GEAR TECHNOLOGY

The Journal of Gear Manufacturing

GEAR EXPO 97 PRE-SHOW ISSUE

July/August 1997

DESIGNING GEARS WITH ASYMMETRICAL TEETH
ADVANCED FREE-FORM HONING
SURFACE ROUGHNESS MEASUREMENT
INVOLUTE INSPECTION METHODS

Plus • Who's Who and What's What at Gear Expo 97 • Interview with Eliot Buckingham • New Gear Data Research • Civil War Gears and More

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The Total Customer Service Experience

What is a quality product? This is not an idle question. In the Darwinian business world in which we operate, knowing the answer to this question is key to our survival. A whole library of standards and benchmarks is available to help us gage how we're doing, but they don't really tell the whole story.

From a customer's point of view, buying an AGMA 14 gear is only part of "quality." The *entire experience* with the product is what will determine customers' perceptions. This is the conclusion of Crispin Brown of Ingersoll Engineers International in his brief article "The Service Chain," which appeared in the newsletter *Manufacturing Insight*.

In this thought-provoking article, Brown suggests that customers don't evaluate the quality of their experience on the basis of the product alone. They instead judge in the context of their entire buying/use/disposal experience with that product. I think what he means is this: It's not enough that the product works as promised with little or no repair or breakdown time. People will not buy (at least not more than once) the best product in the world if delivery is unreliable, if their contact with the supplier is a negative experience, if the installation manual is a nightmare or if disposal is a hassle. Their entire experience with the product, from the moment of first contact with the salesperson to the time the worn-out product is disposed of, is what the customer evaluates when he or she decides what "quality" is.

What this means for manufacturers—including those of us in the gear business—is that we have to look to more than AGMA ratings or ISO 9000 rules to build a quality product. We have to look to our entire organization to see how closely we're keeping our eye on the ball: our customers. They determine the success or failure of our business. They pay our wages; they cover our expenses; they provide our profit, if any. No matter what our product or "core competency," giving the customer what he or she wants is what we have to do.

This means keeping tabs on some obvious things. Do we have a friendly, helpful person answering the phones, or does our automated phone answering system put callers in an endless loop where conversation with a live person is impossible? Do we deliver what our salespeople promise when they promise it? Will our tech support personnel go the extra mile to get a customer's machines up and running the way they're supposed to?

But there are other, more subtle elements in the buying experience to be considered. What does our advertising say about the kind of company we are? What impression do we leave with potential customers who, for whatever reason, aren't buying right now? Is our company's name one they will think of in six months when they are ready? More to the point, will they think of us as potential suppliers or as an organization they wouldn't do business with on pain of death?

What about the "little" things we don't think of as part of the customer service equation? Brown uses the image of the sofa box in his article. Are we willing to haul away the "sofa box" after the product is delivered, or do we build a great product packed in layers of annoying, wasteful material that is at best a nuisance and at worst a major disposal problem? What about the disposal of the product itself at the end of its useful life? Do we want to leave our customer, after 5 or 6 years of good service from our product, with the final experience of a major hassle with the EPA? We can't, of course, eliminate all disposal problems, but customer-centered thinking at the design stage might alleviate some of them.

Customer-centered manufacturing also means providing customers with what they want, even when they don't know that they want it. That's called creativity in product design. It's also called listening to the customers, being aware of their problems and being first out of the blocks to solve them.

Part of our job is to help make our customers successful, because when they're successful, so are we. Understanding their businesses and their needs and taking the time to listen and learn from them are all part of an overall satisfactory customer experience.

We cannot afford the luxury of doing business like Ralph's Pretty Good Grocery in Garrison Keillor's mythical Lake Wobegon, MN. Ralph's motto is, "If you can't find it here, you probably didn't need it anyway." The motto isn't working very well for Ralph now that the megamall has opened the next town over, and it won't work very well for us either.

Customer-centered thinking is not a fuzzy, "feel-good" flavor-of-the-month management guru trick. It's fundamental to running a successful business. If you don't think so, remember, you have a whole list of competitors who will be more than glad to prove how wrong you are.

