# GEAR TECHNOLOGY

THE JOURNAL OF GEAR MANUFACTURING

MAY/JUNE 1992

COMPUTER TECHNOLOGY IN GEAR DESIGN

GEAR FINISHING BY SHAVING, ROLLING & HONING - PART 2

TEMPERATURE EFFECTS ON GAGE REPEATABILITY
& REPRODUCIBILITY

GEAR BLANKING

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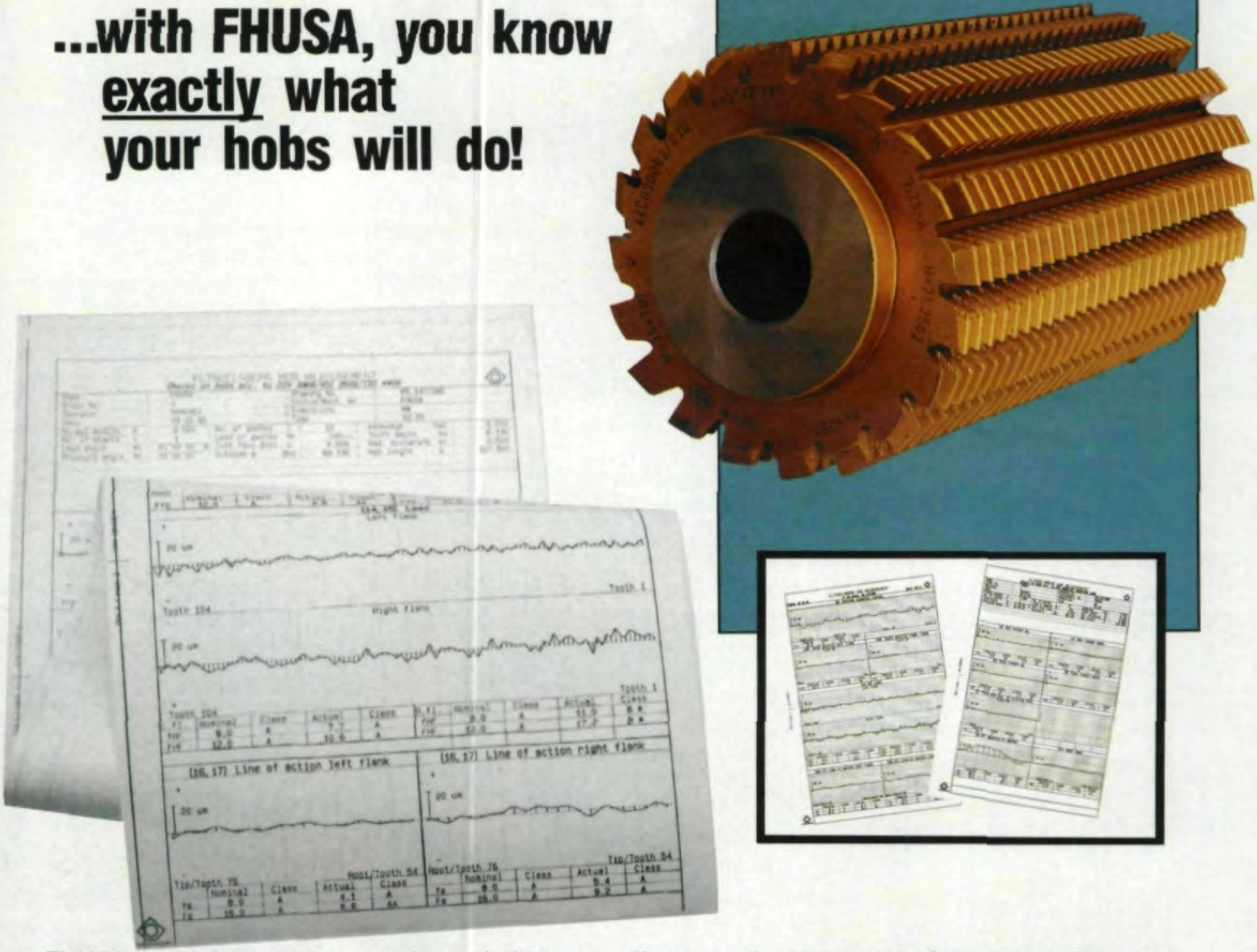

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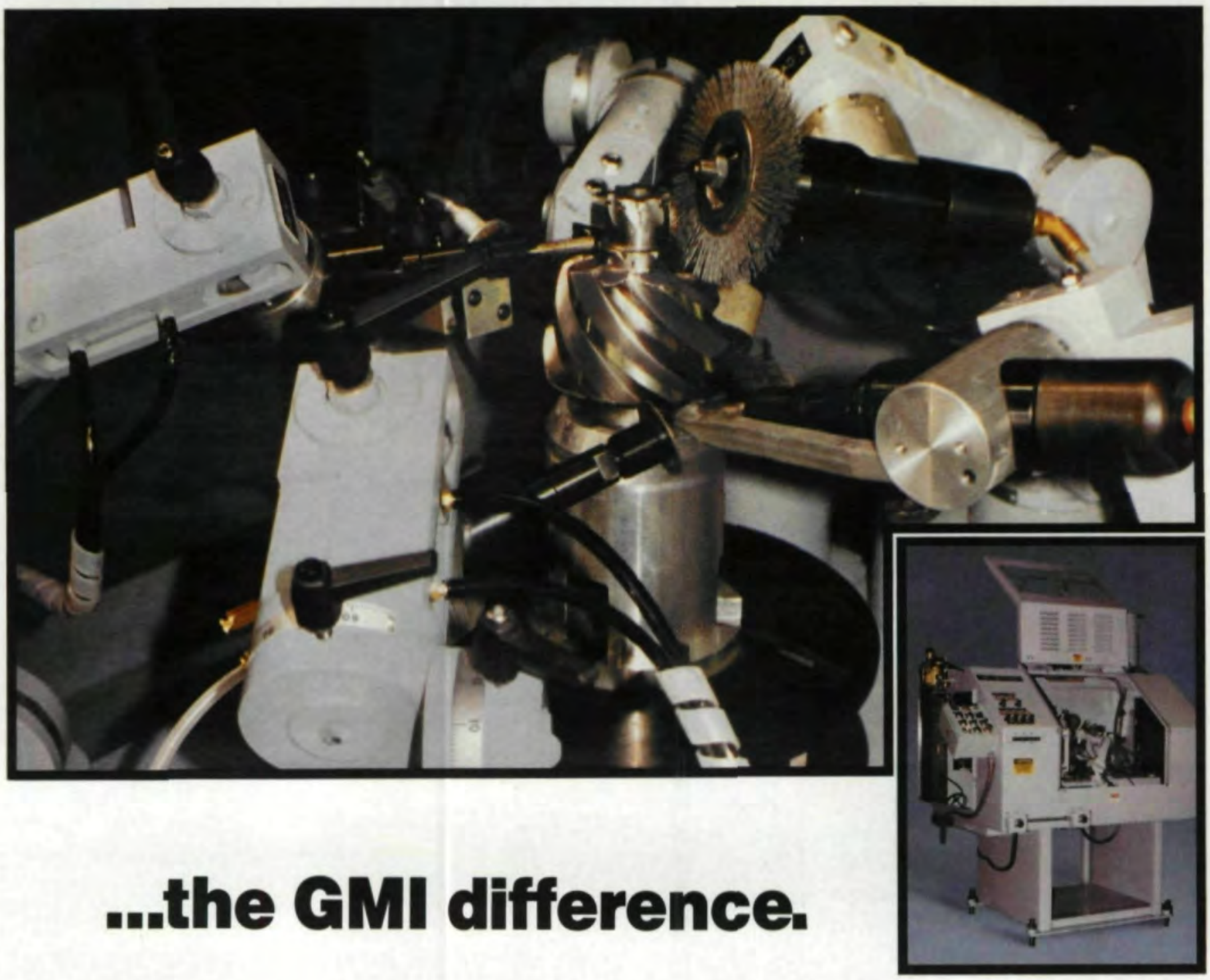
# Gear Deburring
# VERSATILITY...



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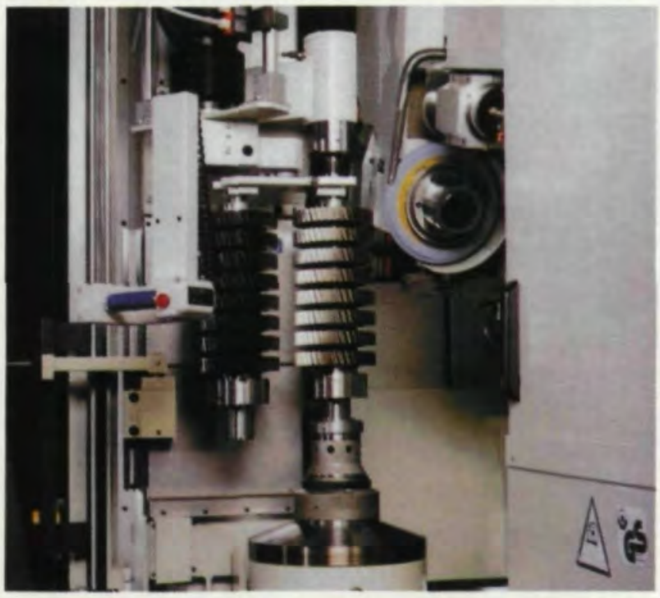

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Controlled by a powerful multi-tasking HP computer, the Opal 420 offers: built-in and remote diagnostics, modem and RS-232 links, and next job programming, even while the grinder is operating. These are just a few of the reasons why gear grinding just got better... much better with the Opal 420.

For further information contact:
American Oerlikon Gear Machines, Inc.
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Phone: (216) 572-2100
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"THE METROLOGY AND MOTION PEOPLE"

# Working Smarter, Not Just Harder

It's a buyer's market these days on solutions for our country's economic problems. Everybody with access to a t.v. camera or a publisher is telling us what we need to do. Usually their solution involves either buying their book or tape or electing them to office.

Without dismissing any of these proposals out of hand, it might be wise to remember that some approaches to the changing economic realities of the 90s lie in simple home truths - the kind that are not necessarily glamorous or "new and improved," but which work. One of these is the old standby of working "smarter." These days it's not enough to be "lean and mean" or "state of the art." You also have to be using every resource you have to the best advantage - in short, you have to work smart as well as hard.

The articles in this issue of *Gear Technology* are all variations on this theme of working smarter. Ken Gitchel titles his discussion on computers in gear manufacturing, "Doing it Right & Faster...," two techniques bound to appeal not only to the toughest cost accountant, but also to the "smart" worker. The second part of John Dugas' article on gear finishing and Robert Endoy's on the fundamentals of gear blanking, both provide important information for determining which processes are the best and most economical for your particular needs - which has always been the "smart" approach. Paul Sagar's report on the effects of temperature variation on the accuracy of gear measurement is another variation on the theme of "working smarter."

Our columns in this issue are also a reflection of this theme. "Management Matters" offers an alternative accounting method that may help to reveal hidden costs in your operation and ways to lower them that do not necessarily involve draconian cutbacks or layoffs. In "Shop Floor," Bob Errichello lists the 10 books no gear engineer should be without, vital sources of information for "working smarter," no matter what the economic climate.

## PUBLISHER'S PAGE

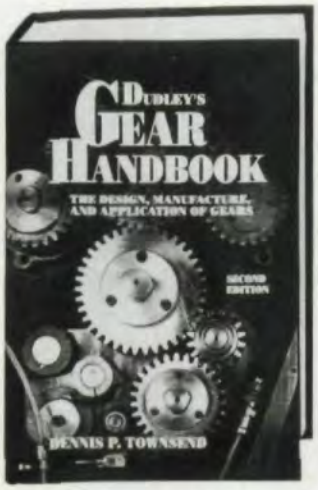
By now, it should be obvious to everyone that no one, quick, painless solution to our current economic woes is anywhere in the future. We will need every resource at our disposal to cope with the present situation - including multiple ways to work smarter. At *Gear Technology* we will continue to bring you articles that one way or another will help you increase your supply of smart approaches to your gear design and manufacturing challenges.

Michael Goldstein

Michael Goldstein,
Publisher/Editor-in-Chief

# 7 BIG REASONS the New *Dudley's Gear Handbook* Belongs on Your Desk.

## (Plus an 8th You May Like Even More.)



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# The Top Ten Books for Gear Engineers

**Robert Errichello**

## SHOP FLOOR

**Address your gearing questions to our panel of experts. Write to them care of Shop Floor, Gear Technology, P. O. Box 1426, Elk Grove Village, IL 60009, or call our editorial staff at (708) 437-6604.**

### Introduction

When I was new to gear engineering, I found the array of gear literature scarce, and the information scattered and conflicting. After investigating the materials available, I set the goal of creating an annotated listing of the references. There are many valuable resources, but for this article I have selected ten of the best. These references, in my opinion, are the most useful, and cover the scope while minimizing redundancy.

***Dudley's Gear Handbook*, 2nd ed., D. P. Townsend, ed. McGraw-Hill, 1991, 815 pages.** It has been nearly thirty years since the first edition of the *Gear Handbook* was published. Over the years the *Gear Handbook* has served as a valuable resource for people who design, manufacture, and use gears. The second edition has been extensively revised and updated with two new chapters on gear vibration and noise.

The *Gear Handbook* shares the strengths and weaknesses of most handbooks in that it is comprehensive but condensed. Nevertheless, it is a convenient, single source for information on gears.

An important feature of the handbook is its extensive reference lists, which help gear researchers locate information.

The handbook comprises 24 chapters written by 26 contributors. With so many authors, some redundancy and inconsistencies are bound to occur. This is not necessarily a disadvantage though, because repetition and diverse opinions can help readers draw accurate conclusions.

Although the second edition is better organized than the first, the index is still too limited for easy access to information.

The *Gear Handbook* covers the following subjects in detail:

The theory of gearing, gear types and nomenclature, gear arrangements, gear tooth design, and detailed calculations of gear tooth geometry; Gear tolerances; Gear materials; Engineering drawings for manufacturing; Gear tooth loads; Gear and bearing load rating; Gear failures; Performance testing; Gear vibration and noise; Gear lubrication; Gear manufacturing including cutting, die processing, shaving, rolling, honing, and grinding; Bevel and hypoid gear manufacturing; Cylindrical and double-enveloping worm and worm gear manufacturing; Gear cutting tools; Gear inspection devices and procedures; and Tables of numerical data, including wire measurement data, trigonometric functions, involute functions, arc and chord data, and hardness testing data.

***Fundamentals of Gear Design*, R. J. Drago, Butterworths, 1988, 560 pages.** Raymond Drago's book is a well organized, comprehensive treatment of gear theory, gear fabrication and inspection, gear failure and load capacity evaluation, and gear lubrication. Most chapters include extensive reference lists and bibliographies. I especially like the bibliography that is grouped by manufacturing method.

One of the strengths of *Fundamentals of Gear Design* is its emphasis on American Gear Manufacturers Association standards and practices. This is important because gear engineers should be aware of the excellent information available through AGMA.

The book contains good descriptions and illustrations of gear failure modes. However, I prefer the term "scuffing" over the author's terms, "frosting" and "scoring."

The chapter on variable, static, and low-cycle loading is unique for a gear text, because it treats both bending yield and contact yield analyses. The chapter also includes an analysis of subsurface stresses, which is useful for determining case depth for case hardened gears.

**Robert Errichello**
*is the principal in GEARTECH, a gear consulting firm in Albany, CA. He is a member of AGMA, ASME, and a Registered Professional Engineer in the State of California.*

Drago's discussion on gear lubricants is one of the best I have seen.

***Gear Drive Systems,* P. Lynwander, Marcel Dekker, 1983, 415 pages.** I like this book because it contains practical information for the gear engineer and for anyone else who is responsible for the specification and operation of gear systems.

*Gear Drive Systems* emphasizes the gearbox applications and discusses installation, operation, maintenance, troubleshooting, failure analysis, and economics. For the beginning gear engineer, there is a good overview of types and arrangements of gear drives, gear tooth geometry and kinematics, and gearbox load rating. Bearings, seals, lubrication systems, materials and heat treatment, and manufacturing methods are also covered.

Operators of gear drive systems will appreciate the chapter on gearbox installation, which discusses couplings and system alignment, and the chapter on gearbox operation, which discusses acceptance testing, initial startup, and condition monitoring. The last chapter covers maintenance and failure analysis.

***Maag Gear Book,* Maag Gear Company, 1990, 435 pages.** This book has been in great demand ever since the German version, *Maag-Taschenbuch,* was released in 1963. A revised edition of the German version came out in 1985, and the first English version *Maag Gear Book,* in 1990.

The *Maag Gear Book* gives a good overview of European practices and ISO methods for gear design and analysis, including gear geometry, load rating, application of gear drives, gear couplings, inspection, gear materials, and heat treatment.

The *Maag Gear Book* is well organized with helpful tables and graphs of data. The chapter on gear geometry gives the essential equations for gear tooth data and includes the best treatment I have seen on profile shift (addendum modification). The charts called "contact condition diagrams" will help the gear engineer apportion the profile shift between the pinion and the gear so that specific sliding is reasonably controlled.

The chapter on load rating treats the ISO-Maag method for calculating pitting resistance and bending strength, and Maag's method for calculating scuffing resistance which is based on Blok's critical temperature criterion.

The chapter on gear drives discusses gear tooth profile and helix modifications, and the chapter on gear materials and heat treatment covers the selection and heat treatment of DIN steels.

An important feature of the book is the English, German, French, and Italian dictionary of gear geometry terms.

***The Geometry of Involute Gears,* J. R. Colbourne, Springer-Verlag, 1987, 532 pages.** This is the best textbook on gear geometry currently available. All the equations are derived from first principles and reduced to useful design algorithms. The clear, straightforward presentation makes complicated gear geometry seem simple. Part I covers spur gears, and Part II covers helical gears.

Colbourne gives a design procedure for internal gearsets that treats fillet interference, tip interference, axial and radial assembly, and manufacturing problems, such as tip trimming and cutter rubbing.

He explains gear cutting, including hobbing and shaping with pinion and rack cutters. Manufacturing engineers will be interested in his discussion of hobbing machines.

The last chapter covers calculating contact stress and bending stress in helical gear teeth, and suggests several improvements over AGMA procedures.

An important feature of the book is its many numerical examples which gear engineers will find helpful for checking their work and validating computer programs.

*The Geometry of Involute Gears* will be extremely useful to graduate students, practicing gear engineers, and gear researchers.

***Gears for Small Mechanisms,* W. O. Davis, N.A.G. Press Ltd., (London), 2nd ed., 1970, 344 pages.** One of the best ways to learn about involute gears is to study noninvolute gears. This book presents the theory of both involute and cycloidal gears. It covers the theory and practice of the design of very small gears, including friction and efficiency of tooth action. It also covers the design of tools for cutting and generating gear teeth and production and testing of gears used in watches, recording instruments, automatic control mechanisms, and similar devices.

Davis's book deals with the special problems presented by fine pitch gears that are not solved by scaling down copies of power transmission gears. The reader will gain an appreciation for the features and limitations of involute and cycloidal gearing. Extremes in the design of involute gears, for example, spur pinions with as few as three teeth, are also explored.

There are good discussions on the dynamic characteristics of gear trains, transmission error, and resonant vibration. Also included is the metrology of fine pitch gears, design of gear trains, and the estimation of gear tooth load capacity. Although the book is relatively old, most of the material is still relevant to current gear engineering.

