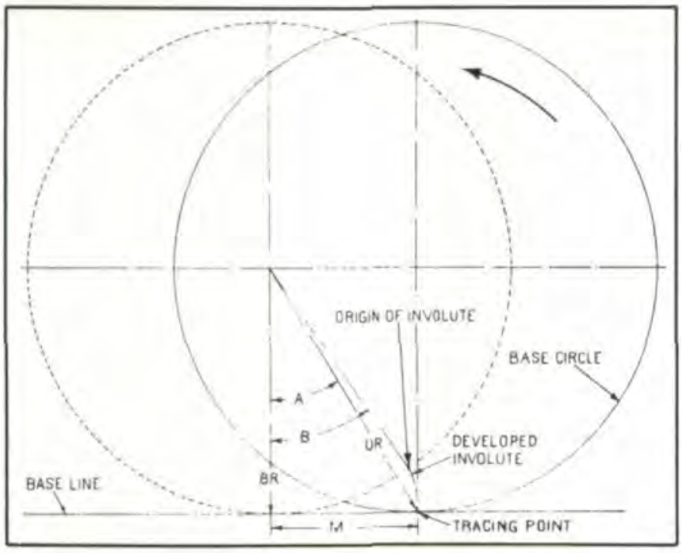


Fig. 12 – Schematic Diagram Showing Development of an Involute Profile.

M can be determined from the following formulas: in which

OR – Radius to end of involute profile

BR – Radius of base cylinder

B – Total angle of involute

Then:

$$\text{Cos } A = \frac{\text{BR}}{\text{OR}}$$

$$B = \frac{\text{Tan } A}{.0174533}$$

$$M = \text{Tan } A \times \text{BR}$$

Determining Angular Location of any Point on Involute Profile; also Length of Contact

As a practical example, we will take the two gears represented in the diagram Fig. 9, the data on which is:

Data	*Pinion*	*Gear*
Number of teeth	20	30
Diametral pitch	10	10
Circular pitch	.3142"	.3142"
Pressure angle	20°	20°
Outside radius	1.100"	1.600"
Pitch radius	1.000"	1.500"
Base radius	.9397"	1.4095"
Center distance	2.500"	

Fig. 13 presents a diagram of the gear and pinion shown in Fig. 9, which will be used in calculating the total angles of involute, active and inactive angles of involute, total length of line of action and active length of line of action.

In this diagram, Fig. 13, the involute profiles of pinion and gear are shown in dotted outline at the "initial" and "final" points of contact. The total length of the line of action is the distance between points O and P. Assuming that the pinion is the driver, contact starts at point R and ends at point S.

The total angle of involute, the active and inactive angles of involute of gear and pinion; the total length of the line of action, and the active length of the line of action, as well as the overlap of action can be determined by the simple formulas which follow. Notation for the 20-tooth pinion follows:

A – The included angle between the point of origin and the point wheer the outside circle of the pinion cuts the line of action

B – Total angle of involute

C – Inactive angle of involute

G – Active angle of involute

OR_{20} – Outside radius

BR_{20} – Base radius

For the 30-tooth gear:

D – The included angle between the point of origin to the point where the outside circle of the gear cuts the line of action

E – Total angle of involute

F – Inactive angle of involute

H – Active angle of involute

OR_{30} – Outside radius

BR_{30} – Base radius

For 20-tooth pinion and 30-tooth gear:

PA – Pressure angle

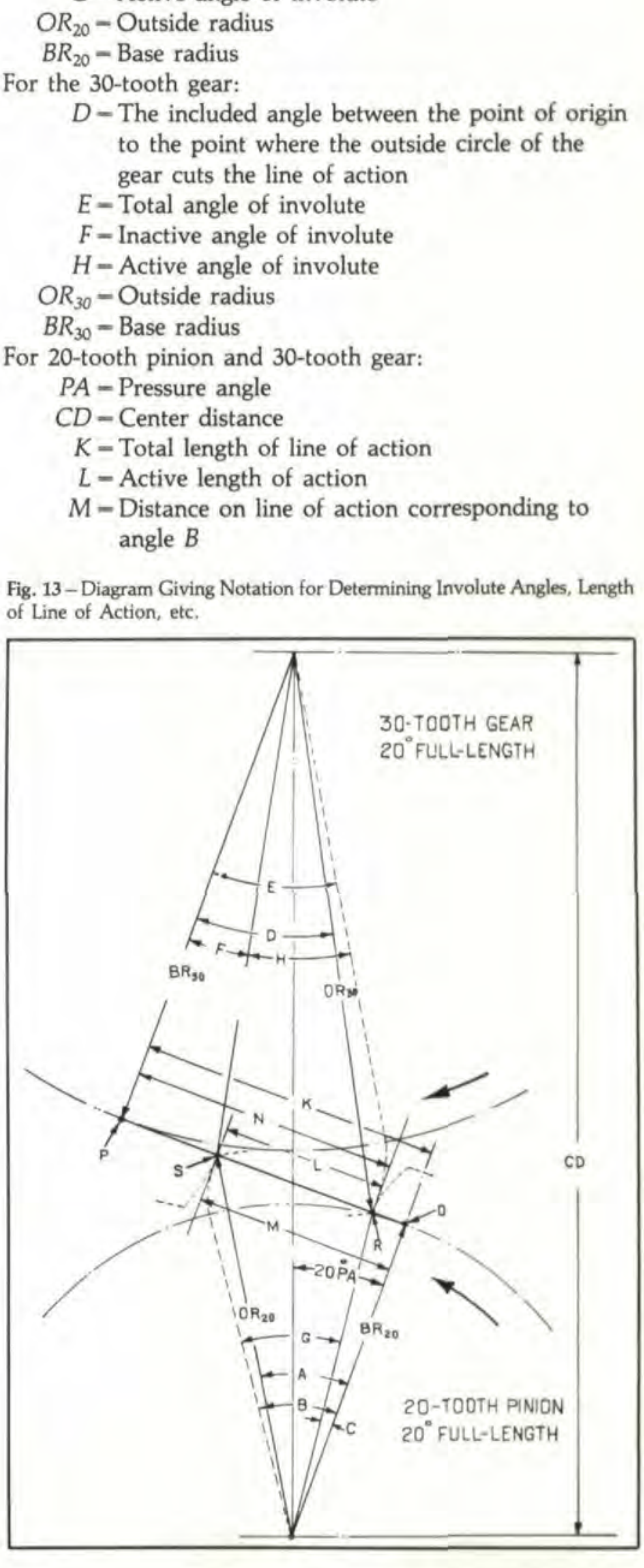
CD – Center distance

K – Total length of line of action

L – Active length of action

M – Distance on line of action corresponding to angle B

Fig. 13 – Diagram Giving Notation for Determining Involute Angles, Length of Line of Action, etc.



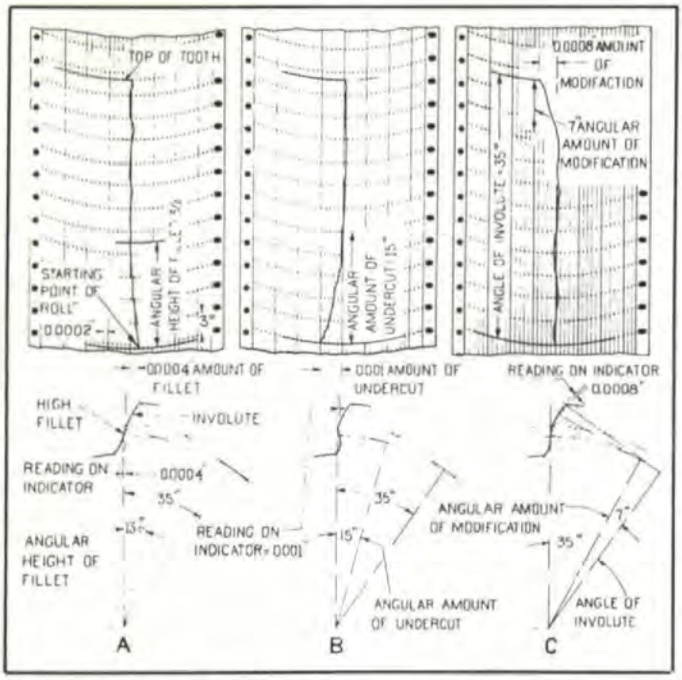


Fig. 14—Diagram of Charts Illustrating High Fillet, Undercut and Tip Modification, Produced on Involute Measuring Instrument.