Michael Goldstein,

Michael Goldstein

Publisher &
Editor-in-Chief

Eliot K. Buckingham

A second-generation gear master

Nancy Bartels

ELIOT K. BUCKINGHAM

EDUCATION
B.S. Massachusetts Institute of Technology, 1949.
M.S. University of New Mexico, 1951.

MILITARY SERVICE
U.S. Army, 1943–1946.
U.S. Air Force, 1951–1953.

MEMBERSHIPS
American Society of Mechanical Engineers.
Licensed Professional Engineer in the State of Vermont.

CAREER EXPERIENCE
University of New Mexico;
A.W. Haydon Co., Waterbury, CT;
Allied Control Co., Plantsville, CT;
Advanced Products Co., North Haven, CT;
Bryant Computer Products Co., Springfield, VT;
Established Buckingham Associates, Springfield, VT, 1960.

SELECTED ARTICLES & PUBLICATIONS

"Accelerated Life Tests," *Machine Design*, July 25, 1974.

"Avoiding Overdesign of Gears," *Machine Design*, Feb., 1980.

"Backlash in Gears," *Power Drive Engineering*, April/May, 1962.

"Controlling Tooth Loads in Helical Gears," *Machine Design*, Oct., 1975.

"Gear Cardiograph." with Weyman S. Crocker. Presented to the AGMA Aerospace Division, Feb., 1966.

"Gears in Action." American Pfauter Gear Process Dynamics Clinic, Oct., 1982.

"Guide to Worm Gear Types," *Product Engineering*, April 26, 1965.

"How Design Errors Influence the Functioning of Gear Trains," with Earle Buckingham, *Machinery*, August, 1964.

"Measurement of Surface Endurance Limit." International Powder Metal Conference, Orlando, FL, June, 1988.

Revised Manual of Gear Design, Sections I–III with Earle Buckingham, 1980–1981.

"Spur Gear and Worm Gear Sets," *Machine Design*, March 3, 1966, *Power Transmission Design*, May, 1966.

"Surface Endurance of Tufftrided® Materials," ASME Design Engineering Conference, April, 1975.

"Tables for Recess-Action Gears," *Product Engineering*, June 8, 1964.

"Taking the Guesswork Out of Worm Gear Design," *Machine Design*, March 20, 1975.

His resume reads like that of many gear engineers of his generation: the stint in the army during World War II; the break for college in the late 40s; deliberately vague descriptions of projects for the Air Force in the New Mexico desert in the early 50s; the corporate engineering jobs later on in the decade.

Then in 1960, long before the term became a euphemism for "laid off by a big corporation," Eliot K. Buckingham struck out on his own and became a gear consultant.

The idea of going one's own way in gear engineering was not new to Eliot Buckingham. In a sense, he was only following the family tradition. He is, after all, the youngest son of Earle Buckingham, author of *The Manual of Gear Design* and other staples of gearing literature. By the time *Gear Technology* spoke with him earlier this year, Buckingham had spent, quite literally, a lifetime in gearing.

Buckingham's view on the industry is something of a contrarian one. Perhaps this is inevitable, having spent most of his professional life analyzing and correcting other people's mistakes. A few weeks ago, he shared his perspective on the American gear industry.

The Last 50 Years

Buckingham sees only two new technologies that have come directly from the gear industry in the last 50 years. These are ITW's Spiroid® system and Novikov-Wildhaber gears.

Spiroid gears fill a niche between bevel, worm and face gear design. They are useful in applications where an offset greater than 20% of the gear radius is required. The pinion is tapered and resembles a worm, and the gear member is a face gear with teeth curved in a lengthwise direction. The tooth inclination is like a helix angle, but is not a true helical spiral.

The Novikov-Wildhaber gears have parallel shafts and circular form teeth and are suitable for low-speed drives. They have applications in low-tech countries because they can be produced on ordinary milling machines, but their use is limited elsewhere.

"Beyond those two," says Buckingham, "most improvements have come from other technologies and been applied to gears."

Buckingham says that, like many others, the gear industry has been a great beneficiary of the space program. Many technologies developed there have made their way into common use throughout the industry. "Better techniques and better materials do improve things," he says.

"Back in the early 60s," he recalls, "we were retained by the Instrumentation Lab at MIT to work on a very accurate indexing device for a space sextant for the Apollo program. Our goal was to get a 4-inch diameter gear with an accuracy of about 5 arc-seconds. That's the equivalent of walking 3.5 miles with no more than an inch deviation off a straight line.