***The Exact Over-Wire Measurement of Screws, Gears, Splines, and Worms,* W. F. Vogel, Wayne State University Press, 1973, 230 pages.** The indirect determination of gear tooth thickness by the measurement over wires (pins) or balls is a popular technique, and gear engineers should understand the theory and calculations underlying this method. It is especially important to understand the limitations of wire measurements; for example, odd-tooth helical gears cannot be accurately measured with only two wires. Vogel shows that they can be accurately measured with three wires under certain conditions, or with one wire with the gear mounted on an arbor, or with two balls under certain conditions.

Vogel gives the derivation of the equations for the over-wire measurement of involute spur and helical gears. He also gives a complete general theory of wire and ball measurement that can be used for the exact measurement of general screws of either involute or noninvolute profiles.

***Steel Selection - A Guide for Improving Performance and Profits*, R. F. Kern and M. E. Suess, John Wiley, 1979, 445 pages.** This book bridges the gap between metallurgical theory and real-world applications. Kern and Suess present guidelines for designing components to reduce distortion and avoid cracking during heat treatment, selecting alloys, and specifying heat treatment. They also explain how to produce gears, shafts, springs, and fasteners, and how to design against surface fatigue, bending fatigue, (high and low cycle), subcase fatigue, and scuffing.

All the major heat treatments are discussed, including through hardening and case hardening by carburizing, nitriding, and induction hardening.

The chapter on selecting steels for carburized gears emphasizes the importance of hardenability and gives guidelines for proper steel selection to obtain adequate case and core hardenability.

Written for engineers and shop personnel, *Steel Selection* is an excellent resource for the gear engineer.

***The Influence of Microstructure on the Properties of Case-Carburized Components*, G. Parrish, ASM, 1980, 236 pages.** This book is a must for the gear engineer who designs carburized gears. It gives an in-depth discussion of the complexities and the significance of the following microstructural features: Internal oxidation, decarburization, carbides, retained austenite, grain size, microcracking, microsegregation, nonmetallic inclusions, core properties and case depth, optimum case depth, tempering, refrigeration, grinding burns, residual stress, and shot peening.

The clear, concise writing makes the book a joy to read, and the contents make it a valuable resource for gear engineers, quality assurance personnel, and gear failure analysts.

***Machinery Vibration - Measurement and Analysis*, V. Wowk, McGraw-Hill, 1991, 358 pages.** There has been a continuing trend toward higher speed mechanical systems, and a greater emphasis on reliability, efficiency, and controlling vibration. There have also been tremendous advances in the technology of vibration measurement in the past fifteen years. Because modern gearboxes must be reliable, efficient and quiet, it is imperative that gear engineers be knowledgeable in gear vibration.

*Machinery Vibration* is an excellent instructional tool for teaching how to take vibration measurements and interpret the results. The book is intended for operation and maintenance personnel and assumes that the reader has no prior knowledge of vibrations. However, an undergraduate course in vibration theory would be useful.

Wowk describes the basic concepts of vibration theory, including mass, stiffness, damping, amplitude, frequency, phase, time versus frequency domains, displacement, velocity, acceleration, steady state versus transient vibration, natural frequency, and resonance. He focuses on conventional instruments to measure machinery vibration, such as the fast Fourier transform (FFT) spectrum analyzer. Displacement, velocity, and acceleration transducers are discussed so that the reader will gain a working knowledge of the capabilities and limitations of each transducer.

Wowk also presents several interesting case histories that illustrate typical vibration problems, including imbalance, misalignment, resonance, cavitation and oil whirl, and excitation from gears, bearings, pumps, and motors.

After studying this book, the reader will have knowledge of the techniques and instrumentation required to solve common vibration problems. ■

# Doing It Right & Faster... The Computer's Impact on Gear Design & Manufacture

**Kenneth R. Gitchel**
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**Introduction:** The availability of technical software has grown rapidly in the last few years because of the proliferation of personal computers. It is rare to find an organization doing technical work that does not have some type of computer. For gear designers and manufacturers, proper use of the computer can mean the difference between meeting the competition or falling behind in today's business world. The right answers the first time are essential if cost-effective design and fabrication are to be realized. The computer is capable of optimizing a design by methods that are too laborious to undertake using hard calculations. As speeds continue to climb and more power per pound is required from gear systems, it no longer is possible to design "on the safe side" by using larger service factors. At high rotational speeds a larger gear set may well have less capacity because of dynamic effects. The gear engineer of today must consider the entire gear box or even the entire rotating system as his or her domain.

We will take a brief look at some of the methods traditionally used by the gear industry and investigate possible improvements using state-of-the-art software technologies.

### Computerize the Right Stuff

In the past, handbooks, rules of thumb, modification of previous designs, etc., were the most commonly used design techniques. Slide rules gave way to hand calculators; the hand calculators gave way to the first desk top calculators, and they gave way to personal computers. The first computer programs for gear design and manufacturing were, for the most part, cookbook computerizing of industry standards and design handbook formulae. Users were not aware that programming the usual formulae for gear design and gear tools can result in serious, unexpected problems. The formulae were used by people who, often without being aware of it, made judgments concerning the results as they went along. The computer does not have the ability to make any judgments without being programmed to do so.

The following equations (marked "linear") for the contact limit radii (Start of Active Profile) for a pair of gears was taken from a text on gear design and entered without change into a computer. The numerical data is for a 20 D.P., 13/30 spur tooth gear set.

cd = operating center distance = 1.075

Gear 1:
  Ro1 = outside radius = 0.375
  Rb1 = base radius = 0.30540
Gear 2:
  Ro2 = outside radius = 0.800
  Rb2 = base radius = 0.70477

$$\text{tpà} = \arccos \frac{\text{Rb1} + \text{Rb2}}{\text{cd}} = \text{operating PA} = 20°$$

**Linear Equations** (from text book):

$$\text{R1c} = \sqrt{\left[\text{cd} \bullet \sin(\text{tpà}) - \sqrt{\text{Ro2}^2 - \text{Rb}^2}\right]^2 + \text{Rb1}^2}$$

= gear 1 contact limit radius (SAP) = 0.30559
(incorrect)

$$\text{E1cL} = \sqrt{\left[\frac{\text{R1c}}{\text{Rb1}}\right]^2 - 1} =$$

= roll angle at SAP 1 = 2.04085°
(incorrect)

$$\text{R2c} = \sqrt{\left[\text{cd}\bullet\sin(\text{tpa`}) - \sqrt{\text{Ro1}^2 - \text{Rb1}^2}\right]^2 + \text{Rb2}^2} =$$

gear 2 contact limit radius (SAP) = 0.72057.

$$\text{E2cL} = \sqrt{\left[\frac{\text{R2c}}{\text{Rb2}}\right]^2 - 1} =$$

roll angle at SAP 2 = 12.19928°

The SAP diameter and roll angle for gear 1 are incorrect. The value of

$$\text{cd}\bullet\sin(\text{tpa`}) - \sqrt{\text{Ro2}^2 - \text{Rb2}^2}$$

is actually negative, but the computer, in precise accordance with instructions, squared it anyway.

The following equations for the SAP of the gears are much better suited to the computer, as there is no necessity to square a number that may be negative, giving the wrong result. The roll angle at the SAP is calculated directly.

**Roll Angle Equations:**

$$\text{ERo1} = \sqrt{\left[\frac{\text{Ro1}}{\text{Rb1}}\right]^2 - 1} =$$

roll angle at OD 1 = 40.82629°

$$\text{ERo2} = \sqrt{\left[\frac{\text{Ro2}}{\text{Rb2}}\right]^2 - 1} =$$

roll angle at OD 2 = 30.77504°

E` = tan(tpa`) = roll angle at operating pitch point = 20.85396°

$$\text{E1c} = \text{E`} - \left[\frac{\text{Rb2}}{\text{Rb1}}\right] \bullet$$

(ERo2 -E`) = roll angle at SAP 1 = -2.04085°
(correct)

$$\text{E2c} = \text{E`} - \left[\frac{\text{Rb1}}{\text{Rb2}}\right] \bullet (\text{ERo1} - \text{E`}) =$$

roll angle at SAP 2 = 12.19928°

The value of the roll angle at the SAP of gear 1 is negative. This, of course, is not possible and indicates that the tip of gear 2 is attempting contact below the base circle of gear 1.

The "linear" equations tell us that the situation is as shown in Fig. 1.

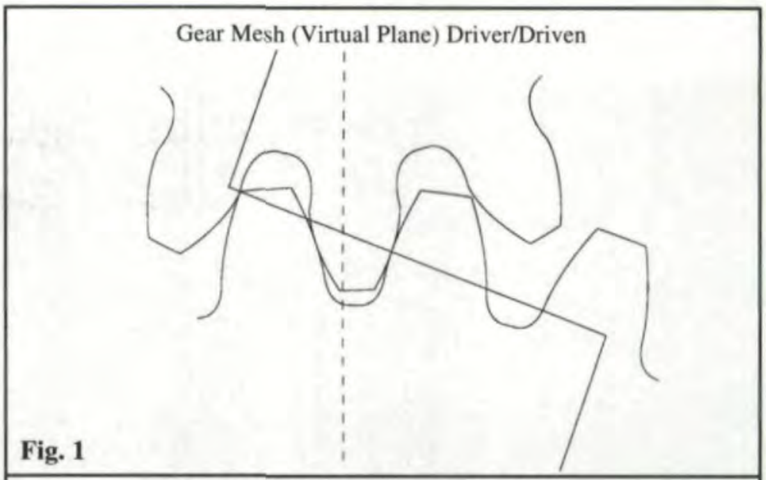

**Fig. 1**

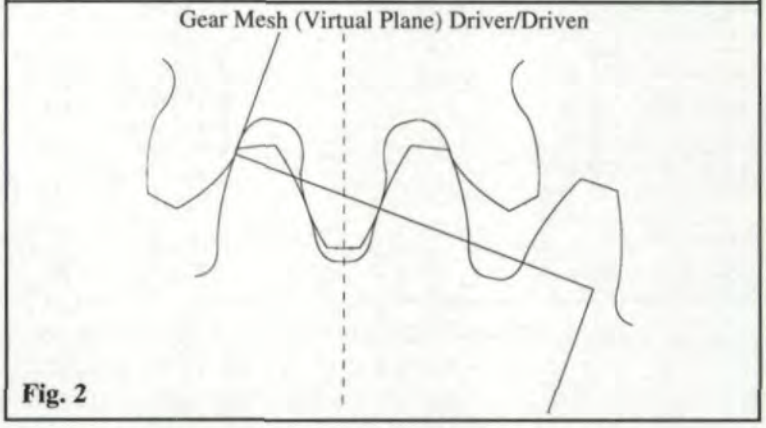

**Fig. 2**

The figure shows the first point of contact on the driver to be at +2.04085°. The actual situation is shown in Fig. 2.

It is obvious that if we believed what the computer told us using the "linear" equations, we would have an unusable gear set. The negative roll angle produced by the "roll angle" equations is the true situation and is easily seen by the computer or the operator.

Cases like our example are quite common in the gear literature. The geometry of a pair of involute gears leads naturally to the use of equations for linear dimensions squared. The use of angles instead of lengths does not seem to be as natural for human beings. However, the use of angular relationships instead of linear relationships wherever possible will keep errors to a minimum, and computer code for gears should be written in this manner.

### Analyze the System

When a gear set is to be designed and manufactured, the usual procedure is to consider it as an independent mechanical pair. The gears must mesh together properly and carry the load imposed upon them for the required length of time. The gear unit may consist of only a single pair of gears, or there may be many stages of the same or different types of gear sets. For a given total

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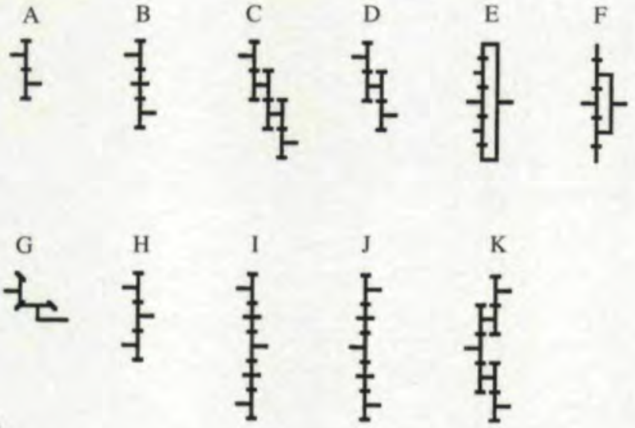

**Fig. 3**

**Fig. 4**

**Fig. 5**

**Table 1 - Minimum Weight Transmission System**

```
Date: 0/0/00
Job ID: Triple Reduction

Total System Ratio = 67.000
Sum (Fd2/C), min   = 349.041
Ratios listed are minimum weight ratios.

TRIPLE REDUCTION GEAR SET
 (Pin->Gear->C.S.Pin->Gear->C.S.Pin->Gear)
Helical Gears, Low Pressure Angle
Capacity Factor for Tooth Type & Pressure Angle = 1.30
Branches     = 1
  Ratio (1)   = 5.685
  Ratio (2)   = 3.725
  Ratio (3)   = 3.164
```

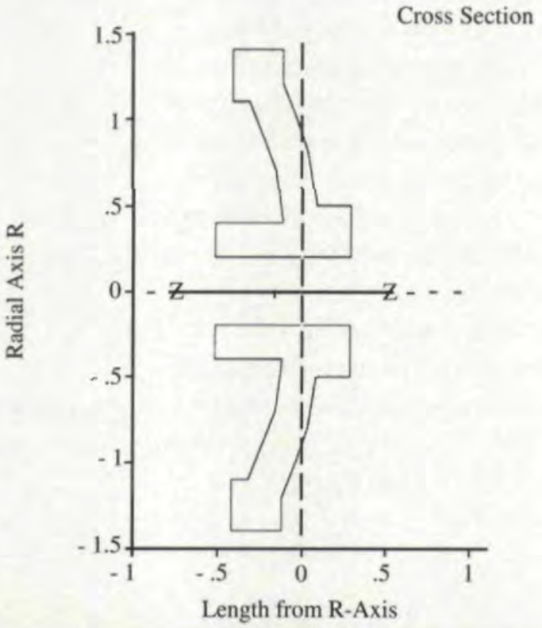

**Fig. 6**

ratio, there is a combination of gear sets (maybe a single set) that will produce the optimum result. The optimization criteria may be reducing failures, increasing life, reducing noise, minimizing cost, maximizing reliability, minimizing weight, etc. The optimum will usually be the gear set combination with the least total gear rotor volume; i.e., the sum of the face * diameter squared for all gears in the unit. The computer is capable of quickly giving us this information for various combinations of gear sets. In addition, for any combination of gear sets, there is only one set of ratios which will produce the required overall ratio and at the same time yield the lowest total gear rotor volume. The computer can give us the "best" ratios at the same time as the total rotor volume.

Fig. 3 is the menu sheet from a program for minimum weight (volume) for gear units.

A gear unit may be made up of single sets as shown, or various sets may be combined.

As an example, we will look at a gear unit with an overall ratio of 67 to 1, first as a triple-reduction, parallel axis unit, and then as a double-reduction connected to a final planetary set.

Fig. 4 is a schematic for the triple-reduction from the program.

Table 1 is the computer output for the triple-reduction with minimum rotor volume. Any other ratio combination that produces 67 to 1 will have a larger rotor volume factor (349.041) and hence will weigh more.

Fig. 5 is the schematic for the double-reduction driving a planetary. Table 2 is the output for the double-reduction driving a planetary with minimum rotor volume.

The triple-reduction unit, even when made with minimum weight ratios, would be more than twice the weight of the double-reduction and planetary at this overall ratio. Other combinations would be lighter still. The possible extra cost of the parts for a planetary set would have to be weighed against the benefits of the smaller volume and weight, but the computer will furnish solid data with which to make the choice.

Since a gear unit is used to transmit motion or power from one shaft to another, it is always part of a larger system. Any rotating system has natural frequencies of torsional vibration. (There are as many natural frequencies as rotating masses less one.) If there is an exciting source which produces pulsating energy input at about the same frequency as one of the natural frequencies, the system is said to be in resonance. The amplitude of vibration will build up in such a system until the exciting energy is dissipated by damping in the system. Many systems containing gear units do not have enough damping to keep the amplitude of vibration (and the vibratory shaft torques) from becoming destructive. The computer can help us determine the natural frequencies of a rotating system, so that we can make sure that resonance will not be a problem.

In order to determine the natural frequencies of a system, we first need to build a mathematical model. Fig. 6 is from a computer program used to determine, among other things, the moment of inertia about the rotation axis for solids of revolution. The figure might represent a wheel or a gear blank with a hub.

Table 3 is the output from the program for solids of revolution.

Computers can also be used for finding the torsional spring rate of the connecting shafts between the inertias.

Once we have all the inertias of the masses and the spring rates of the connecting shafts, the computer can quickly find the natural frequencies of the complete rotating system.

For example, a simple six-mass system might consist of an electric motor driving a rotary pump through a two-gear reducer. The masses would then consist of the motor, the input coupling, the driving gear, the driven gear, the output coupling, and the pump. Fig. 7 is a schematic plot of such a system with the first natural frequency relative amplitude plotted (the mode shape) from mass to mass. Table 4 is the numerical output for the first natural frequency. All the natural frequencies that are near excitation frequencies can be quickly found, and if a resonance exists, the system can be "detuned" by changing masses or shaft stiffness.

### Concurrent Engineering

There is a move in American industry to use "concurrent engineering" to develop a design that can be produced in the least time and at the least cost.