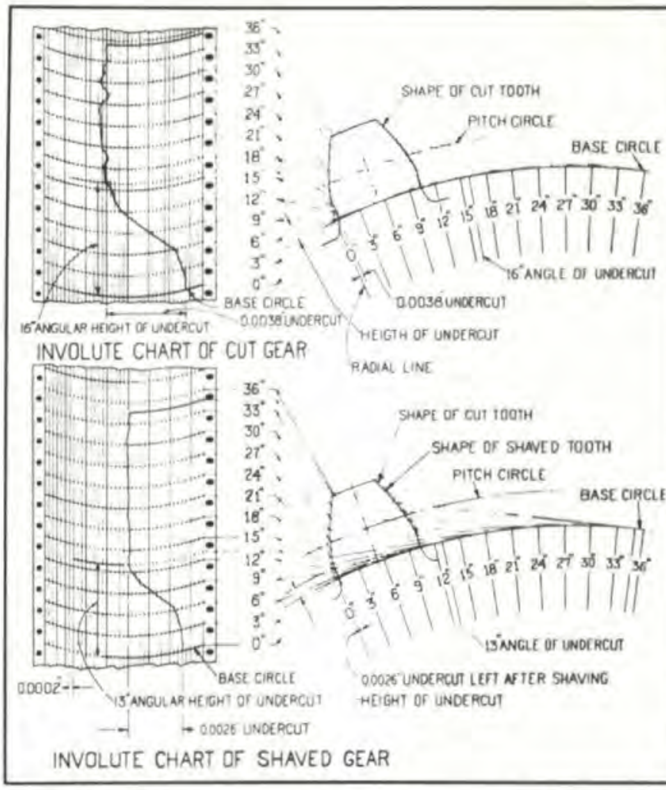


Fig. 15—Charts Made on Involute Measuring Instrument of a Gear after Cutting and after Shaving.

N = Distance on line of action corresponding to angle E

CP = Circular pitch

BP = Base pitch

Then:

$$\text{Cos } A = \frac{BR_{20}}{OR_{20}}$$

$$B = \frac{\text{Tan } A}{.0174533}$$

$$M = \text{Tan A X BR}_{20}$$

$$K = \text{CD X Sin PA}$$

$$\text{Cos } D = \frac{\text{BR}_{30}}{\text{OR}_{30}}$$

$$E = \frac{\text{Tan D}}{.0174533}$$

$$N = \text{Tan D X BR}_{30}$$

$$L = (\text{M} + \text{N}) - \text{K}$$

$$G = \frac{\text{L}}{.0174533 \text{ X BR}_{20}}$$

$$C = B - G$$

$$H = \frac{\text{L}}{.0174533 \text{ X BR}_{30}}$$

$$F = \text{E} - H$$

$$BP = CP \text{ X Cos } PA$$

$$\text{Percentage of overlap of contact} = \frac{\text{L}}{\text{BP}} - 1$$

Determining the various values for pinion and gear, using the foregoing formulas, we find that:

$$\text{Cos } A = \frac{.9397}{1.100} = .85427$$

$$A = 31° \ 19' \ 16'' \text{ and Tan A} = .60852$$

$$B = \frac{.60852}{.0174533} = 34° \ 51' \ 54''$$

$$M = .60852 \text{ X } .9397 = .57182 \text{ inch}$$

$$K = 2.5 \text{ X } .34202 = .855 \text{ inch}$$

$$\text{Cos } D = \frac{1.4095}{1.600} = .88094$$

$$D = 28° \ 14' \ 39'' \text{ and Tan D} = .53719$$

$$E = \frac{.53719}{.0174533} = 30° \ 46' \ 43''$$

$$N = .53719 \text{ X } 1.4095 = .75717 \text{ inch}$$

$$L = (.57182 + .75717) - .855 = .47399 \text{ inch}$$

$$G = \frac{.47399}{.0174533 \text{ X } .9397} = 28° \ 54'$$

$$C = 34° \ 51' \ 54'' - 28° \ 54' = 5° \ 57' \ 54''$$

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

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

This paper was presented at the AGMA Fall Technical Conference Oct. 1985.