"We made a spur gear 4" in diameter, with 64 pitch and 256 teeth. We spent $40,000 to make the gear. That includes rebuilding a Fellows/Reishauer grinder. All the spindles were ground down for accuracy. We ended up with a drive accurate to 5 arc-seconds overall and 2–2.5 arc-seconds in any 90° quadrant.

"In the meantime, someone else was working with a company in New York on an optical disc and got it to an accuracy of .5 arc-seconds. That work contributed to the whole field of optical machine control."

The American Approach

In spite of many improvements in material, technique and technology, Buckingham is less than sanguine about some aspects of American industrial development. For most of his adult life, American manufacturing, says Buckingham, has been its own worst enemy in some respects. "A friend of mine in manufacturing was fond of saying that when you came up with a new machine and took it to Europe, the first question you would be asked would be 'What's the principle behind it?' In the U.S., what they want to know is 'How much does it cost, and who else is using it?' We ask those questions too often here. We keep our eye too much on the bottom line.

"We don't do enough research. Many companies that 20 or 30 years ago had large research departments don't have one at all now. The only kind of research we're doing is product development.

"I have the feeling that we're big here into supporting planned obsolescence," Buckingham continues. "We tend to design products (not just gears) with the attitude that if the thing runs 4 or 5 years, then that's good enough."

Eliot K. Buckingham, his wife "Max" and their granddaughter Sabrina.

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Buckingham feels that this attitude is one that has cost the industry over the long run. "I spoke with a fellow who's in charge of a sugar refinery in Germany. He told me that the only time he ever had any gear failure problems were when he bought an American-made gearbox."

It also leads to the kind of shoddy business practice that leaves a bad taste in the mouth. "I was called in to consult for a power station out in New Mexico. The main bull gear was coming to pieces, and a local shop was trying to cut a replacement. The data they sent me didn't make any sense, so I went out to look at it. It turns out that the bull gear had been cut with a different hob than the pinion. A nonstandard hob had been used. I'm convinced the only reason it was done this way was so that the original supplier would be the only one who could provide a replacement."

Buckingham admits not every gear company is this way. "I've worked with products from gear companies where I've never seen a gear failure."

But this tendency to look to short-term profit runs against the grain for Buckingham. "Some people seem to think that they make their money selling gears," he reflects. "Actually, I think you make money on new gears and on the reputation for quality. One of the things my dad taught me was that, whenever I took a job, to work myself out of it as soon as possible. It's worked. People always come back. Sometimes the only way I know a job has been successful is that I never hear from the customer. Then five years down the road I'll get a call: 'You know that job you did five years ago? Can you do another one?'"

Buckingham on AGMA

Eliot Buckingham also takes a somewhat contrarian view of AGMA. While admitting the usefulness and even necessity of such an organization, he states, "Sometimes I think what we really need is an American Gear *Users* Association."

Buckingham parts company with AGMA over technical and philosophical issues.

"AGMA was started during the First World War by engineers who were interested in setting standards for gears and in cooperating to develop better gear technology. Somewhere along the way, I believe in the 1930s, the association became dominated by salesmen rather than engineers," Buckingham says.

The approach to developing standards changed. The emphasis was placed on faster and cheaper methods of manufacture, rather than on producing better quality gears. Very little attention was placed on end use. What this means is that ". . . [the standards] give a base rating and then proceed to reduce it with service factors for various types of conditions. AGMA ratings are based on 'average' conditions, but how do you tell which specific application is 'average'?"

Buckingham says that a better way to design would be to "determine the maximum dynamic load that the gears will see in service and then calculate the beam strength and wear load capacity accordingly. That is general engineering practice for all load and stress calculations, except for gears."

Buckingham says that the dominance of sales personnel in the AGMA standards setting process has lessened. "In the last years good engineers have again become involved, and there is a real interest in furthering gear technology," he says. But, he adds, there is still a tendency on the part of some users to drift away from the AGMA standards and use their own whenever it is possible to do so. On the other hand, because AGMA

GROWING UP BUCKINGHAM

"What was it like growing up with someone obsessed with gears?" asks Eliot Buckingham. "I don't know. You'll have to ask my kids. The oldest was 12 and the youngest 5 when I got started [in business on my own]. My dad never brought his work home."