In the past, the design of a product was usually done by the design department, the drawings were produced by the drafting department, and then the drawings and specifications were sent to the manufacturing engineering department. Little consideration was given to the design and availability of required tools or the capabilities of manufacturing equipment at the design stage. These concerns

**Table 2 - Minimum Weight Transmission System**

**Date:** 0/0/00
**Job ID:** Double Reduction and Planetary

Total System Ratio = 67.000
Sum (Fd2/C), min = 155.108
Ratios Listed Are Minimum Weight Ratios

**DOUBLE REDUCTION GEAR SET**
(Pin->Gear->C.S.Pin->Gear)
Helical Gears, Low Pressure Angle
Capacity Factor for Tooth Type & Pressure Angle = 1.30
Branches = 1
Ratio (1) = 4.395
Ratio (2) = 3.366

**PLANETARY GEAR SET**
(Pin->Planets->Carrier: Ring Gear Fixed)
Spur Gears, High Pressure Angle
Capacity Factor for Tooth Type & Pressure Angle = 1.04
Actual Planets = 4
Effective Planets = 3.7
Ratio (3) = 4.529

***Table 3 - Output From Solids of Revloution Program***

| St Input | Name | Output | Unit | Comment |
|---|---|---|---|---|
| | | | | SOLIDS OF REVOLUTION<br>Axes: Z-rotation, R-radial |
| .284 | rho | | lb/in3 | Density of Material |
| | As | 18.406816 | in2 | Surface Area |
| | V | 1.8232757 | in3 | Volume |
| | M1 | .00134009 | lb-s2/in | Mass |
| | M2 | .51781029 | lb | Mass |
| | Irr | .00068583 | lb-in-s2 | Transverse Moment About R-Axis |
| | Zc | -.1420155 | in | R-Axis to Center of Gravity |
| | Izz1 | .00125142 | lb-in-s2 | Moment of Inertia About Z-Axis |
| | Izz2 | .48355008 | lb-in2 | Moment of Inertia About Z-Axis |
| | Zz | .96635209 | in | Radius of Gyration About Z-Axis |

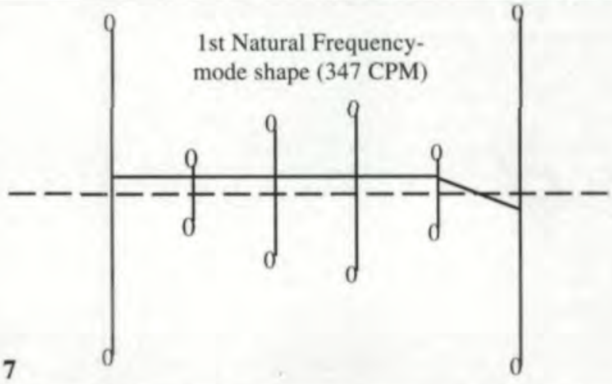

**Fig. 7**

**Table 4 - Relative Amplitude & Torque**

| Mass/Spr # | Rel Vel | Rel Amp | Rel Torque | |
|---|---|---|---|---|
| 1 | 1 | 1 | 5.97119E4 | |
| 2 | 1 | .917067 | 6.02972E4 | |
| 3 | 1 | .916273 | 6.59176E4 | |
| 4 | 1 | .847166 | 6.60926E4 | |
| 5 | 1 | .843881 | 6.65497E4 | NODE |
| 6 | 1 | -.87842 | | |
| | | 347.467 | NAT. FREQ. NO. | 1 |

**Table 5 - Optimum Gear Hob Designed by "Expert System"**

| Driver<br>Non-Topping Hob | #1 | #2 | #3 |
|---|---|---|---|
| Tool Number | DEFAULT TOOL | #1 | #2 |
| Nominal Pressure Angle | 20 | 20 | 20 |
| Flank Angle | 20 | 20 | 20 |
| Tip to Reference Line | 0.125 | .1157 | .125 |
| Tooth Thick at Ref Line | 0.1571 | .1571 | .1571 |
| Tip Radius | 0.025 | .0157 | .03 |
| Protuberance | 0 | 0 | 0 |
| Root Diameter | 1.3043 | 1.3229 | 1.3043 |

DEFAULT TOOL OK

*(Press F1 for Help)*

**Table 6 - Output Sheet for "Expert System" Program**

```
UTS
Gear Analysis

*Denotes Input Data
*Normal Diam Pitch       =   10.0000
*Normal Pressure Angle  =   20.0000
*Helix Angle             =    0.0000
Trans Diam Pitch         =   10.0000
Trans Pressure Angle     =   20.0000
*Face Width              =    1.0000                      (Deg Roll)

        *Number of Teeth             =  22
        *Outside Diameter            =  2.6000             (43.70)
        *Cut Transverse Backlash     =  0.0030
        *Delta Addendum              =  0.1000
        *Total Normal Finish Stock   =  0.0000


  HOB FORM DATA                         NON-TOPPING
  *Hob Pressure Angle                 = 20.0000
  *Hob Tip to Ref Line                = 0.1250
  *Hob Tooth Thickness at Ref         = 0.1571
  *Hob Tip Radius                     = 0.0300
  *Hob Protuberance                   = 0.0000

  Hob SAP from Ref Line               = 0.0451
  Hob Space Width at Hob SAP          = 0.1243
  (<0.3/NDP) Normal TT at OD          = 0.0180
  Normal Tooth Thickness, (Hobbed)    = 0.2269
  Pitch Diameter, (Ref)               = 2.2000             (20.85)
  Base Diameter                       = 2.0673
  Root Diameter                       = 2.1418
  Max Undercut                        = 0.0000
  Dia at Involute-Fillet Tangent      = 2.1819             (19.34)
  Minimum Fillet Radius               = 0.0300
  Hob Tool Number                     = UTS#2
  Steel Gear
```

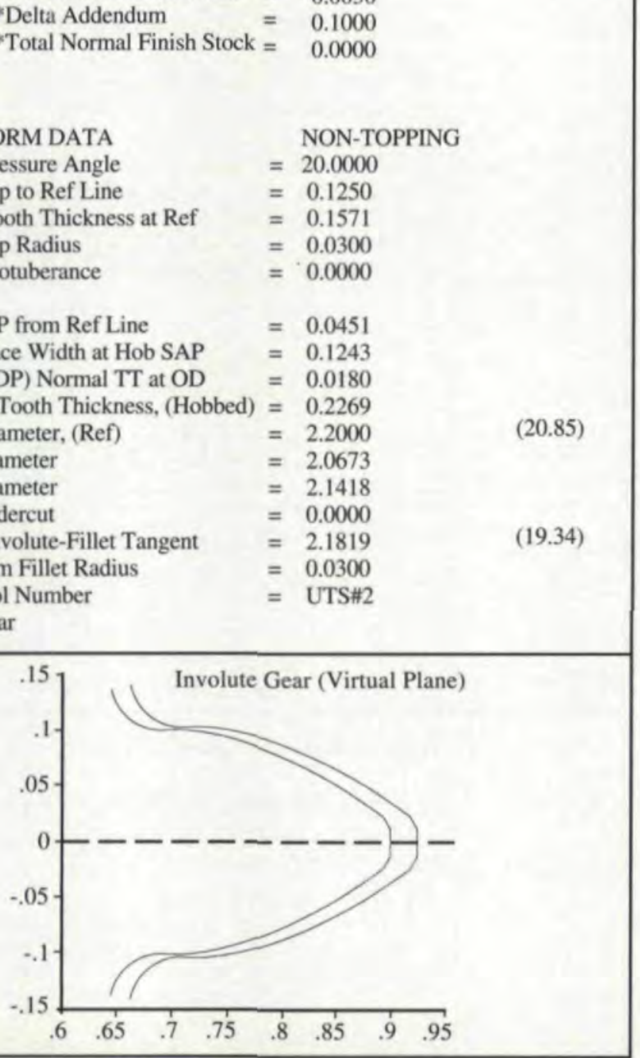

**Fig. 8**

were the responsibility of the manufacturing engineering department, and cooperation concerning changes between the design and manufacturing engineers was sometimes difficult after the design was frozen. Usually new tools had to be purchased because tools on hand were not considered at the design stage.

The "concurrent engineering" concept requires the design and manufacturing engineering functions to be addressed right from the first design specifications. Available tools and machines can *thus be considered as the design is developed.* This reduces initial manufacturing costs along with lead times for new tools. Any new tools can be placed on order long before the design is finalized and the drawings sent to manufacturing. The computer can support this concept by furnishing information on tools presently on hand and, if not suitable, furnishing specifications for new tools long before the production drawings are made.

• *Selection of gear tools at the design stage.* A good example of the use of the computer in concurrent engineering is the selection of tools required to make gears during the design of the gears. Table 5 is from an "expert system" gear design program at the stage where the program has designed an "optimum" gear hob. The program designed hob is listed as the "default tool," and two more hobs that are presently on hand are listed, along with their tool numbers and cutting edge geometry. The designer may then complete the design analysis using the new hob designed by the program, or he may use one of the hobs already on hand. Table 6 is the output sheet for the program. Hob 2 was selected and the analysis completed using this hob.

• *Design data for molded gears.* Gears made of plastic or powdered metal require a mold of proper size and shape. Molds for these gears must take into account the fact that the plastic materials shrink when cooling, and the powdered metals sometimes change shape when being sintered.

The steel molds have usually been made by machining an electrode and then using the electrode to produce the mold by electric discharge machining. This required long lead times to procure a special hob to cut the electrode to the oversize dimensions required for the mold, cut the electrode, and machine the mold. Many times the part did not meet the dimensional requirements, and the process had to be repeated.

A more direct method of making the mold can be used if coordinates of the mold are available. This method is called wire electric discharge machining. A wire is used as an electrode, and the wire is moved in accordance with a programmed path, producing the mold cavity. The coordinates must, of course, take into account the shrinkage of the material. The computer can quickly produce the required coordinates. The necessity for the gear-shaped electrode and the tooling required to make it, along with the lead time, are eliminated. If any changes to the mold are necessary, a corrected set of coordinates can be quickly produced. Fig. 8 shows the gear tooth and the required mold. (Only one tooth is shown, but, of course, coordinates for the entire mold are produced.)

### Prototype Design and Testing

The traditional method of proving a design is to build a prototype and subject it to testing that simulates the service for which the equipment is to be produced. In many cases, the prototype fails the test and must be altered and tested again. The computer can help us by utilizing sophisticated software to identify possible problems before the prototype is built and tested. This can result in considerable saving of costs and time, as building and testing are very expensive.

- *A high-speed precision gear set problem.* A precision ground Class Q12, 8 DP, 34/133 tooth gear set is designed to transmit 2,000 HP at 20,000 RPM. The lubrication was to be with MIL-L-23699 synthetic turbine oil at 160°F. The set was built and tested. The surfaces of the teeth showed distress almost immediately and the test was aborted. The failure was diagnosed as hot scoring due to the lubricant being raised above its flash point in the mesh. Another set of gears was made with the proper amount of tip relief and retested with no further difficulty.

A computer analysis of the gears might have saved the time and expense of the failure of the first prototype. Fig. 9 is a computer-generated plot of the lubricant temperature rise from the start of active profile to the O.D. of the pinion for the first prototype. Table 7 is the computer output for the hot scoring probability for various oils. Note that the scoring probability for MIL-L-23699 is 64%.

Fig. 10 is a plot of the lubricant temperature rise for the second prototype with the tip relief applied. Table 8 shows the hot scoring probability

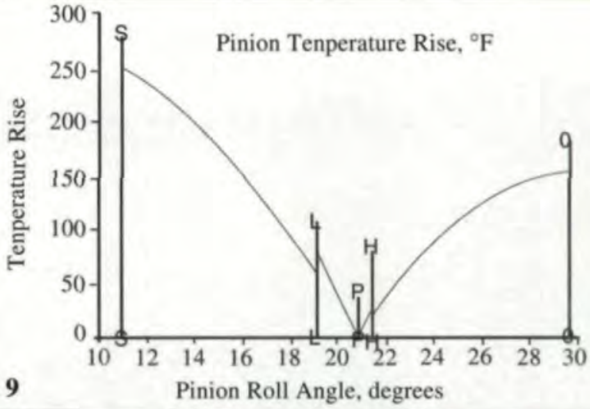

**Fig. 9**

**Table 7 - Scoring Probability - Non-Reactive AGMA & SAE Oils**

| Flash | AGMA | Score Prob | SAE | Score Prob | SAE | Score Prob |
|---|---|---|---|---|---|---|
| 413°F | Gear Oil | | Crank Oil | | Gear Oil | |
| | #1 | 98% | #5W | Over 99% | #75 | Over 99% |
| | | 94% | | Over 99% | | 95% |
| | #2 | 87% | #10W | Over 99% | #80 | 95% |
| | | 69% | | Over 99% | | 20% |
| | #3 | 49% | #20W | Over 99% | #90 | 17% |
| | | 23% | | 57 | | 2% |
| | #4 | 23% | #20 | Over 99% | #140 | 2% |
| | | 7% | | 66% | | Under 1% |
| | #5 | 17% | #30 | 66% | | |
| | | 5% | | 35% | MIL-L- | |
| | #6 | 5% | #40 | 35% | 23699 | 64% |
| | | 2% | | 11% | | |
| | #7 | 2% | #50 | 11% | | |
| | | Under 1% | | 3% | | |
| | #8 | Under 1% | | | | |
| | | Under 1% | | | | |

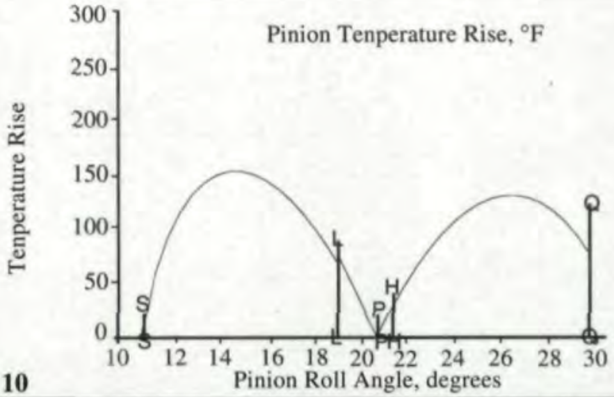

**Fig. 10**

**Table 8 - Scoring Probability - Non-Reactive AGMA & SAE Oils**

| Flash | AGMA | Score Prob | SAE | Score Prob | SAE | Score Prob |
|---|---|---|---|---|---|---|
| 317°F | Gear Oil | | Crank Oil | | Gear Oil | |
| | #1 | 12% | #5W | 61% | #75 | 61% |
| | | 6% | | 39% | | 7% |
| | #2 | 3% | #10W | 39% | #80 | 7% |
| | | Under 1% | | 19% | | Under 1% |
| | #3 | Under 1% | #20W | 19% | #90 | Under 1% |
| | | Under 1% | | Under 1% | | Under 1% |
| | #4 | Under 1% | #20 | 19% | #140 | Under 1% |
| | | Under 1% | | Under 1% | | Under 1% |
| | #5 | Under 1% | #30 | Under 1% | | |
| | | Under 1% | | Under 1% | | 10% |
| | #6 | Under 1% | #40 | Under 1% | MIL-L- | |
| | | Under 1% | | Under 1% | 23699 | |
| | #7 | Under 1% | #50 | Under 1% | | |
| | | Under 1% | | Under 1% | | |
| | #8 | Under 1% | | | | |
| | | Under 1% | | | | |

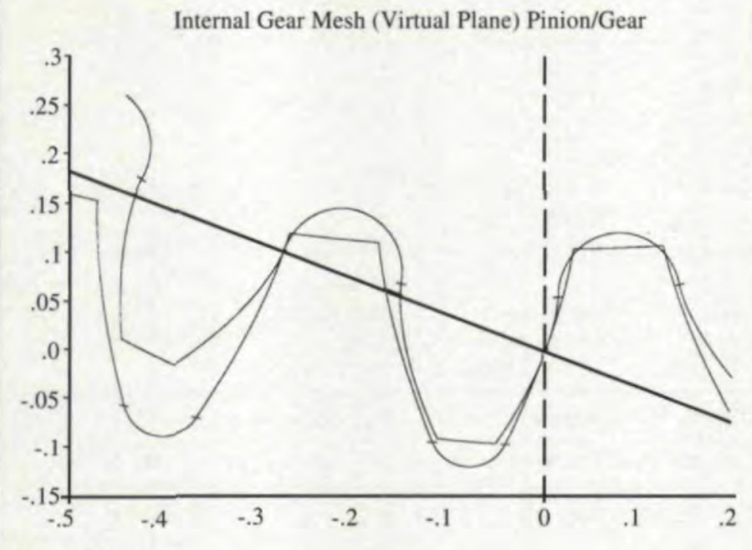

**Fig. 11**

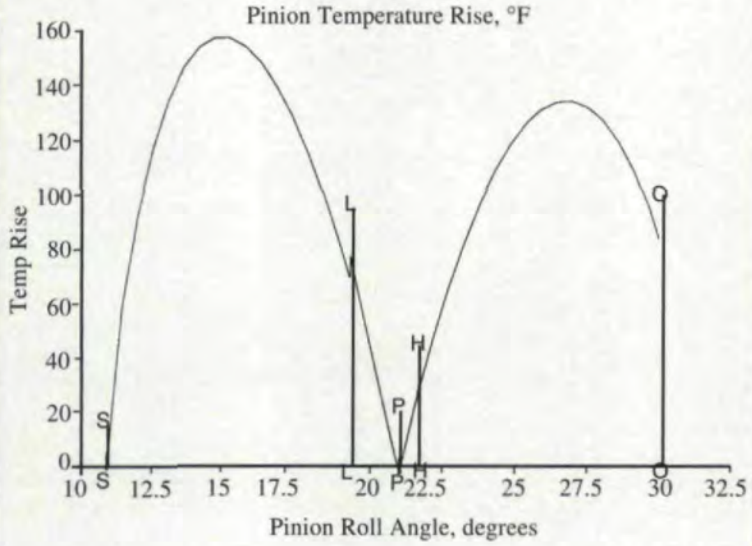

**Fig. 12**

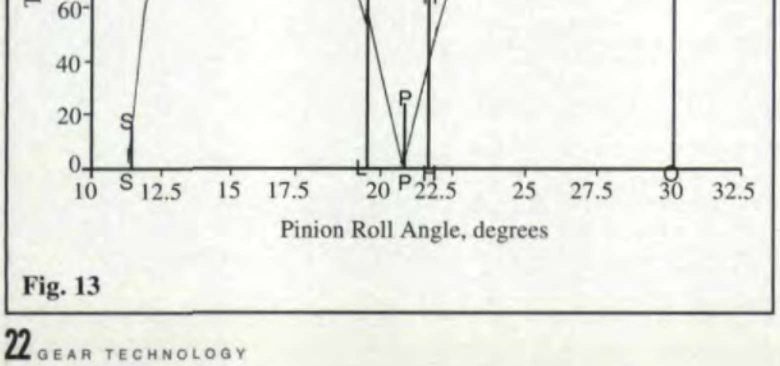

**Fig. 13**

for the second prototype. Note that the scoring probability for MIL-L-23699 is now only 10%. If the probability of scoring had been checked before the first prototype was built and tested, the expense of the first gear set and testing might have been avoided.

• *An internal gear set geometry problem.* Fig. 11 is a computer plot of an internal spur gear set with a 17-tooth pinion driving a 46-tooth internal gear. The gear set is designed in accordance with standard handbook dimensions. The gears are to be molded and have full circular fillets. On the pinion the fillet starts at the base circle. It is obvious that the tips of the internal gear teeth are interfering with the pinion roots. A test of a prototype would certainly have found this problem, but new molds would have to be made to correct it.

Computer software can be used to generate the plot from only the production prints. This is an advantage because these, not the engineering data, which never reaches the shop floor, are the only documents the manufacturing department sees. The production prints control what is built.

### Design Optimization

Without the help of computer software written with it in mind, design optimization seldom takes place. Once a design is obtained that meets the requirements of a job, the process usually stops. It is hard to justify spending more time on improving a successful design when it is not known if there will be a payback. The optimization should be done at the same time as the initial design work.

As an example, we will look at the probability of scoring for a gear set. The temperature rise in a gear mesh is dependant upon, among many other things, the load and rate of sliding between the teeth. For most gears with some tip relief, there are two zones of high temperature rise. One zone occurs when contact is between the first point of contact and the pitch point (where sliding is zero), and the other zone is between the pitch point and the outside diameter. Fig. 12 is a computer plot of the temperature rise vs. the location on the tooth from the first point of contact to the OD. The temperature rise is maximum between the start of action and the pitch point. In this case it is about 157°F. The scoring probability is about 28% for the lubricant being used.

With a small change in the outside diameters of the gears, it is possible to decrease the rise between the start of action and the pitch point at the expense of increasing the rise between the pitch point and the OD. When they are both the same, we have optimized the scoring probability controlled by gear geometry. Fig. 13 is the plot after optimization. The rise is now about 144°F, and the probability of scoring has been reduced from 28% to 20%.

The cost of the improvement is only the cost for getting the gear geometry right. The tooling cost remains exactly the same for either design. A small amount of time asking "what if" with computer software designed for this type of interaction can pay off quickly with a better design at no extra cost.

### Communication with Management Personnel

Good computer software can make communication between technical and management personnel much easier. In many cases, management personnel may not have the time to get into the technical issues, resulting in lack of management backup. This can cause delays in adoption of the latest technologies and even result in delays in production caused by a manager's need to dig for the information he or she needs to make a proper decision. Showing a busy manager a long list of numbers and trying to explain what they mean can take a lot of time and be frustrating for both parties. Computer graphics that can be quickly generated to make a problem immediately clear are most welcome to busy people.

As an example, we will look at a system reliability report on a system containing nine bearings. The required life of the system is 9,000 hours. Each bearing has a calculated life that is different, and so the likelihood that each bearing will run 9,000 hours is different. The total reliability of the system is 43.6%. We wish to improve the overall reliability of the system. Table 9 is the computer data in table form.

The information is in the table to decide the best course to improve the system reliability. Fig. 14 is the same data in graphical form. From the graph it is immediately apparent that the reliability of bearing 3 is the main problem. It is a pretty safe bet that a busy manager would rather be presented with the graph than with the table.

### Summary

Use of computers in product design and manufacturing is now fairly routine. However, to get the best results, it is important to keep the following helpful hints in mind.

**Table 9 - Anti-Friction Bearing System Reliability**

| Brg # | B-10 Life | Required Life | Reliability |
|---|---|---|---|
| 1 | 22150 Hr | 9000 Hr | 96.4% |
| 2 | 18450 Hr | 9000 Hr | 95.6% |
| 3 | 3250 Hr | 9000 Hr | 70.7% |
| 4 | 26500 Hr | 9000 Hr | 97.1% |
| 5 | 34600 Hr | 9000 Hr | 97.8% |
| 6 | 52350 Hr | 9000 Hr | 98.7% |
| 7 | 9360 Hr | 9000 Hr | 90.4% |
| 8 | 7840 Hr | 9000 Hr | 88.4% |
| 9 | 8633 Hr | 9000 Hr | 89.5% |
| System |  | 9000 Hr | 43.6% |

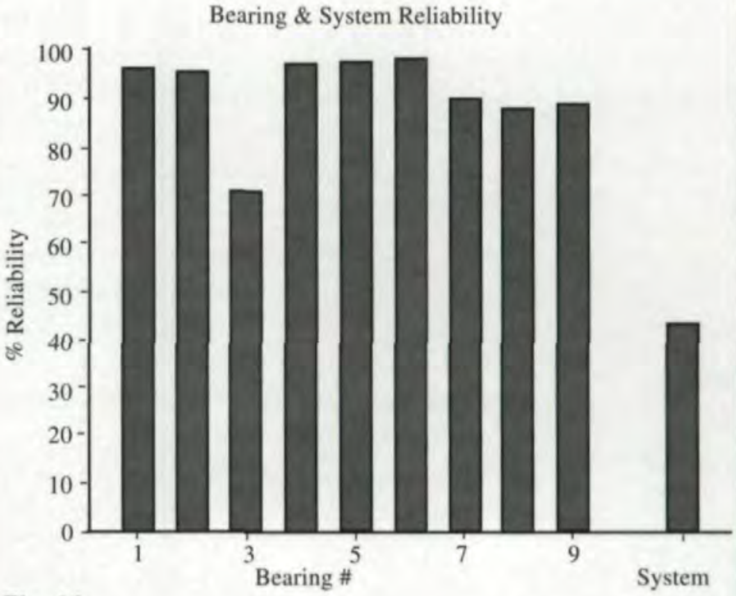

**Fig. 14**

- Do not simply computerize cook book formulae. Instead, first organize the underlying mathematics properly.

- Analyze and optimize the total system by first defining and then focusing on your objectives, such as reducing failures, increasing life, reducing noise, reducing cost, reducing lead times, etc.

- Use the concurrent engineering approach to develop product and tooling designs up front.

- Cut down on trial and error by designing correctly to start with.

- Use graphics to present your results to your colleagues and to management. A picture is worth a thousand words. ■

*A version of this article was presented at the SME Advanced Gear Processing and Manufacturing Clinic, Indianapolis, IN, September 17-19, 1991.*

# Gear Finishing by Shaving, Rolling & Honing - Part II

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The first part of this article, which has been excerpted from *Dudley's Gear Handbook*, 2nd ed., covers rotary gear shaving and appeared in our March/April issue.

### Gear Roll-Finishing

Gear roll-finishing is a fast and economical means of finishing the gear teeth of helical gears. Helical overlap is required in order to insure the smooth flow of material across the entire gear face.

Due to the speed at which gears are finished, this process is usually restricted to mass production facilities, such as in the auto industry. It is not unusual for a set of rolling dies to produce over 1 million pinions before being reconditioned. Rolling dies can normally be reconditioned between three and five times before their end of life.

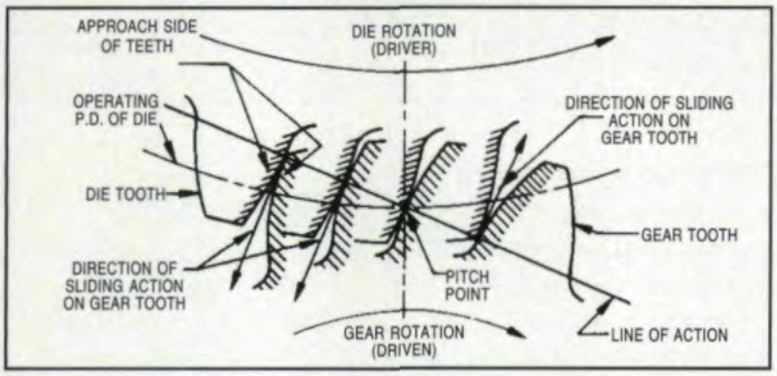

**Fig. 1 - Contact action between one tooth of a work piece and the approach side of a rolling die tooth.**

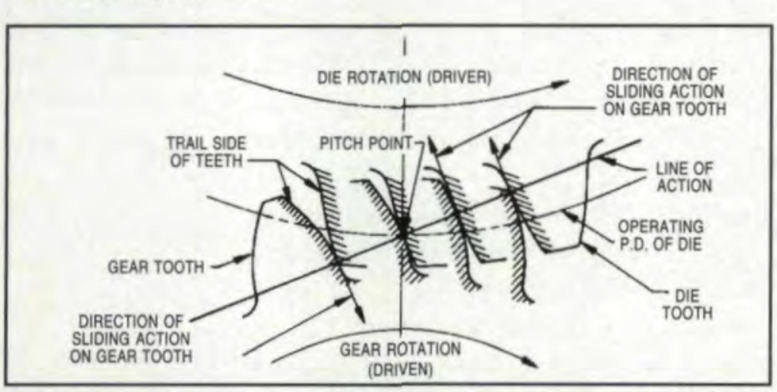

**Fig. 2 - Contact action between the tooth of a work piece and the trail side of a rolling die tooth.**

Gear rolling is a finishing operation requiring the teeth to be rough-cut by hobbing or shaper cutting.

In this discussion of gear roll-finishing, particular attention is called to the special tooth nomenclature resulting from the interaction between the rolling die teeth and the gear teeth. To eliminate confusion, the side of a gear tooth that is in contact with the "approach" side of a rolling die tooth is also considered to be the approach side. The same holds true for the "trail" side. Thus, the side of the gear tooth that is in contact with the trail side of a rolling die is also considered to be the trail side.

Gear roll-finishing is much different from gear shaving in that a flow of material is involved, rather than a removal of material. A study of gear tooth action is required to analyze the material flow in the rolling process. In Fig. 1 it can be seen that as a gear rolling die tooth engages the approach side of a work piece tooth, sliding action occurs along the line of action in the arc of approach in a direction from the top of the gear tooth toward the pitch point where instantaneous rolling action is achieved. As soon as the contact leaves the pitch point, sliding action occurs again, but in the opposite direction toward the pitch point in the arc of recession.

What is more interesting, however, is that the contact between the die and work gear teeth on the trail side produces exactly the opposite direction of sliding to that on the approach side (Fig. 2). The result of these changing directions of sliding is that material is being compressed toward the pitch point on the approach side and extended away from the pitch point on the trail side (Fig. 3).

This action causes a greater quantity of material to be displaced on the trail side than on the approach side by a ratio of about 3:1. On the approach side, the tendency is to trap the material rather than permit it to flow toward the top and root of the teeth as on the trail side. Thus, completely different from what occurs in a metal removal process such as gear shaving, the amount of material to be flowed during the rolling process, as well as the hardness of that material, have a significant effect on the accuracy of the produced form.

For successful roll-finishing, it appears that an undercut is desirable near the root section, such as with conventional preshave tooth forms. Since most production gears are also provided with a tip chamfer, the material will tend to be pulled up into the chamfer on the trail side and down away from the chamfer on the approach side.

As a result, some adjustment in hobbed tooth tip chamfer depths and angle are required to balance out the opposed metal flow conditions on each tip side. These chamfer depths and angles have to be held to close tolerances. If too much stock is left for gear roll-finishing, or if the gear material tends to be too hard (above approximately 20 Rc), several conditions may result. The sliding action on the approach side of the tooth may cause a "seaming" of material that builds up in the area of the pitch point. On the trail side, the flow of excess material may result in a burr on the tip of the gear tooth and a "slivering" of material into the root area. Fig. 4 shows the condition of a roll-finished gear tooth when too much stock is flowed or high-hardness conditions are encountered.

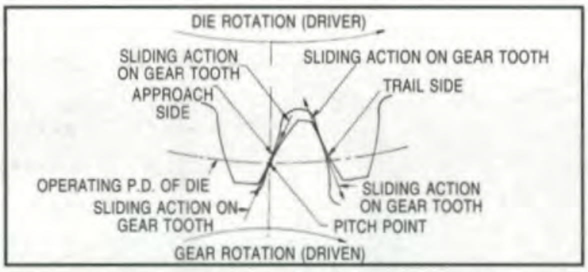

**Fig. 3 - Differing flow directions induced by each side of a die tooth with gear roll-finishing.**

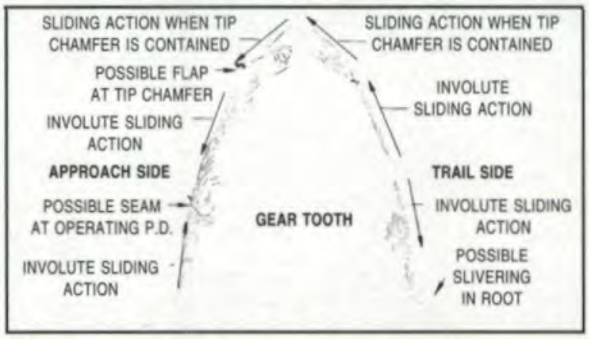

**Fig. 4 - Tooth flow pattern that results when too much stock is left for roll-finishing, or when material hardness is excessive.**

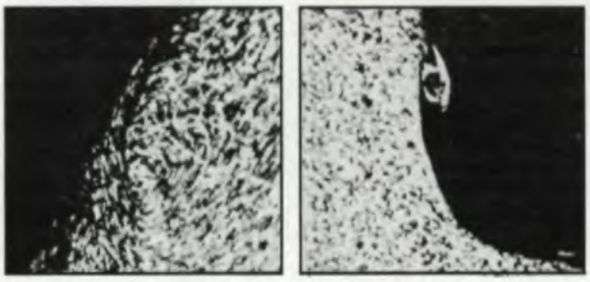

**Fig. 5 - Photomicrographs of a gear tooth with high hardness. The approach side, left, has a seam in the area of the pitch diameter. The trail side, right, shows where excessive stock has caused cold working and a sliver near the root.**

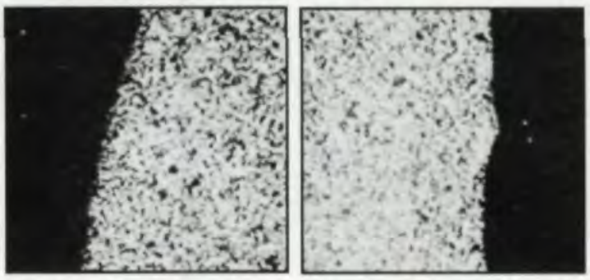

**Fig. 6 - Photomicrographs of a gear tooth that has been properly roll-finished. The approach side, left, has no seaming. The trail side, right, shows no slivering or cold working.**

In Fig. 5 photomicrographs show the conditions encountered when stock removal is excessive, material is excessive, and material hardness is too high. A seam is evident in the approach side of the tooth at the left in the area of the operating pitch diameter. The trail side photomicrograph at the right in Fig. 5 shows slivering in the root portion with about 0.1 mm (0.004") of lapped-over metal, and about 0.05- mm (0.002-in) deep surface cold working of the material.

In contrast, photomicrographs in Fig. 6 show the excellent tooth structure that can be achieved with roll-finishing if stock reduction is held to a minimum and material is not too hard. No evi-

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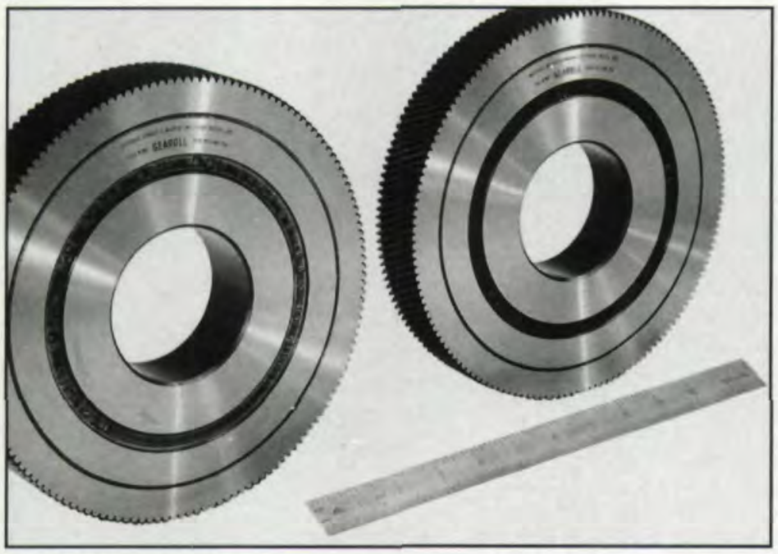

**Fig. 7 - Gear roll dies.**

**Table I - Standard tolerances for rolling dies**

| Die Specification | Tolerance - In. |
|---|---|
| Involute Profile (True Involute Form) - Active Length, tiv | |
| Through 0.177" working depth | 0.00015 |
| 0.178 through 0.395" working depth | 0.00020 |
| Lead - (Uniformity-tiv Per Inch of Face) | 0.0003 |
| Parallelism - (Opposite Sides of Same Tooth Alike Within) | 0.0002 |
| Helix Angle - (Deviation From True Angle-Per Inch of Face) | 0.0005 |
| Tooth Spacing - (Adjacent Teeth at Pitch Diameter) | 0.00015 |
| Circular Pitch - (Variation-tiv) | 0.0002 |
| Spacing Accumulation - (Over Three Consecutive Teeth) | 0.00025 |
| Runout - (tiv at Pitch Diameter) | 0.0004 |
| Face Runout - (tiv Below Teeth) | 0.0002 |
| Tooth Thickness | Minus 0.0010 |
| Hole diameter | Plus 0.0002 |

Note: Dies can be made in pairs alike within 0.0005" measured over pins if necessary.

dence of cold working or seaming is seen in the approach side at the left. In the trail side at the right in Fig. 6, no evidence of slivering or cold working is seen.

The amount of stock reduction with roll-forming should be held to about one-half that normally associated with shaving if seaming and slivering are to be avoided. The burr condition on the tip of the trail side of the tooth can be improved by close control of the angle and location of the protective tooth chamfer generated by the hob in the course of the tooth-generating operation.

*Gear Rolling Dies* - Since roll-finishing involves material flow rather than metal removal, it should be expected that the tooth form on the die would not be faithfully reproduced on the work piece tooth due to minute material springback and material flow conditions.

Even with gear shaving, it has been found necessary to modify the shaving cutter teeth profiles somewhat to produce a desired form on the work gear teeth. Experience to date has shown that a different type of tooth form modification is required for gear roll dies than for gear shaving cutters. The correct amount of gear rolling die tooth form modification is determined, as with gear shaving cutters, from an extensive development program. Less rigid gear roll-finishing machines usually require greater and varying die form modifications.

Gear roll dies (Fig. 7) are made from special

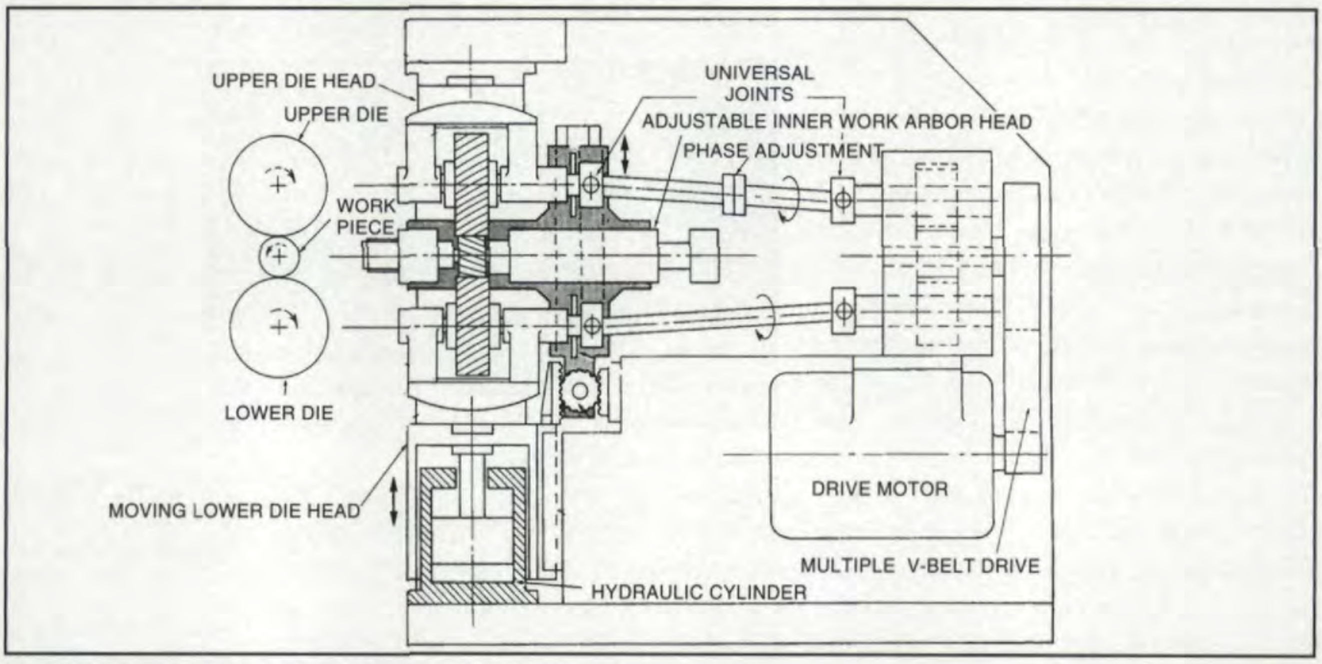

**Fig. 8 - Schematic of vertical roll machine.**

fatigue- and impact-resistant high-speed steel to the tolerances shown in Table 1.

*Gear Rolling Machines* - Several important design considerations have to be met in a roll-finishing machine. These include rigidity, strength, high-speed loading capability, die phasing, and independent adjustment for die axis and die positioning.