But he was very focused. Says Buckingham of the time when he and his father worked together: "He'd get completely wrapped up in his work. He had a very small office, and he'd be working, and I'd come in, work awhile and go out again, and he'd never know I'd been there."

On the other hand, growing up in the Buckingham household, it was hard to escape the gear theory entirely. When Earle Buckingham was working on his books, he would bring them home to the resident editor, his wife.

"My grandfather, my mother's father, was a librarian at Trinity College," Eliot Buckingham explains. "My mother used to say that books had to read smoothly aloud, so she used to read all my father's books out loud to him, so they could see how the words sounded."

Perhaps it was through just such an exercise that one of Earle Buckingham's most famous observations acquired the form we're most familiar with: "Man-made . . . laws have little in common with the laws of nature. They are incomplete, ambiguous, and often inconsistent; one often contradicting another. . . . Nature's laws, on the other hand, are complete and coordinated, whether we know them all or not. They are also self-enforcing and the penalty for violation is always exacted to the precise degree that the offense has earned. About the only thing in common between the laws of nature and those of man is that ignorance of the law is no defense."

does set the standards for the gear community, companies may feel forced to design to those standards, whether they reflect the best approach or not.

The Training Gap

One place where Buckingham does agree with many others is about the seriousness of the training gap for young engineers. In his view, there simply aren't enough places training young engineers in gearing, with the result that ". . . we'll fall farther and farther behind other countries. . . The industry needs people who know how to do the basics."

He acknowledges that there are some good training progams out there, but the problem is that they are offered on a hit-or-miss basis, and many people don't know about them. Buckingham also feels that many engineering curricula neglect training in gear design.

"There's good information out there," he says, "but people have to really work at getting it."

Gears of the Future

In spite of some of the problems facing the industry, Buckingham sees gears as being with us for a long time to come. "It's just a very economical way to transfer power at a reasonable cost," he says.

He is predicting a bright future for both plastic and powder metal gears. "Right now the big problem with plastic gears is that there is very little wear test data available for them."

He also admits to being "very enamoured" of powder metal gears. "We've found that the surface durability of powder metal is greater than that of base alloys. You can impregnate powder metal with lubricants. You can make alloys out of powder metal that you can't make otherwise."

Buckingham also suggests that he's already seen one of the most significant changes in the way gears are designed—the computer. "When my dad was writing the *Manual of Gear Design*, he calculated everything by hand from 15-place trig tables. He literally wore out an old hand-run calculator. Nowadays, you'd just do the whole thing on a computer.

"Before the computer, there were a lot of things we did by rule of thumb. You just didn't go beyond certain parameters. Now you can automatically check things out on the computer. You can take things right up to the edge of the manufacturing and performance capability."

One development Buckingham would like to see in the future is in the area of gears in the 40–45 Rc range, hardened to 50 Rc. Some are available now in high-volume production applications, but there is also a need for them in smaller lots, he says.

"What happens now is that there's this gap. You frequently have to go from the soft steels all the way up into hardened steels, and sometimes you'd like to have something in that gap area."

Buckingham sees changes in the gear industry coming slowly, which, he thinks, may not be altogether a bad thing. "Many problems are caused by solutions," he remarks.

He also likes to quote George Grant, who in 1890 commented about the advantages of using the involute over the old epicyclic gear: "The old system was easy to draw, easy to make, long established, and there was a reluctance to accept a change, particularly a change for the better."

Nancy Bartels is Gear Technology'*s senior editor.*

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CIRCLE 114

Structural Analysis of Teeth With Asymmetrical Profiles

G. DiFrancesco & S. Marini

Abstract

This article illustrates a structural analysis of asymmetrical teeth. This study was carried out because of the impossibility of applying traditional calculations to procedures involved in the specific case. In particular, software for the automatic generation of meshes was devised because existing software does not produce results suitable for the new geometrical model required. Having carried out the structural calculations, a comparative study of the stress fields of symmetrical and asymmetrical teeth was carried out. The structural advantages of the latter type of teeth emerged.