The force required to roll-finish a gear depends on its width, diametral pitch, tooth shape, cycle time, material, and hardness.

*Double-Die Gear Rolling* - The double-die gear roll machine shown in Fig. 8 is a vertical design with the dies mounted one above the other. It is designed to handle gears up to 10 cm (4") wide and 15 cm (6") in diameter. Die speeds are from 40 to 160 r/min. Dies up to 11.4 cm (4 1/2") wide and 24.4 cm (9 5/8") in diameter can be mounted in the machine.

The upper die head is fixed and the lower die is fed upward by a hydraulic cylinder. The gears are fed into rolling position by an air-operated automatic loader (Fig. 9). Here they are picked up on a work arbor that is advanced by a hydraulic rotary actuator utilizing a gear rack arrangement. The work gears are advanced against a pneumatically loaded cup.

The work arbor is pre-rotated by a hydraulic motor at a speed slightly slower or faster than the die speed to ensure clash-free engagement. The lower die then feeds upward to a predetermined operating position to control finish-rolled gear size.

Table 2 illustrates the range of gearing for which gear rolling dies have been produced for finish-rolling production applications.

*Single-Die Gear Rolling* - Machines have been developed to finish-roll gears with a single die. This process has proven economical in low and medium production.

A single gear rolling die is mounted in a heavy-duty gear head above the work piece (Fig. 10). The die is driven by an electric motor to provide rotation of the work piece that meshes with it. Normally semiautomatic loading methods are utilized on single-die roll-finishing machines whose work cycles are somewhat longer than those of the fully automatic, double-die machines. The work piece is mounted on an arbor between head and tailstock (Fig. 11). In operation, the table supporting the head and

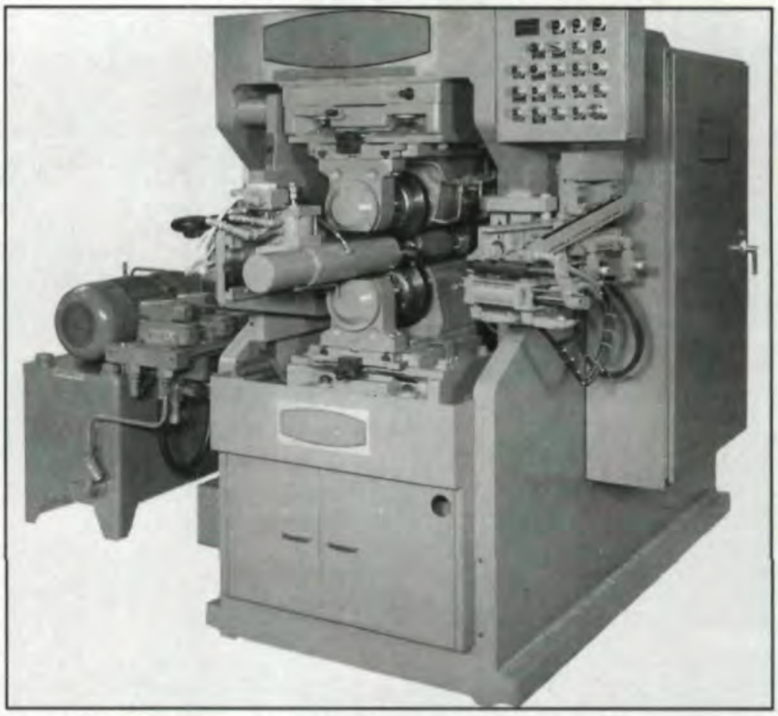

**Fig. 9 - Hinge-type auto loader on gear roll machine.**

Table II - Data on Roll-Finished Gears

| No. Teeth | Pitch Diameter (in.) | Normal Diametral Pitch | Normal Pressure Angle | Helix Angle | Hand | Face Width (In.) | Material |
|---|---|---|---|---|---|---|---|
| 26 | 4.6666 | 6.539 | 18° 28' | 23° 25' | L | 1.380 | 8620 |
| 25 | 3.3667 | 8.8709783 | 16° 30' | 33° 10' | L | 0.918 | 8620 |
| 14 | 1.0711 | 14 | 20° | 21° | L | 0.727 | 5140H |
| 17 | 1.2143 | 15.1535 | 18° 35' 09" | 22° 30' | L | 0.758 | 4024 |
| 28 | 2.0000 | 15.1535 | 18° 35' 09" | 22° 30' | R | 3.04 | 4024 |
| 18 | 1.2542 | 15.5 | 17° 30' | 22° 11' 30" | R | 1.935 | 4620 |
| 16 | 0.9621 | 18 | 18° 30' | 22° 30' | R | 0.728 | 5130, Fine Grain (5-8) |
| 34 | 2.0445 | 18 | 18° 30' | 22° 30' | L | 0.860 | 5130, Fine Grain (5-8) |
| 20 | 1.1580 | 18.5 | 18° | 21° | R | 0.874 | 4027H |
| 19 | 1.0549 | 19.3 | 20° | 21° 03' 42" | R | 0.705 | 4027H |

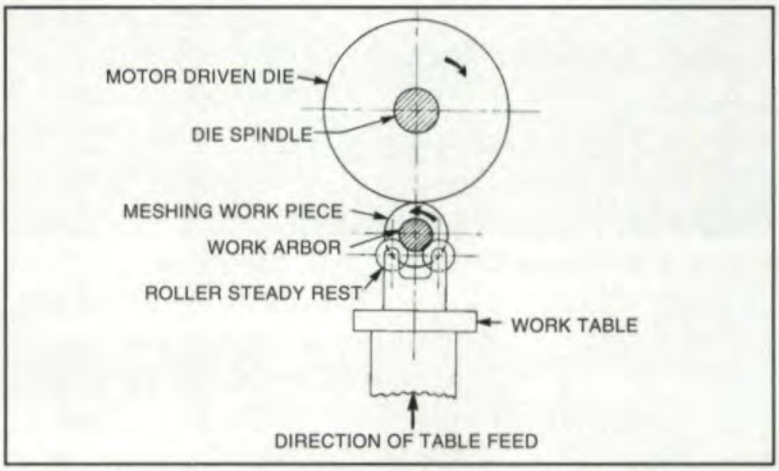

**Fig. 10 - Operating principle of single-die gear roll finishing.**

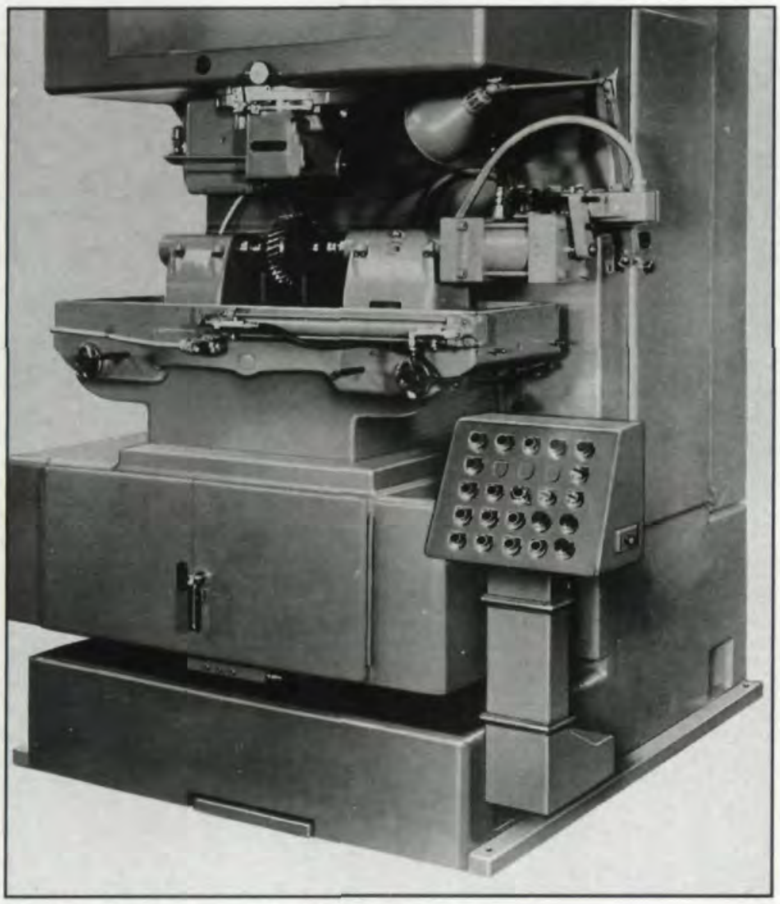

Fig. 11 - Single-die gear roll machine.

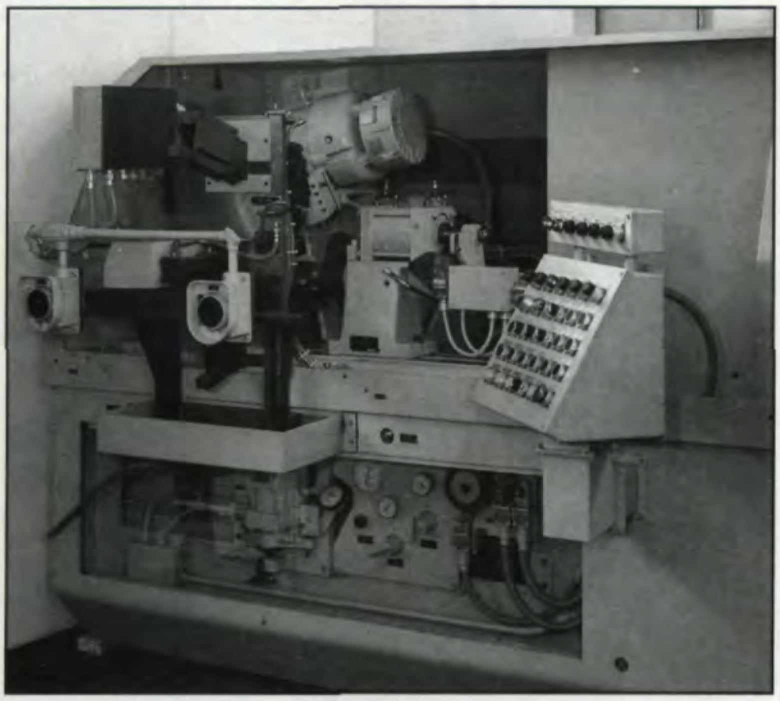

Fig. 12 - External gear honer.

tailstock is fed upward by a unique, air-powered, heavy-duty radial feed system. The continuous upfeed of the table provides the large force necessary to roll-finish the gear teeth.

During the work cycle, the work piece can be rotated in one direction for one part of the cycle, then reversed and rotated in the other direction for the balance of the cycle. This double rotation sequence tends to balance the metal flow action on the approach and trail sides of the work gear teeth.

Tooth thickness size of the work piece is controlled by adjusting the height of the table with a handwheel-controlled elevating screw.

### Rotary Gear Honing

Rotary gear honing is a hard gear finishing process that was developed to improve the sound characteristics of hardened gears by:

1. Removing nicks and burrs
2. Improving surface finish
3. Making minor corrections in tooth irregularities caused by heat-treat distortion.

The process was originally developed to remove nicks and burrs that are often unavoidably encountered in production gears because of careless handling. Further development work with the process has shown that minor corrections in tooth irregularities and surface finish quality improvement can be achieved. These latter improvements can add significantly to the wear life and sound qualities of both shaved and ground hardened gears.

Gear honing does not raise tooth surface temperature, nor does it produce heat cracks or burned spots or reduce skin hardness. It does not cold work or alter the microstructure of the gear material, nor does it generate internal stresses.

Honing machines are available for external (Fig. 12) and internal (Fig. 13) spur and helical gears. Both taper and crown honing operations can be carried out on these machines.

*How the Process Works* - The process uses an abrasive-impregnated, helical-gear-shaped tool. This tool is generally run in tight mesh with the hardened work gear in crossed axes relationship under low, controlled center-distance pressure.

The work gear is normally driven by the honing tool at speeds of approximately 183 surface m (600 surface ft) per minute. During the work cycle, the work gear is traversed back and forth in a path parallel to the work gear axis. The work gear is rotated in both directions during the honing cycle. The process is carried out with conventional honing oil as a coolant.

The honing tool is a throw-away type that is discarded at the end of its useful life. The teeth are thinned as the tool wears. This tooth thickness reduction can continue until root or fillet interference occurs with the work gear. The O.D. of the hone can be reduced to provide proper clearance.

Eventually, thinning of the hone teeth also results in root interference with the outside diameter of the work gear. When this condition occurs, the hone is generally considered to be at the end of its useful life. In some isolated cases, it has been found practical to recut the hone root diameter with a grinding wheel to provide additional hone life.

Usually the amount of stock removed from the gear tooth by honing ranges from 0.013 to 0.05 mm (0.0005 to 0.002") measured over pins.

The production rate at which honing operations can be carried out depends on the pitch diameter and face width of the work. A gear 2.5 cm (1") in diameter by 2.5 cm (1") in width can be honed in approximately 15s. A gear 61 cm (24") in diameter by 7.6 cm (3") in face width will require approximately 10 min. of honing time. Of course, honing of salvage gears required longer cycles.

A typical external gear honing machine has the motor-driven honing tool mounted at the rear of the work spindle. The work spindle is mounted on a tilting table that can be positioned to provide four selective modes of operation.

The first mode is called loose backlash, where the hone and work gear are positioned in loose backlash operation on a fixed center distance. This method is sometimes utilized to slightly improve surface finish only, primarily on fine-pitch gears with minimum stock removal.

The second mode of operation is called zero backlash. Here the work gear is positioned in tight mesh with the honing tool. The table is locked in fixed center-distance location with a preselected hone pressure. This method is sometimes used to provide maximum gear tooth runout correction with a minimum stock removal.

The third and most generally applied mode of operation is called constant pressure. The work gear is held in mesh with the honing tool at a constant pressure. This method removes nicks and burrs and provides maximum surface finish improvement in minimum time.

The fourth mode of operation is called differential pressure. A preselected low pressure is

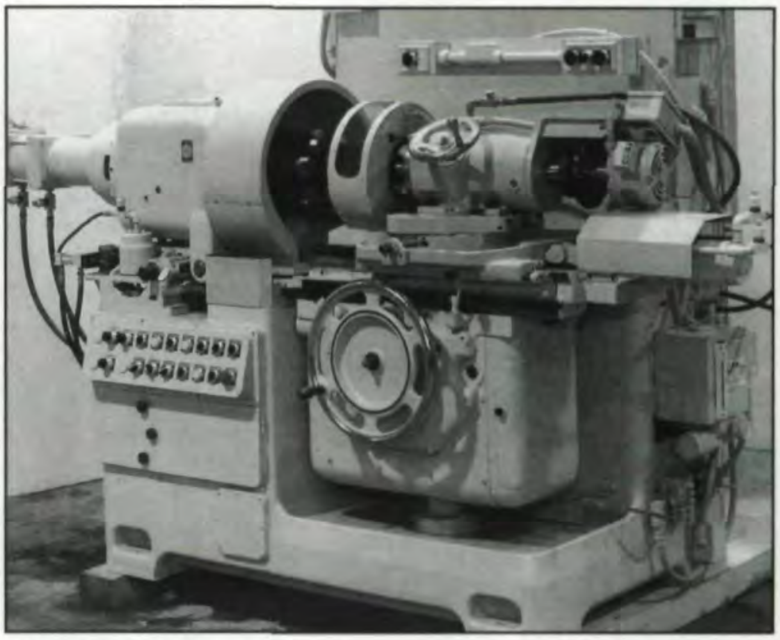

**Fig. 13 - Internal gear honer.**

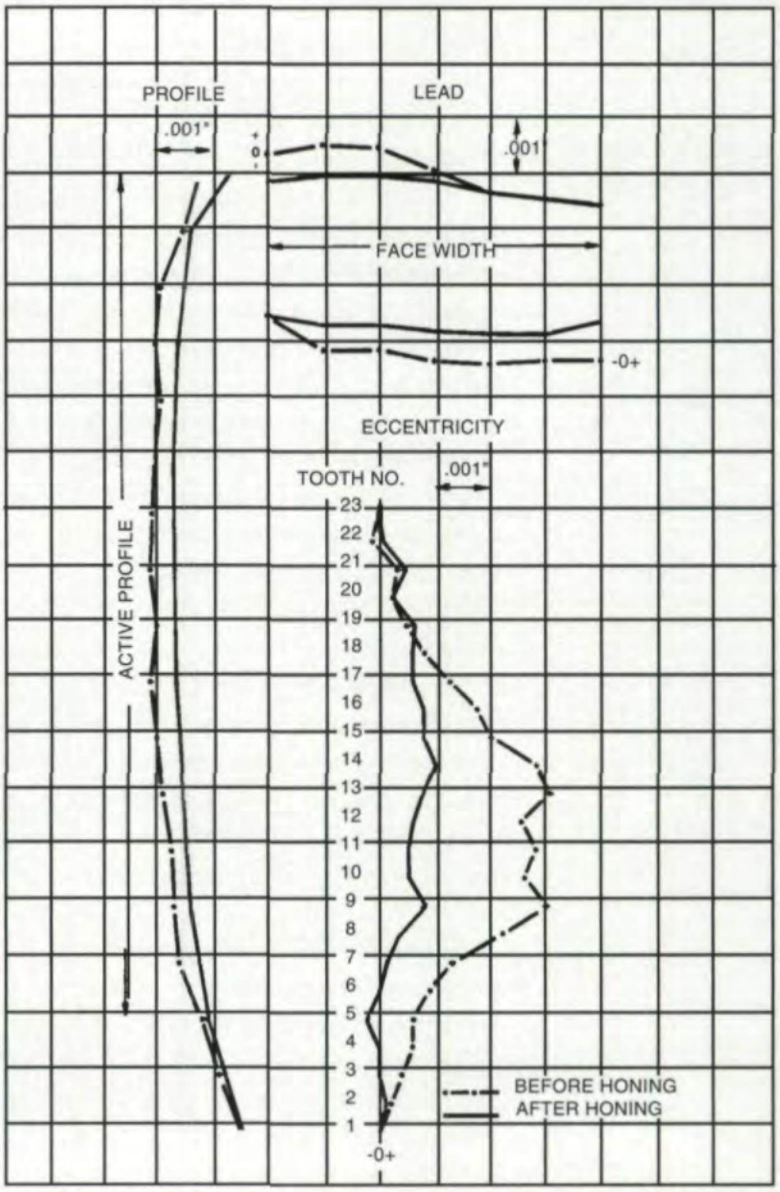

**Fig. 14 - Improvement in tooth accuracy achieved by honing.**

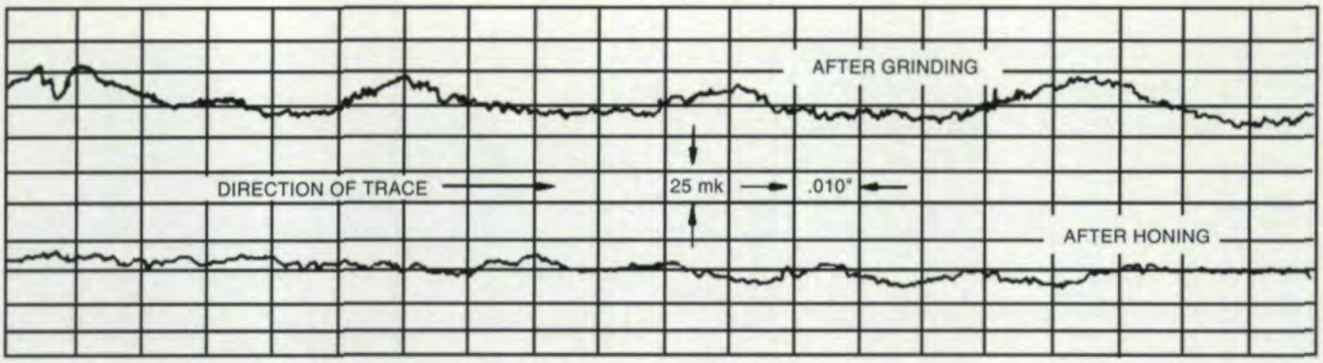

**Fig. 15 - Surface finish improvement after honing.**

present between the hone and the low point of an eccentric gear; and a preselected increased amount of pressure is present between the hone and the high point of eccentricity. This method has all of the desirable features of the constant pressure method plus the ability to slightly correct eccentricity. The amount of eccentricity in the gears with differential pressure honing may cause the hone to wear faster than with the constant pressure method.

*Rotary Gear Honing Tools* - Standard rotary gear honing tools are a mixture of plastic resins and abrasive grains such as silicon carbide, which are formed in a precision mold. They are made in a wide variety of mix numbers with grits ranging from 60 to 500, to suit special production and parts requirements.

Special tools have been developed to do salvage-type honing. The tools are made from hardened steel and the active tooth surface is plated with carbide or diamond. These harder materials give the process the ability to remove an increased amount of stock and thereby make larger corrections in tooth irregularities.

*Honing Shaved Gears* - Traditionally, tooth surface finishes in the range from 15 to 40μ in. have been provided by the rotary gear shaving operation. The honing process, because it is not basically a heavy stock removal or tooth correction process, cannot substitute for gear shaving, which is performed on the soft gear. In fact, the tendency of a hone to charge a gear under 40 Rockwell C hardness with abrasive particles makes honing of soft gears a questionable application.

However, because a gear has to be heat treated, a process that usually roughens the tooth surface to a degree, the honing process tends to restore the hardened tooth surface finish to its original shaved condition and actually improves it. In all cases, the honed surface finish is better than the surface finish before honing. (Fig. 14).

To hone production gears, economy dictates that one grit of tool and a relatively short honing cycle be used. What is produced then, in the way of surface finish, represents a compromise. First, the honing tool must remove nicks and burrs, then it should make minor tooth corrections that will improve sound level and wear life. The improvement in surface finish, which is in reality a by-product of the honing process, is a valuable adjunct that will help promote long wear life as well as improve sound characteristics.

*Honing Ground Gears* - In the aerospace industry, gears are traditionally operated at high speeds under heavy loads. They are usually cut, heat treated, and ground to provide tooth surfaces (usually of sophisticated modified forms) of the highest order of accuracy. However, tests with exotic surface measuring equipment have shown that ground surfaces have a jagged, wavy profile that will not support heavy loads or wear long unless costly break-in procedures are carried out.

Ground tooth surfaces usually have a surface finish in the 16-μ to 32-μ in range. Honing with type AA honing tools can bring the surface finish down to the 8- 10-μ in range (Fig. 15). In one 39-tooth, 5-m (5-D.P.), 20° P.A., 20-cm (7.800-in.) P.D. spur helicopter drive gear, honing of the gear teeth down to 8-μ in surface finish increased wear life by 1000% and increased load-carrying capacity by 30%. Other tests by the gearing industry have shown 100% load-carrying capacity increases by honing ground gears. ■

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HOMMELWERKE

# Effects of Temperature on Gage Repeatability & Reproducibility

**Paul B. Sagar**
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### Temperature Induced Dimensional Changes

Temperature causes various materials to change size at different rates, known as their Coefficients of Expansion (COE). The effects of this phenomenon on precision dimensional measurements are continuous and costly to industry. Precautions can be taken to allow parts and gages to temperature stabilize before conducting gage R & R studies, but the fact remains that on the shop floor temperatures vary all the time. The slow pace at which industry has accepted this reality probably has to do with the subtlety of these tiny size variations and our inability to sense gradual, but significant temperature changes.

Table 1 shows how much a steel part of a given dimension will change as its temperature varies from 70°F. The data shows, for example, that a four-inch steel work piece will change size by .001 inch when its temperature changes by 40°F, from 70° to 110°F (Table 1). Aluminum, another commonly used material in the metal working industry, has a COE almost twice that of steel, so that it expands and contracts nearly twice as much.

Depending on the overall dimension and the allowable tolerances, temperature can have a greater or lesser impact on the accuracy of measurements. The larger the work piece, the greater will be its size variation for a given temperature change. More significant, however, the tighter the tolerance spread or total tolerance, the more chance there is of a significant portion of that tolerance being used up by thermal errors.

The ratio of a dimension to its total tolerance may be known as its Tolerance Ratio. For example, if the 4.0000-inch work piece had a tolerance of +/ -.0005" (total tolerance of .001") it would have a .25% tolerance ratio. As a rule of thumb, if the tolerance ratio for a specified part is around .05% or less, it is probable that temperature should be taken into account when measurements are made. At this level of precision, even small thermal variations cause dimensional changes which start to consume a significant portion of total tolerance.

### Effects of Dimensional Changes on Gages

If, in addition to parts changing temperature between measurements, the gage should also change temperature (through handling or changes in ambient, for example), it will change size too. It is often thought that these changes will offset each other, so that the net effect will be immaterial.

As Tables 2 and 3 demonstrate, however, the net error can be considerable, particularly if the gage and the part are made of different materials. For example, an aluminum gage at 70°F, measuring a 4-inch steel part which is at 105°F, will register an error as large as .0011" (Table 2).

The temperature of the Master or Setting Standard is also a major consideration. These calibration tools are often to be found on the shop floor. But they have been meticulously manufactured to accurate dimensions at 68°F (20°C). A few degrees variance from that international standard temperature will cause this vital reference to be erroneous, so that a conventional measuring instrument that is set to zero on it will necessarily be inaccurately calibrated.

Most gages used in production today were not originally designed for the tighter tolerances required by modern manufacturing. Thermal stability and compensation were not issues when tolerance ratios were greater. Indeed, in general, modern machine tools have reached the point at which their ability to hold to highly accurate settings exceeds the capabilities of most of the gages on shop floors to measure their output. The next shop floor revolution has to be in gaging. One of the principle areas to be addressed has to do with the effects of

**Table 1 - VARIATIONS FROM NOMINAL DIMENSION WITH TEMPERATURE CHANGES**

70° being reference temperature

TEMPERATURE INDUCED DIMENSIONAL ERRORS: STEEL

Coefficient of Expansion: 6.4000 parts/million/°F

| Nominal | 30f | 40f | 50f | 60f | 70f | 80f | 90f | 100f | 110f |
|---|---|---|---|---|---|---|---|---|---|
| 1.0000 inch | -0.0003 | -0.0002 | -0.0001 | -0.0001 | 0.0000 | 0.0001 | 0.0001 | 0.0002 | 0.0003 |
| 2.0000 inch | -0.0005 | -0.0004 | -0.0003 | -0.0001 | 0.0000 | 0.0001 | 0.0003 | 0.0004 | 0.0005 |
| 3.0000 inch | -0.0008 | -0.0006 | -0.0004 | -0.0002 | 0.0000 | 0.0002 | 0.0004 | 0.0006 | 0.0008 |
| 4.0000 inch | -0.0010 | -0.0008 | -0.0005 | -0.0003 | 0.0000 | 0.0003 | 0.0005 | 0.0008 | 0.0010 |
| 5.0000 inch | -0.0013 | -0.0010 | -0.0006 | -0.0003 | 0.0000 | 0.0003 | 0.0006 | 0.0010 | 0.0013 |
| 6.0000 inch | -0.0015 | -0.0012 | -0.0008 | -0.0004 | 0.0000 | 0.0004 | 0.0008 | 0.0012 | 0.0015 |

Steel - Thermally Induced Variations

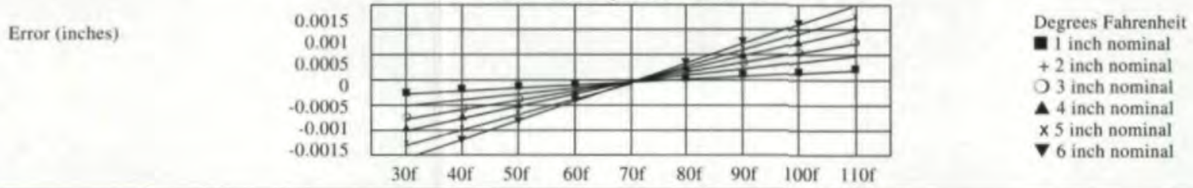


**Table 2 - NET EFFECTS OF PART AND GAGE THERMAL ERRORS**

Remaining error after partial cancellation of temperature-induced errors

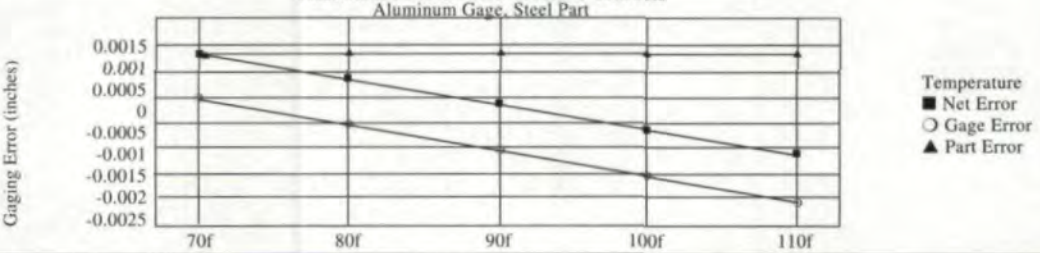
THERMAL ERROR AS ALUMINUM GAGE TEMPERATURE CHANGES

| | | | |
|---|---|---|---|
| Steel part dimension, nominal: | 4.0000 inches | Part temperature: | 105°F |
| Part dimension at 105°F: | 4.0009 inches | COE of gage: | 12.4 parts/million/°F |
| Aluminum gage starting temp: | 70°F | | |

| | 70f | 80f | 90f | 100f | 110f |
|---|---|---|---|---|---|
| GAGE ERROR | 0.0000 | -0.0005 | -0.0010 | -0.0015 | -0.0020 |
| NET ERROR | 0.0009 | 0.0004 | -0.0001 | -0.0006 | -0.0011 |

THERMALLY INDUCED GAGING ERRORS

Aluminum Gage, Steel Part



temperature on low tolerance ratios.

### Effect on Gage R & R

Specifications imply, in accordance with standards such as ANSI Y14.5M-1982, that all dimensions are to be true at 68°F. To quote the Fundamental Rules, section 1.4(k) of that standard: "Unless otherwise specified, all dimensions are applicable at 20°C (68°F). Compensation may be made for measurements made at other temperatures."

Traditional gage Repeatability and Reproducibility (R & R) studies neglect to consider the effects of temperature. Standard procedures for these studies do go out of their way to specify that gage and parts must be normalized at laboratory temperature before commencing. We go to elaborate lengths to evaluate gage performance under strictly controlled conditions, but we then put the gages out on the shop floor where environmental controls are minimal at best.

Gages are continually changing in temperature during use, and even small changes can have a major effect on their R & R. Tables 4 and 5 show the effects of temperature on a gage. Two separate R & R studies were run on the same gage. Table 4 shows the results when the setting standard (master), gage, and work piece were maintained at a constant 68°F. Table 5 shows the results of conducting the same test with the gage increasing in temperature by just 5°F.

The results show that a possibly acceptable 18.5% R & R Tolerance Analysis can deteriorate to 93.8% with just a minor temperature variation. Gage thermal error has consumed the majority of the total tolerance.

Clearly, an R & R study that disregards thermal effects when a gage is to be used in an uncontrolled environment is going to be unreliable. A review of some of the key terms relating to dimensional metrology is revealing.

We probably all remember that the work "accuracy" relates to the ability to measure true size. And that "precision" refers to the fineness of a range of measurements. A precise gage will give highly repeatable, but not necessarily accurate, results. The gage may, for example, indicate a reading of 1.2345"

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**TABLE 3 - THERMAL ERROR AS STEEL GAGE TEMPERATURE CHANGES**

Steel part dimension, nominal: 4.0000 inches
Part dimension at 105°F: 4.0009 inches
Steel Gage starting temp: 70°F
Part temperature: 105°F
COE of gage: 6.4 parts/million/°F

| | 70f | 80f | 90f | 100f | 110f |
|---|---|---|---|---|---|
| GAGE ERROR | 0.0000 | -0.0003 | -0.0005 | -0.0008 | -0.0010 |
| NET ERROR | 0.0009 | 0.0006 | 0.0004 | 0.0001 | -0.0001 |

THERMALLY INDUCED GAGING ERRORS
Steel Gage, Steel Part

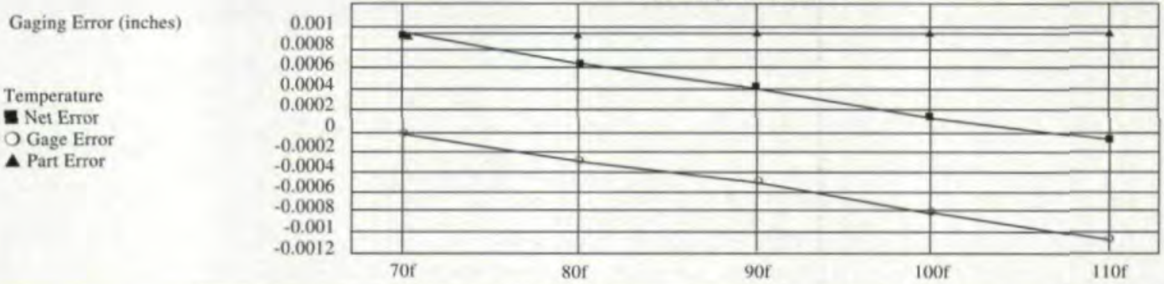

**Table 4 - MASTER, GAGE, AND PART ALL AT CONSTANT 68°F (20°C)**

GAGE REPEATABILITY AND REPRODUCIBILITY DATA SHEET

| Operator | A | | | B | | | C | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample # | 1st Trial | 2nd Trial | Range | 1st Trial | 2nd Trial | Range | 1st Trial | 2nd Trial | Range |
| 1 | 0.00025 | 0.00020 | 0.00005 | 0.00025 | 0.00020 | 0.00005 | 0.00020 | 0.00020 | 0.00000 |
| 2 | 0.00030 | 0.00025 | 0.00005 | 0.00030 | 0.00025 | 0.00005 | 0.00020 | 0.00025 | 0.00005 |
| 3 | 0.00030 | 0.00015 | 0.00015 | 0.00030 | 0.00020 | 0.00010 | 0.00020 | 0.00030 | 0.00010 |
| 4 | 0.00025 | 0.00020 | 0.00005 | 0.00025 | 0.00020 | 0.00005 | 0.00020 | 0.00020 | 0.00000 |
| 5 | 0.00025 | 0.00020 | 0.00005 | 0.00025 | 0.00020 | 0.00005 | 0.00020 | 0.00020 | 0.00000 |
| 6 | 0.00030 | 0.00025 | 0.00005 | 0.00030 | 0.00025 | 0.00005 | 0.00020 | 0.00020 | 0.00000 |
| 7 | 0.00020 | 0.00020 | 0.00000 | 0.00020 | 0.00020 | 0.00000 | 0.00020 | 0.00020 | 0.00000 |
| 8 | 0.00020 | 0.00025 | 0.00005 | 0.00020 | 0.00025 | 0.00005 | 0.00020 | 0.00020 | 0.00000 |
| 9 | 0.00025 | 0.00025 | 0.00000 | 0.00025 | 0.00025 | 0.00000 | 0.00025 | 0.00025 | 0.00000 |
| 10 | 0.00025 | 0.00020 | 0.00005 | 0.00025 | 0.00020 | 0.00005 | 0.00025 | 0.00020 | 0.00005 |
| Totals | 0.00255 | 0.00215 | 0.00050 | 0.00255 | 0.00220 | 0.00045 | 0.00210 | 0.00220 | 0.00020 |
| | - -> | 0.00255 | 0.00005 | - -> | 0.00255 | 0.00004 | - -> | 0.00210 | 0.00002 |
| | Sum | 0.00470 | $\bar{R}a$ | Sum | 0.00475 | $\bar{R}b$ | Sum | 0.00430 | $\bar{R}c$ |
| | $\bar{X}a$ | 0.00024 | | $\bar{X}b$ | 0.00024 | | $\bar{X}c$ | 0.00022 | |

Sum $\bar{R}a + \bar{R}b + \bar{R}c$ $\boxed{0.0001}$

$\bar{R}$ $\boxed{0.0000}$

Max $\bar{X}$, Min $\bar{X}$ Diff $\boxed{0.00002}$

GAGE R & R REPORT SUMMARY
Gage Type: Steel Comparator
Nominal Dimension: 5.6910 inches Total Tolerance: 0.00100 inch

| | Measurement Unit Anaylsis | Tolerance Analysis |
|---|---|---|
| Repeatability - Equipment Variation: | 0.1748 | 17.48% |
| Reproducibility - Appraiser Variation: | 0.0607 | 6.07% |
| Repeatability & Reproducibility: | 0.1851 | 18.51% |

ten times in ten separate measurement tests, being highly precise and repeatable, although a more accurate measurement may be 1.2300".

A precision measuring instrument without temperature compensation is inaccurate if the master, part, and gage are not all constantly at 68°F (20°C). The precision instrument will repeatedly give the same wrong answer until a temperature varies.

## On-Line Temperature Compensation Is A Feasible Solution

One solution is to apply on-line thermal compensation to gages on the floor. Such systems are now readily available and in use in many industrial applications. Attempts to apply this methodology to CMMs are complicated by the three-dimensional aspects of measurements, but most shop floor gaging is concerned with relatively simple, single axis dimensions, such as outside and inside diameters. This discussion is primarily focused on such gaging.

A true temperature compensating system compensates for all three of the most probable causes of thermal distortion: namely, the effects of temperature on: 1) work piece, 2) master, and 3) gage. In some cases it may also be necessary to compensate for temperature-induced electronic drift.

There are a variety of sensors which can be used to monitor the relevant temperatures. Non-contact means for high-speed applications are limited primarily to infrared, with response times measured in hundredths of a second. However, their calibration can be tricky, and they are unreliable unless constant emissivity can be guaranteed. Many contact sensors are available, some of which have fast response times, in the order of one to five seconds, and some of which are suited to slower needs.

It is usually desirable to sense the temperature of a work piece or master rapidly. However, gages tend to change temperature at slower rates, and slower temperature sensing allows a system to ignore brief, local variations.