Introduction

In a previous study (Ref. 1), the possibility of creating a gear wheel with teeth having asymmetrical profiles capable of conferring a more efficient structure upon the teeth was discussed. This holds for all those numerous uses where the forces employed during rotation in one direction are greater than those engaged in rotation in the opposite one.

The teeth proposed have an asymmetrical form. The two sides of each tooth are, in fact, characterized by loaded profiles with different pressure angles.

As pointed out in the above-mentioned study, asymmetry is achievable by adopting different α_{01} and α_{02} values for the profiles of the two sides of the rack. It is, therefore, not necessary to further modify the cutting tools. The two different tooth profiles thus obtained have two base circles, each with a different radius: $r_{b1} = r \cos\alpha_{01}$, $r_{b1} = r \cos\alpha_{02}$.

Fig. 1 is an enlargement of gear wheels having teeth with asymmetrical $\alpha_{01} \neq \alpha_{02}$ profiles.

In order to estimate the quantitative advantages obtainable using the kind of tooth proposed, the authors compared the stress field of a traditional tooth and that of an asymmetrical one, all other conditions being equal. The study was carried out applying the finite elements method. The symmetrical tooth ($\alpha_{01} = \alpha_{02}$) and the asymmetrical one ($\alpha_{01} \neq \alpha_{02}$) examined had the same h_{a0} as the tool, the same r, the same m_0, the same x and the same k.

The calculation methods applied to the state of stress were also used to verify whether and to what extent actual calculation modes applied to asymmetrical tooth profiles may prove useful when designing asymmetrical teeth, and whether and how said modes ought to be modified, or whether they need to be replaced by new ones devised in order to obtain procedures useful to the task at hand.

Mesh Generation: Study and Operative Proposal

In this work, reference is made to external, cylindrical wheels having straight teeth.

A study of a system for calculations capable of tracing the tooth profile was carried out and involved the root diameter, tooth root fillets, sides and major diameter.

The particularity of the asymmetrical profile form and the need to concentrate a large number of elements (discrete variable speed mesh) regarding the more critical areas of the structure, with a view to carrying out a rapid comparison between

Symbols

The following symbols, based on those recommended by ISO/R 701 (UNI 6773) for notations pertaining to gears, shall be used:

- h_{a0} — reference tool addendum
- k — lowering of head coefficient
- m_0 — reference module
- r — reference pitch radius
- r_b — base circle radius
- x — addendum modification coefficient
- α_{01}, α_{02} — reference pressure angle during rotation in preferential and non-preferential directions.

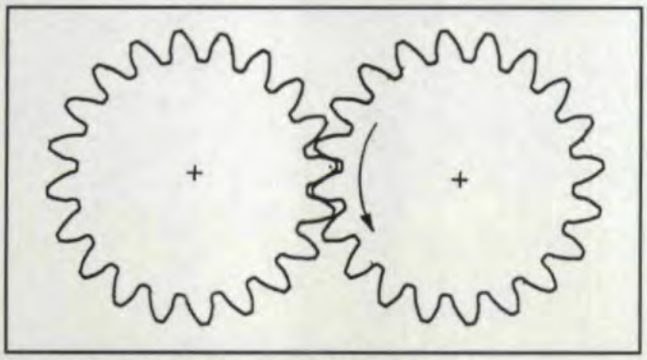

Fig. 1 — Gear wheels with asymmetrical tooth profiles.

stress fields, urged the authors to devise some specific software for the study of the problem. This was elaborated and supported by software capable of precise and accurate analysis of the tooth areas under considerable degrees of stress.

To this end, the tooth profile was divided into a series of variable sectors based on degrees of accuracy with which the various areas need to be studied. On the basis of the software drawn up to trace profiles, it is possible to find the coordinates for the points of each sector into which one decides to divide the profile itself.

The structural analysis was carried out on the section of the tooth contained on the axial median of the gear wheel. In this mesh generation, the four-juncture, plane stress-element formula was applied.

In the construction of the mesh, we have tried to maintain as regular a form as possible, above all where the need for deeper structural investigation existed.

Automatic Tracing of the Mesh

The mesh generation program was studied and perfected in such a manner as to allow the user to interact through a "dialogue window" devised specifically for that purpose.

The program was conceived in such a way as to create a basic mesh automatically with a profile divided into a number of pre-chosen sectors. It is therefore possible to depart from this mesh by varying the mesh density wherever and whenever the examination and experience may require it.

Here is a run-down of the chief features in the program:

- The geometric parameters of the teeth and of the cutting tool, as well as the exact number of the sectors into which the profile is to be divided, are included.
- The program elaborates input data and carries out a basic division of the variable pace profile.
- If required, it is possible to distribute (depending on the number of sectors on the profile) the diversified density in a manner different from that offered by the basic program; this is achieved simply by using the dialogue window.
- The program, on the basis of the two tooth profiles, recognizes points upon the same radial quota and traces circumference arcs between them. These arcs intercept the profiles perpendicularly with a high degree of precision in both the standard and the asymmetrical teeth.
- The program, having carried out this subdivision along the radial direction, then does likewise along the circumferencial direction. For this latter division, it is sufficient to input the appropriate number of sectors into which each of the arcs is to be divided. The division along the circumferencial direction, too, is established in such a way as to obtain the highest concentration in those areas (near the tooth's lateral surfaces) where the tension field is at its peak.

The program has been studied so as to match radial and circumference concentrations, thus obtaining elements as square as possible in those areas considered most important to structural analysis.

The program allows for dislocation of the areas of greatest concentration at any point whatsoever along the tooth. In the case of structural analysis of symmetrical and asymmetrical teeth, it is considered convenient to dislocate the concentrations (as in the case of symmetrical teeth) at the fillet at the root of the tooth (Fig. 2).

It is important to underline the fact that programs devised especially for the study of gears are based on general characteristics to allow them to be used for teeth with different geometrical patterns: high or low number of teeth (even in the case of considerable undercut, as in gear pumps), tools having sharp or rounded corners, symmetrical forms or asymmetrical contours, as in the present study.

As mesh generation programs were devised to be applied to a broad range of geometric solutions, the following must be kept in mind:

- In asymmetrical teeth, the tangents to the profiles at points along the same radius may be of the same sign (this occurs when one of the profiles has considerable undercut).
- In the vicinity of angular points of the tooth profile (teeth with considerable undercut), the arcs may curve in the opposite directions.
- The consecutive sides of an element may be far from acceptable perpendicularity values,
- The ratio between the lengths of the greater and lesser sides of an element may not fall within acceptable parameters.

This software was designed to compensate for these failings, automatically modifying the mesh parameters. In particular, one or more circumference arcs may be added or eliminated or automatically substituted by curves based on the coordinates of the nearby arc points. In any case, the program automatically optimizes the mesh according to criteria established for a specific kind of structural analysis.

It is evident that in areas of lesser interest from a structural point of view and, there-

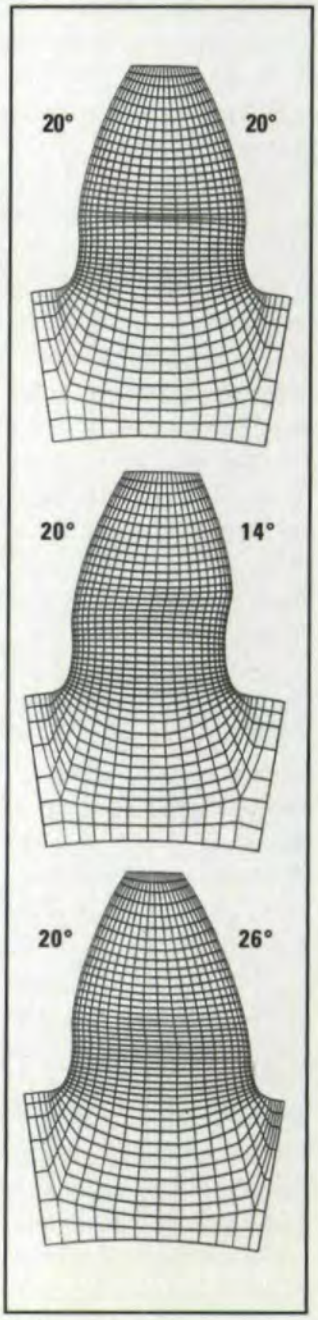

Fig. 2

fore, of minor concentration of elements, a kind of mesh quality closer to admissible limits is acceptable.