**Table 5 - MASTER AND PART AT CONSTANT 68°F (20°C), GAGE INCREASES**
BETWEEN 68°F to 73°F BETWEEN 1st AND 2nd TRIAL

GAGE REPEATABILITY AND REPRODUCIBILITY DATA SHEET

| Operator | A | | | B | | | C | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample # | 1st Trial | 2nd Trial | Range | 1st Trial | 2nd Trial | Range | 1st Trial | 2nd Trial | Range |
| 1 | 0.00025 | 0.00000 | 0.00025 | 0.00025 | 0.00005 | 0.00020 | 0.00020 | 0.00000 | 0.00020 |
| 2 | 0.00030 | 0.00005 | 0.00025 | 0.00030 | 0.00005 | 0.00025 | 0.00020 | 0.00005 | 0.00015 |
| 3 | 0.00030 | 0.00005 | 0.00025 | 0.00030 | 0.00005 | 0.00025 | 0.00020 | 0.00010 | 0.00010 |
| 4 | 0.00025 | 0.00005 | 0.00020 | 0.00025 | 0.00005 | 0.00020 | 0.00020 | 0.00000 | 0.00020 |
| 5 | 0.00025 | 0.00000 | 0.00025 | 0.00025 | 0.00000 | 0.00025 | 0.00020 | 0.00000 | 0.00020 |
| 6 | 0.00030 | 0.00010 | 0.00020 | 0.00030 | 0.00010 | 0.00020 | 0.00020 | 0.00000 | 0.00020 |
| 7 | 0.00020 | 0.00000 | 0.00020 | 0.00020 | 0.00000 | 0.00020 | 0.00020 | 0.00005 | 0.00015 |
| 8 | 0.00020 | 0.00005 | 0.00015 | 0.00020 | 0.00005 | 0.00015 | 0.00020 | 0.00000 | 0.00020 |
| 9 | 0.00025 | 0.00005 | 0.00020 | 0.00025 | 0.00005 | 0.00020 | 0.00025 | 0.00005 | 0.00020 |
| 10 | 0.00025 | 0.00000 | 0.00025 | 0.00025 | 0.00000 | 0.00025 | 0.00025 | 0.00005 | 0.00020 |
| Totals | 0.00255 | 0.00035 | 0.00220 | 0.00255 | 0.00040 | 0.00215 | 0.00210 | 0.00030 | 0.00180 |
| | - -> | 0.00255 | 0.00022 | - -> | 0.00255 | 0.00022 | --> | 0.00210 | 0.00018 |
| | Sum | 0.00290 | | Sum | 0.00295 | | Sum | 0.00240 | |
| | | | $\bar{R}$a | | | $\bar{R}$b | | | $\bar{R}$c |
| | $\bar{X}$a | 0.00015 | | $\bar{X}$b | 0.00015 | | $\bar{X}$c | 0.00012 | |

Sum Ra + Rb + Rc
0.0006

$\bar{R}$
0.0002

Max $\bar{X}$, Min $\bar{X}$ Diff
0.00003

GAGE R & R REPORT SUMMARY
Gage Type: Steel Comparator
Nominal Dimension: 5.6910 inches Total Tolerance: 0.00100 inch

| | Measurement Unit Anaylsis | Tolerance Analysis |
|---|---|---|
| Repeatability - Equipment Variation: | 0.9348 | 93.48% |
| Reproducibility - Appraiser Variation: | 0.0742 | 7.42% |
| Repeatability & Reproducibility: | 0.9377 | 93.77% |

**Table 6 - PISTON DIAMETERS**
**Nominal Dimension: 1.75000 inches**

| | Part at 72°F | | Part at 82-88°F | | Part at 77°F | | | |
|---|---|---|---|---|---|---|---|---|
| | Gage at 75°F | | Gage at 75°F | | Gage at 86-92°F | | Ranges | |
| Part # | No Comp | With Comp | No Comp | With Comp | No Comp | With Comp | No Comp | With Comp |
| 1 | -0.00195 | -0.00210 | -0.00175 | -0.00200 | -0.00235 | -0.00200 | 0.00060 | 0.00010 |
| 2 | -0.00230 | -0.00235 | -0.00195 | -0.00240 | -0.00270 | -0.00245 | 0.00075 | 0.00010 |
| 3 | -0.00195 | -0.00195 | -0.00160 | -0.00200 | -0.00270 | -0.00195 | 0.00110 | 0.00005 |
| 4 | -0.00190 | -0.00195 | -0.00155 | -0.00195 | -0.00270 | -0.00200 | 0.00115 | 0.00005 |
| 5 | -0.00170 | -0.00170 | -0.00140 | -0.00170 | -0.00245 | -0.00180 | 0.00105 | 0.00010 |
| 6 | -0.00185 | -0.00190 | -0.00150 | -0.00185 | -0.00250 | -0.00195 | 0.00100 | 0.00010 |
| 7 | -0.00215 | -0.00215 | -0.00190 | -0.00215 | -0.00275 | -0.00225 | 0.00085 | 0.00010 |
| 8 | -0.00215 | -0.00220 | -0.00195 | -0.00225 | -0.00310 | -0.00225 | 0.00115 | 0.00005 |
| 9 | -0.00210 | -0.00210 | -0.00165 | -0.00200 | -0.00285 | -0.00205 | 0.00120 | 0.00010 |
| 10 | -0.00195 | -0.00195 | -0.00155 | -0.00190 | -0.00270 | -0.00190 | 0.00115 | 0.00005 |
| Ave: | -0.00200 | -0.00204 | -0.00168 | -0.00202 | -0.00268 | -0.00206 | 0.00100 | 0.00008 |
| | | -0.00200 | - -> | -0.00168 | - -> | -0.00268 | Range of Ave. | |
| Ave. Variation: | | -0.00004 | | -0.00034 | | -0.00062 | Variation | 0.00096 |

Microprocessors are used to collect the electronic signals from the sensors and the measuring probe(s) or system. An algorithm applies programmable coefficients of expansion for work piece, master, and gage to nominal dimension and the collected data, and outputs a dimension as if all these components were at a constant 68°F, regardless of their true temperature.

A setup such as this must of necessity assume that the components are all at some stable temperature. It does not matter when that temperature is (within reason), so long as each component is at some constant temperature throughout its body. It would be possible, but overly complex, to use multiple sensors to verify that this were true. In practice, however, it is unusual to find significant variations within any single component.

To illustrate the effectiveness of these systems, a study of ten aluminum pistons was performed. The results appear in Table 6. Using the same gage, with thermal compensation mode first switched off (No Comp) and then turned on (With Comp), the parts were measured while temperatures were varied. At first the gage and part were at roughly the same temperature. Then the parts were heated by about ten to fifteen degrees F. Finally, the gage was heated by approximately fifteen degrees.

The range of non-compensated errors averaged .001", while the average error range of the gage when in temperature compensating mode was less than .0001", representing a greater than ten fold improvement. Clearly, this represents a significant upgrading capability, and demonstrates the significance of considering compensation for thermal effects when specifying shop floor, close tolerance gaging.

Temperature compensation for gaging holds out the real possibility of constantly measuring under uniform conditions, without going to the extreme trouble and expense of providing environmental control. Here is a significant opportunity to substantially improve quality and save costs of scrap, downtime, and rework, that should be considered for all precision gaging and production processes.■

# Gear Blanking

**Robert Endoy**
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### Scope

The term "blanking" refers to the initial metal cutting operations in the process planning sequence which produce the contour of a part starting from rough material.

The scope of blanking is:

- To remove the excess material
- To machine the part to print specifications, except for those surfaces with subsequent finishing operations.
- To leave adequate machining stock for finishing operations
- To prepare good quality surfaces for location and clamping of the part throughout the process.

*Process Selection.* Processes and machines for blanking of driveline parts are selected based on part configuration and production volume.

<u>Part Configuration</u>. Gears, countershafts, and cluster gears can be described as being rotational parts. As such, the contour of the part can be generated by a single point tool travelling longitudinally along the axis of the part, while the part rotates around its axis.

Depending on the diameter-to-length ratio, rotational parts can be further classified as disk type and shaft type parts (Fig. 1).

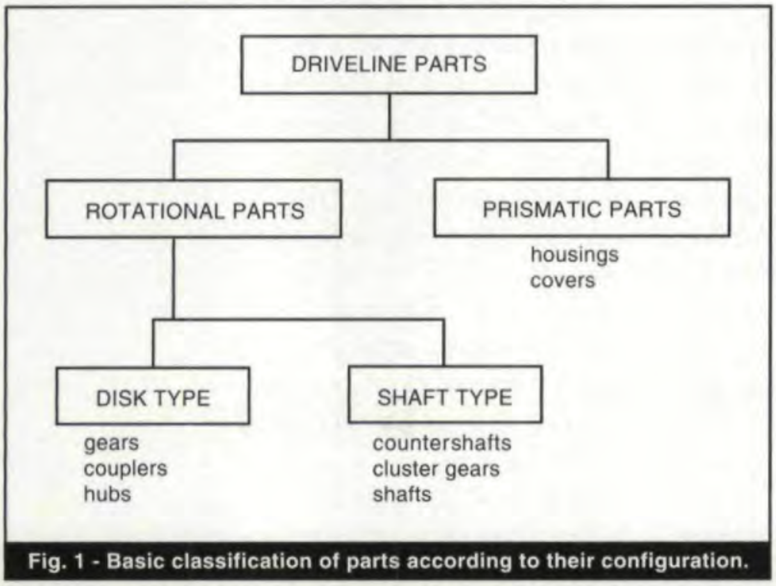

**Fig. 1 - Basic classification of parts according to their configuration.**

The sequence of operations and machinery required to produce blanks is characteristic for each basic configuration.

Disk-type parts, such as gears, are turned on open-ended lathes or chuckers, which locate and clamp the part on internal or external diameters in concentric chucks.

Shafts, on the other hand, are located between centers. The first operation consists in machining the end faces of the shaft to a specific length and drilling opposite and in-line center holes.

<u>Production Volume</u>. The type of machine used for a specific blanking operation and the degree of automation is determined by the required output in pieces per hour of the operation.

Low-volume production is processed on manually operated, universal machinery with standard low-cost tooling. This type of job shop equipment typically handles a wide variety of parts in lot sizes of one to several hundred.

A medium-volume production line is set up to handle a family of 10 to 20 parts in quantities of several thousand per year. Monthly requirements are produced in batches of 500 to a few thousand, with line change-over between production runs.

This is the sector of the manufacturing industry where CNC machines are employed to their fullest potential. The versatility and change-over flexibility of CNC equipment make it ideally suited for short intermittent production runs. The universal tooling packages used on CNC lathes and chuckers, combined with short change-over time, result in efficient batch production at low inventory level.

The inherent accuracy of CNC machines offers the added advantage of roughing and finishing in the same setup, reducing the number of machining operations in the process plan.

Characteristically for a high-volume production line, machining operations must be completed in very short cycle times. For instance, to make one million pieces per year in a three-shift operating pattern at 80% efficiency, machine cycle time plus part handling must be less than 15 seconds per part.

To meet line speed demands, roughing and finishing operations are processed on separate machines. Multi-spindle machines with special dedicated tooling are used to cut more than one part per cycle. Automatic loading and unloading of parts is used extensively to reduce idle time to the minimum.

Rough Material. Barstock, forgings, extrusions, or precision forgings are used to make driveline gears and shafts. The most suitable raw material form is selected, based on a financial evaluation which includes all manufacturing costs, raw material, vendor tooling, inhouse machining cost, and investment in facilities and tooling.

Barstock is the simplest and cheapest form of raw material frequently used for small-lot sizes. More complex fabricated forms like forgings and extrusions become economically attractive with increasing production volumes.

### Barstock

Hot rolled barstock is extensively used in job shop work. The advantages of barstock are:

- Low purchase cost. Rolled barstock from the mill is the least costly material available.
- Short lead time. Barstock is offered in standard sizes which are available from stock.
- No vendor tooling cost. Barstock is selected from existing standard sizes and requires no special operations by the vendor.
- Many sources. Changing from one supplier to another does not create problems. Purchasing is not locked in with only one supplier.

The disadvantages of barstock are:

- High material waste. Parts with large variation in diameter have a high percentage of wasted material.
- Long machining time. Removing excess material requires many turning passes on lathes.
- More machining operations. Barstock needs to be cut to individual lengths before it can be processed.
- Special handling for transport and storage.
- Material strength may be affected due to the interrupted fiber flow in the part.

In general, there is no cost advantage in using barstock instead of fabricated raw material. It is the appropriate solution for low-volume production because it avoids investment in vendor tooling and is readily available. The low material cost is, however, more than offset by the cost of additional machining and the high proportion of wasted material.

**Table 1 - Process, Machines, and Equipment Characteristics in Low-, Medium-, and High Volume Manufacturing Operations**

| Process Characteristics | Low Volume | Medium Volume | High Volume |
|---|---|---|---|
| Machines and Equipment | | | |
| Universal Machines | yes | yes | no |
| CNC Machines | yes | yes | no |
| Multi-spindle Machines | no | no | yes |
| Special Machines | no | no | yes |
| Manually Operated | yes | no | no |
| Automatic Cycle | no | yes | yes |
| Material Handling | | | |
| Manual Part Handling | yes | yes | no |
| Automated Part Handling | no | no | yes |
| Flexible Automation - Robots | no | yes | yes |
| Tooling | | | |
| Universal Tooling | yes | yes | no |
| Special Tooling | no | no | yes |
| Operating Conditions | | | |
| Change Over | yes | yes | no |
| Number of Different Parts | >100 | 10-20 | 1 |
| Labor Content | High | Low | Low |
| Floor Layout | Stand alone | Line | Line |
| Retooling Cost for New Parts | Low | Low | High |
| Production Lot Sizes | 1-500 | 500-2,000 | Continuous |
| Annual Production Volumes | 1-500 | 500-20,000 | >100,000 |

When the variation in section is small, barstock can be used economically for high-volume production. Examples are screw machine parts, shifter rails, spool valves, pins, etc.

### Forgings

Forgings are used for medium- and high-volume production. The fabricated form is made as close as possible to the finish contour of the part to reduce machining time and to keep the

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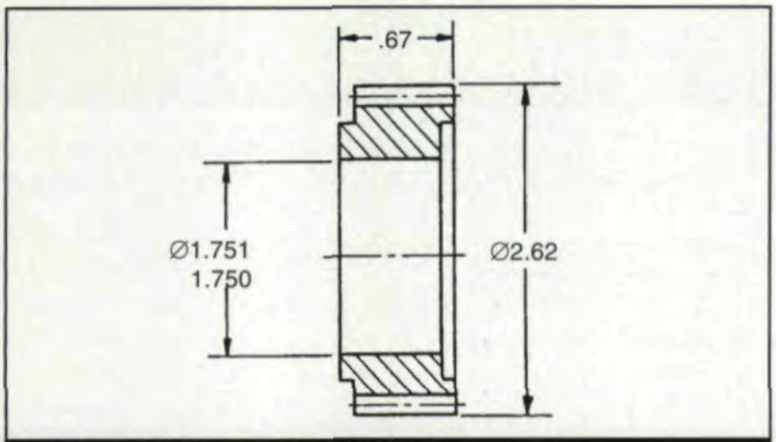

Fig. 2 - Planet gear made from barstock.

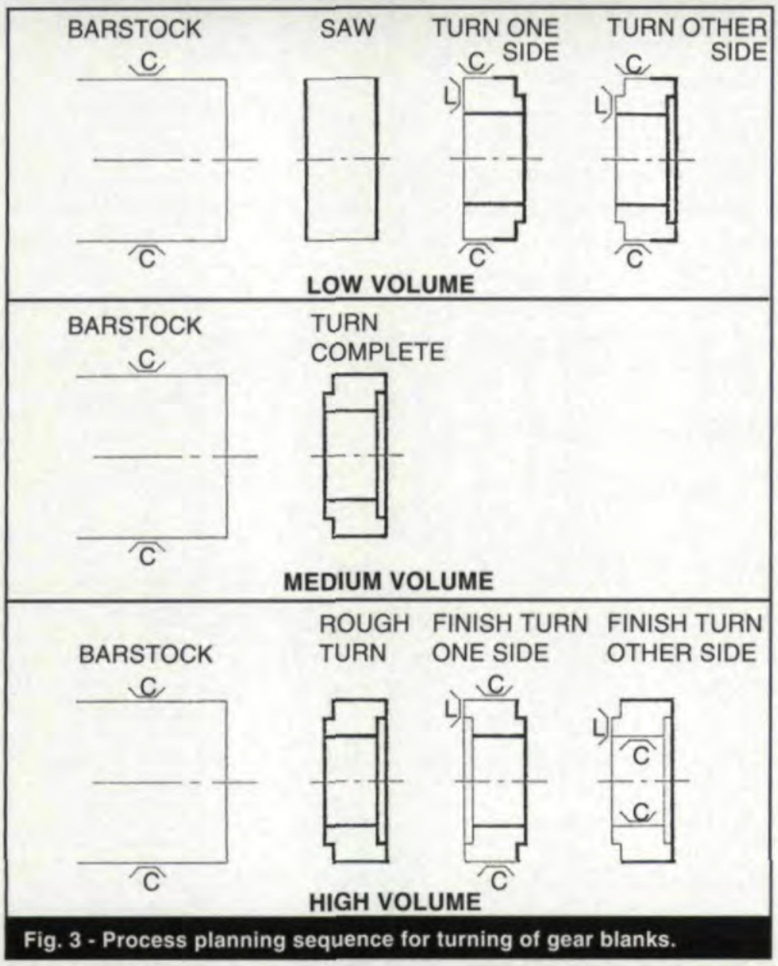

Fig. 3 - Process planning sequence for turning of gear blanks.

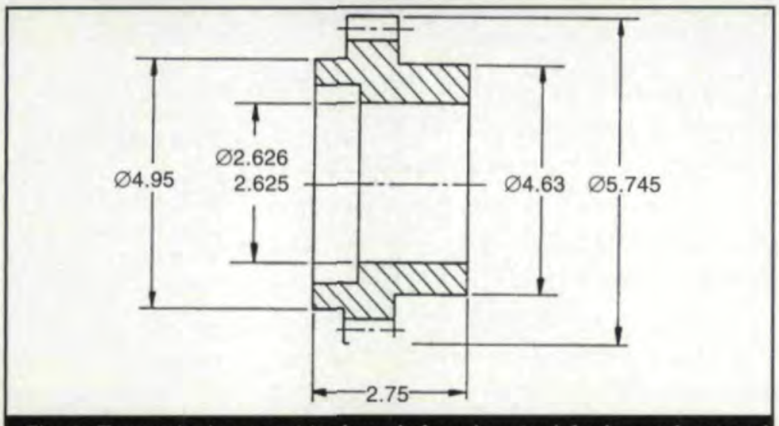

Fig. 4 - Transmission gear blank made from barstock for low-volume and from forging for medium- and high-volume.

amount of wasted material low. Forging tolerances are held within ±0.030" (0.8 mm) and machining stock allowance is in the range of 0.080 to 0.120 per side. The surface finish of forged surfaces is around 500 micro-inches.

The advantages of forgings are:

- Short machining times. The raw material is shaped close to the final contour of the part and excess material can usually be removed in a single turning pass.
- Less machining. Nonfunctional surfaces do not require machining. Forging tolerances and surface conditions permit usage of parts with surfaces in forged condition.
- Higher material strength due to the oriented fibers and the compact material structure.
- Easy to handle and transport.

The disadvantages of forgings are:

- Forgings have parting lines, draft angles of 3 to 6°, and flash trim marks which affect tooling performance.
- Higher material cost in dollars per unit of weight.
- Forgings require vendor tooling and lead time.

Forgings are economically feasible even at relatively low volumes of 500 to 1,000 pieces per year. Vendor tooling cost for drop forgings and upset forgings commonly used for gears and shafts can be written off over a few thousand pieces.

Precision hot forgings or flashless forgings for automotive parts are produced on transfer forging presses. Precision forgings have minimum draft angles of $^1/_2$ to 1° and no parting lines. Machining stock allowance is only 0.040" (1.0 mm) and length and diameter dimensions are held within ±0.012" (0.3 mm) tolerance.