The calculation program generates two output files: an editable .dxf file using a common CAD program and an information summary file for the user.

Calculation of Stress and Results

The program drawn up, perfected and described in the previous paragraph permits many easy and rapid structural analyses of teeth having considerably different parameters.

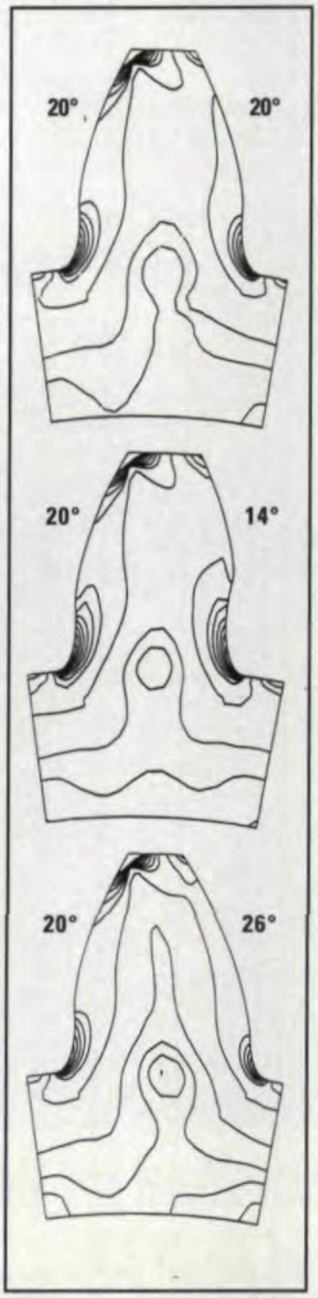

Fig. 3 — Three sets of ideal constant stress curves.

In all the cases mentioned, the binding system considered is that with the joints of the line external to the circumference of the internal circle. Numerous trials have permitted us, in fact, to limit the area subjected to structural analysis to those outside of which the stress and strains are practically of no importance even in the presence of considerable loading.

The analysis was carried out by charging the structure with a normal concentration of force along the side of the tooth. Among the various possibilities, particular emphasis was placed on the extreme case where pressure was placed on the top of the tooth.

The comparison between the stress fields of symmetrical and asymmetrical teeth obtained by varying the α_{02} value only while keeping the same module, was carried out, applying the same force value to the top of the tooth.

Every series of geometrical calculations for teeth different from each other (each having a specific α_{01} and variable α_{02}) and the object of the study, was rendered discrete by imposing the same mesh generation parameters for all geometrical types (for example, the same number of sectors in which to divide the profile, etc.) on the calculation program.

Each series in the geometrical calculations involved fixing a constant for α_{01} and variable value for α_{02}.

The structural analysis was carried out by comparing the stress fields obtained by FEM analysis.

An overall comparison between the stress fields obtained using various types of geometry was carried out. Fig. 3 illustrates the ideal constant stress curves for the following three cases: $\alpha_{01} = \alpha_{02} = 20°$; $\alpha_{01} = 20°$, $\alpha_{02} = 14°$; $\alpha_{01} = 20°$, $\alpha_{02} = 26°$.

Furthermore, because the areas that undergo the highest stress are those closest to the tooth root fillet, a qualitative and quantitative comparison of these areas was provided. In particular, it is possible to compare significantly the maximum ideal stress values calculated both for symmetrical and asymmetrical teeth.

Fig. 4 shows the trends for $\Delta\sigma_i\%$ of the function of the α_{02} angle, where $\Delta\sigma_i\%$ is the percentage variation of the variation of the α_{02} angle, of the ideal maximum stress in case of $\alpha_{01} = \alpha_{02}$.

Two geometrical series were examined. The first had values of $\alpha_{01} = 20°$ and an α_{02} varying from 10° to 30°. The second series had $\alpha_{01} = 17°30'$ and an α_{02} that varied from between 10° and 30°.

The structural analysis, carried out using a calculation code of proven trustworthiness, permitted the calculation of element by element ideal stress values; the maximum ideal stress value present in the corresponding tooth root fillet area situated on the same side as that from which the solicitation came was calculated for each tooth geometry type.