### Extrusions

Cold extrusion is the most sophisticated form of rough material which finds economic application in high-volume production of automotive parts.

The advantages of extruded parts are:

- Close tolerance control. Extrusion tolerances can be held within 0.005" (0.13 mm) on the diameter and 0.060" (1.5 mm) overall length.
- Excellent surface finish. Cold extrusion produces surfaces with finishes ranging between 32 and 125 microinches (0.8 and 3 mm).
- Improved mechanical properties. The work hardening effect of cold forming in-

creases the tensile strength and yield strength.

- Minimum wasted material because of the close tolerances which can be held with extrusion techniques.
- Machining savings. Extruded surfaces may be used in the final product because they provide extremely smooth finish and close tolerance control.

The disadvantages of extrusions are:

- High piece cost
- Very high vendor tooling cost. Investment in equipment and tooling is virtually never justified by low- and medium-volume production requirements.

### Examples of Blanking Operations

The following three examples of blanking operations illustrate the principles explained in this section.

*Example 1.* A small planet gear which, because of the small outside diameter and the uniformity in section, is made most economically from barstock (Fig. 2).

When a small quantity of parts is required, as for prototype work, the barstock is sawed into individual pieces, and the part is turned completely in two setups on a lathe (Fig. 3).

Short intermittent runs of 500 to 2,000 pieces are produced most effectively on a single spindle CNC barchucker that performs the complete rough and finish turning operation in one setup.

A mass production manufacturer will utilize a multi-spindle barchucker to perform the rough turning operation, followed by two separate setups to finish-turn both sides of the gear.

*Example 2.* Transmission gear blank made from barstock for low-volume and from forging for medium- and high-volume (Fig. 4).

The low-volume process consists of cutting the barstock to length and roughing and finishing in two setups on a lathe (Fig. 5).

Medium-volume processing starts with a forging which is rough- and finish-turned in two setups on a single-spindle CNC chucker.

To meet the required output per machine, the high-volume process splits the turning operations in separate roughing and finishing setups on multispindle machines.

*Example 3.* Fig. 6 illustrates a transmission countershaft with a gear on one end of the shaft.

The low-volume process starts with barstock which is cut to length and prepared for turning by facing both ends and drilling center holes (Fig. 7). Two turning operations are planned to finish-turn the external contour of the part. This is followed by an internal turning operation on a chucker where the part is clamped and located on the outside diameter near the gear. This example illustrates the inefficient material utilization of barstock, as almost half the material is wasted in chip removal.

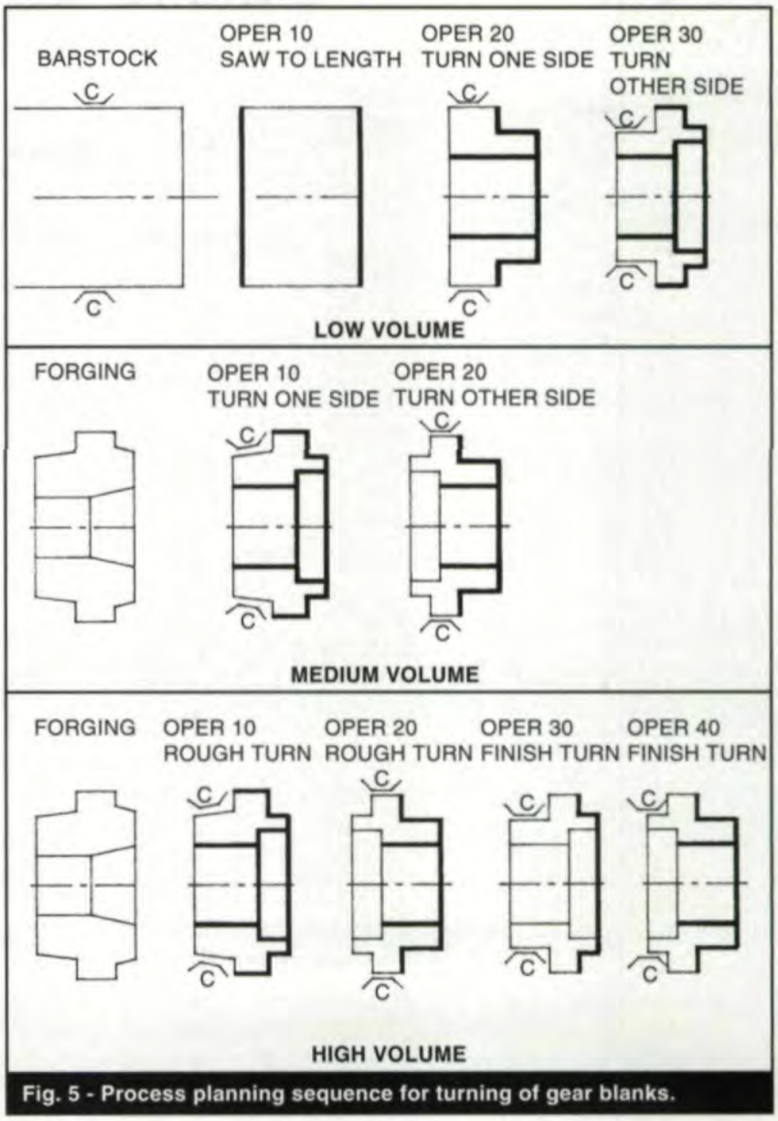

Fig. 5 - Process planning sequence for turning of gear blanks.

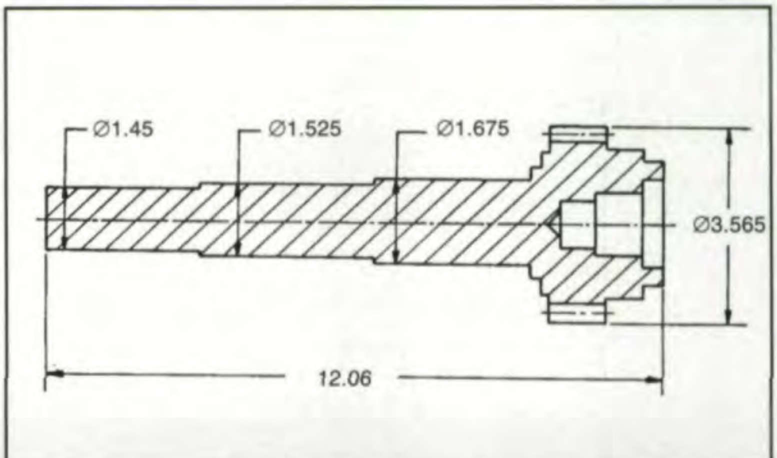

Fig. 6 - Transmission countershaft with a gear on one end of the shaft.

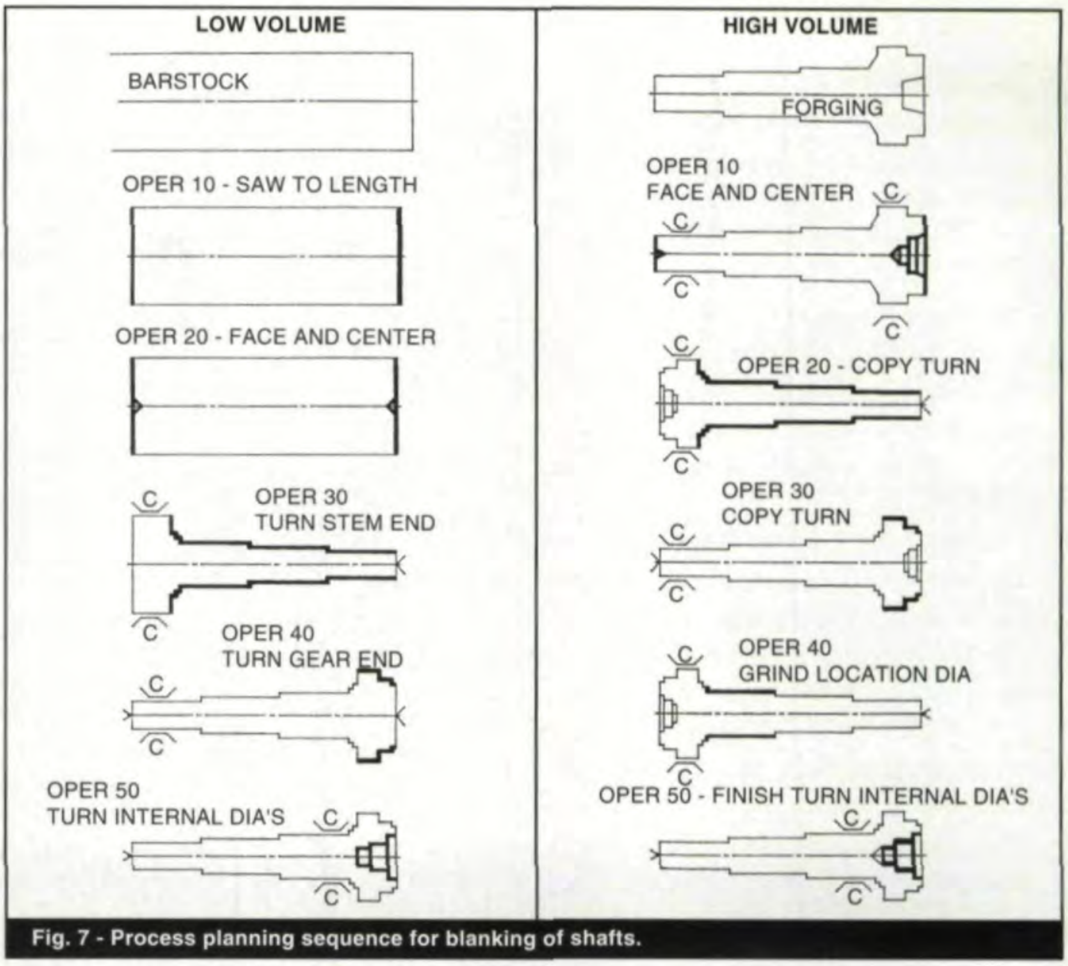

Fig. 7 - Process planning sequence for blanking of shafts.

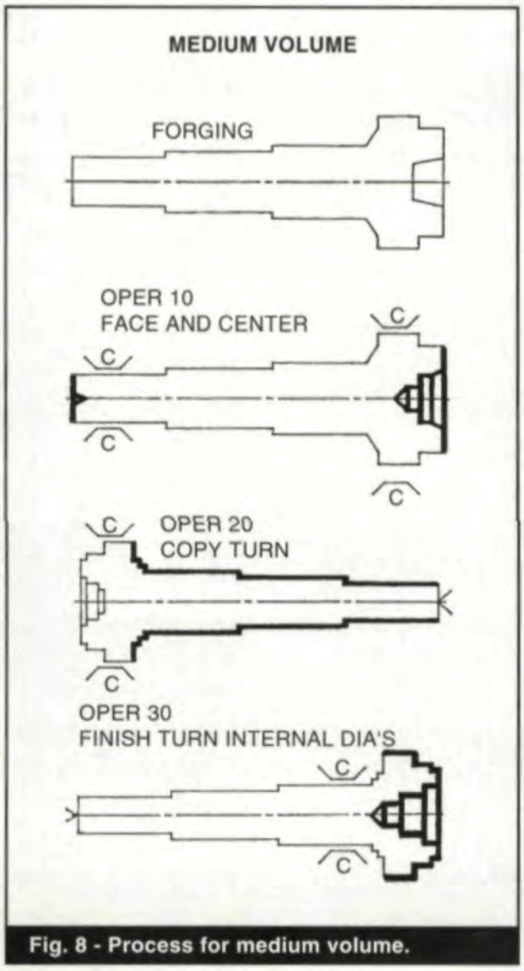

Fig. 8 - Process for medium volume.

The high-volume process starts with a forging which is faced and centered on both sides, while the internal diameters are roughed in the same setup. Two copy turning operations turn the external contour. The outside diameter near the gear is ground in operation 40 to control the runout of the diameter used as locator in operation 50 (Fig. 7) and in the gear cutting operation, which is not shown here.

A medium-volume process with fewer operations is possible by combining operations 30 and 50 in one setup. The external and internal diameters are rough- and finish-turned on a CNC chucker in operation 30. Grinding of the location diameter is not required, provided good runout tolerance can be maintained in operation 20. If operation 20 also is performed on a CNC lathe, the location diameter can be machined to close tolerances in one additional finishing pass (Fig. 8). ■

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*Excerpted from Gear Hobbing, Shaping & Shaving by Robert Endoy. ©1990, Society of Manufacturing Engineers, Dearborn, MI. Reprinted with permission. For information on this publication, call 800-733-4SME.*

# Cost-Cutting ABCs

***A new approach to accounting - Activity-Based Cost Management - can reveal hidden assets and liabilities.***

**Lawrence M. Kohn**

Cost cutting. It's the aerobics of the 90s for businesses large and small. More than just the latest buzzword or 90-second flash-in-the-panacea, it's a survival technique. Companies that aren't trimming the fat now may not be around in five years to regret that they didn't.

But cost cutting is a lot easier to talk about than to do. Some cuts, like key personnel, can be a false economy; much of the waste may be hidden; and maybe, as a manager, you feel you've cut costs to the bone already. So how to cut more, and where?

One technique for getting the crucial information you need to make *effective* cost cuts is a system called ABC - Activity-Based Cost Management. Corporations like Tektronix, IBM, Hewlett-Packard, and Weyerhaeuser are using this system to find the real costs of production.

ABC involves breaking down the entire production process into segments and then, through analyzing direct costs and through a process of allocation, discovering the costs and revenues that are associated with each step. The cycles of activity in each step and how those change over time are also analyzed. The end result is some solid intelligence about what each step is costing on a per-unit basis.

"ABC means you have to understand your process in detail, not just labor and materials, but the particular thorny piece - the overhead and indirect costs. The goal is to understand all the things you have to do to produce a unit - what the costs are, both direct and indirect, for every step of the way," says Steve Duffy, Managing Director, Managing Consulting Services for Kenneth Leventhal & Co., an accounting firm with offices in 13 cities.

> **"WHAT YOU WANT TO DO IS GIVE THE NUMBERS TO THE PEOPLE IN THE PROCESS, WHO, WHEN THEY CHANGE THEIR BEHAVIOR, CAN AFFECT THEM."**

## MANAGEMENT MATTERS

Many of these indirect costs are overlooked by conventional cost management systems, which were developed at a time when direct labor was the main variable cost of production, and, hence, was the one most closely monitored. Now, according to *Business Week*, automation has cut hands-on labor costs to 15% of manufacturing costs, and overhead accounts for 55%. But these indirect costs are spread across all products using the same formula. As a result, managers seldom know a product's real costs, making it difficult, if not impossible, to trim them effectively.

ABC tracks the costs of overhead functions - everything from R&D to advertising - and attaches them to the products and services that use them. "What ABC gives you," says Duffy, "is a fully loaded profit and loss profile of a unit on a manufacturing basis." This profile, in turn, makes it easier for managers to pinpoint places where cost-cutting or improved efficiency are called for.

Successful implementation of ABC requires a de-

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**Lawrence M. Kohn**
*is president of Kohn Communications, a Los Angeles-based marketing and management consulting firm. He is a writer on business subjects and a local media personality.*

tailed understanding of how a company works and how each product manufactured is brought to market, step by step. It requires the accountants to go out and visit the factory floor, and, even more important, according to Duffy, the entire production team to be really in touch with the actual numbers involved in manufacturing the product.

When a company decides to implement the ABC system, usually the first step is to gather a team, including the shop workers and the secretaries, to chart each step of the manufacturing process, from the beginning of design until the finished product is delivered to the customer. These charts reveal which steps add value to the product, and which ones don't. This knowledge then enables a company to go to work on reducing "hidden" costs.

Sounds good, but how much work - and expense - is involved in getting an ABC system up and running? That depends, says Duffy. "...on how far a company has already gone in terms of breaking down production and really allocating costs. Typically, the tighter a company has been because of low profit margins or keen competition, the easier it is."

And the difficulty of implementing the system? Not a lot if done properly. Careful planning is the key. Duffy suggests that creating a we/they situation between the accountants and the manufacturing team could be a serious mistake.

**"WHAT ABC GIVES YOU IS A FULLY LOADED PROFIT AND LOSS PROFILE OF A UNIT ON A MANUFACTURING BASIS."**

"These initial steps can be a false start, even though the intentions are good," he says. "If you bring the numbers people in and set them up as a kind of separate organization, apart from the people involved in the productive process, you may just add to the overhead."

What is needed instead is a cohesive, joint team of accountants, management and shop floor personnel. "What you really want to do is give the numbers to the people in the process, who, when they change their behavior, can affect them," says Duffy.

This empowerment of the production staff is the secret to the success of ABC. "[This system]...requires the people operating it to really be in touch with the numbers. There are all sorts of views about not letting the workers really understand all of the costs because they might figure out what the profit is, and that might not motivate them," Duffy says. "But what you find at the best companies is that kind of information is power. You can't expect people to help your overall objective if you don't give them the information, if they're not allowed to see how their behavior in the production process is taking shape in terms of real numbers.

"Once you give individuals reliable information about the cost of their operation, and then track that information over time, then, when you state objectives about lowering costs, you can expect to see some results," he adds. "People will come up with ideas about how to improve performance. Basically you... [convert] your work force into men and women who are not just working at jobs, but who really understand the costs associated with every action."

This is not to belittle the accounting function. The basic numbers are an essential beginning, but, "The way to change behavior is to have people that are doing the work be sensitive to what happens to costs when they make changes...In effect you have given them real time power to be able to distinguish which of their actions are efficient and which are not," says Duffy.

But cost cutting is not the only advantage to ABC. The same kind of analysis can give managers an effective tool to justify fresh investments. Many times managers know an investment should be made, but more traditional accounting systems can't deliver hard numbers to demonstrate why. For example, an ABC system can reveal the hidden costs in storing raw materials and moving them about the factory, thereby helping a manager to justify investment in a system to reduce quantities held in temporary storage.

**ABC BEGINS WITH FORMING A TEAM THAT CHARTS EACH STEP OF THE MANUFACTURING PROCESS FROM THE BEGINNING OF DESIGN UNTIL THE FINISHED PRODUCT IS DELIVERED TO THE CUSTOMER.**

ABC can also help make accurate bids for jobs. Some computer models using this system can predict which activities will be needed to complete a particular job, so management can predict more accurately what an acceptable profit margin should be.

While ABC is relatively new and unfamiliar to many, Steve Duffy sees it as becoming more common in the 1990s. "I think more companies will focus on this. Many economists are predicting relatively low growth in the 90s, which is really a function of the high debt levels we have in this country. When you have that kind of burden and relatively low margins and less money for investment, then companies are going to find that their bottom line improvement is going to come less from revenue growth and market share, and more from holding their costs down. I think these kinds of systems and the products that help implement them have a good future in the near term." ■

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**JUNE 3-4**

AGMA Technical Education Seminars. Radisson Hotel Detroit Airport, Romulus, MI. June 3 - Gear Failure Analysis, led by Bob Errichello. June 4 - Bearing Failure Analysis, led by Chuck Moyer. For more information, contact AGMA Headquarters, (703) 684-0211.

**SEPTEMBER 9-11**

Gear Noise Symposium. Ohio State University, Columbus, OH. Three-day course covering all aspects of gear noise. For more information, contact Carol J. Bird, Conference Coordinator, (614) 292-3204 or Dr. Donald R. Houser at (614) 292-5860.

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