The outcome shows that modules and active side α_{01} pressure angles being equal, the maximum ideal stress at the root of the tooth diminishes when the α_{02} pressure angle on the inactive side increases.

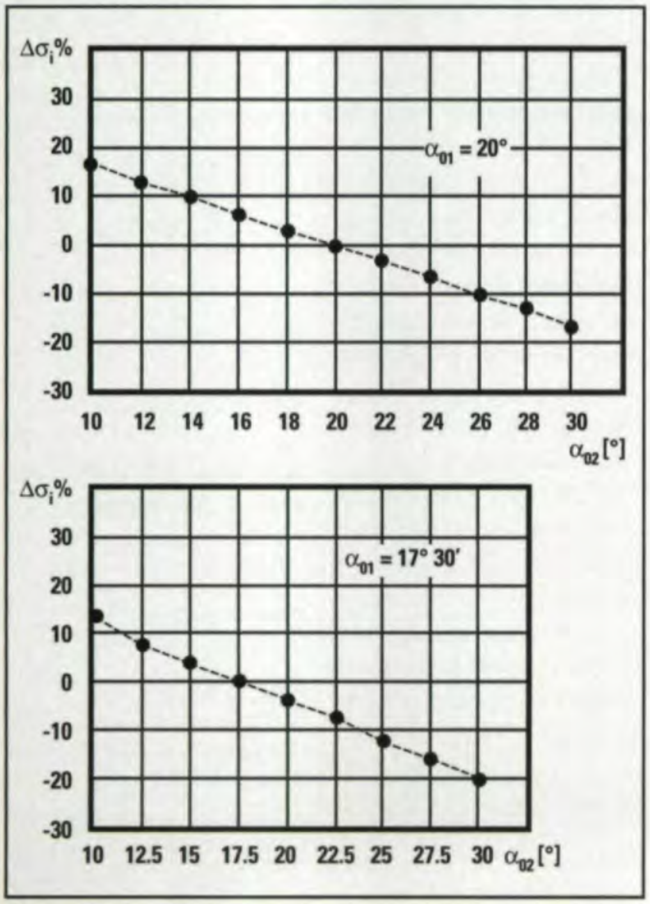

Fig. 4 — Maximum ideal stress values for symmetrical and asymmetrical teeth.

The results from the structural analyses emphasized the noteworthy convenience of using as high α_{02} pressure angle values as possible (Ref. 1), α_{01} pressure angles being equal.

In fact, for α_{01} - α_{02} = 12° 30', the diminution of the maximum ideal stress value $\Delta\sigma_i$ = - 18.5%.

Conclusion

The "mesh generation" program for asymmetrical teeth, characterized by $\alpha_{01} \neq \alpha_{02}$ values projected and designed within the present limits, permits the swift and easy structural analysis of a broad range of geometrical types for teeth.

Comparing the results obtained, all else being equal, for teeth whose α_{02} angle values differ, it appears evident that structural strength increases with an increase in the aforementioned angle.

This implies, when maximum ideal stress at the tooth root is equal, that it is possible to create an asymmetrically toothed wheel having dimensions less than those of a symmetrically toothed one; this allows for a convenient reduction in the weight and size, not only of gear wheels but also of the box and housing containing them.

On the basis of the results of the present study, the authors are now examining the possibility of elaborating general criteria so that smaller (lighter) asymmetrically toothed wheels with the same strength as symmetrically toothed ones may be created.

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Basic Honing & Advanced Free-Form Honing

Ned W. Wright & Herbert Schriefer

Rotary gear honing is a crossed-axis, fine, hard finishing process that uses pressure and abrasive honing tools to remove material along the tooth flanks in order to improve the surface finish (.1–.3 µm or 4–12µ" Ra), to remove nicks and burrs and to change or correct the tooth geometry. Ultimately, the end results are quieter, stronger and longer lasting gears.

The process is similar to shaving in that a crossed-axis setup is used to produce the sliding velocity necessary to remove stock. Shaving is a soft cutting process that uses a serrated tool to remove stock. Honing is a hard finishing process that removes stock by means of high pressure, sliding action and an abrasive honing stone. Oscillation of the workpiece along its axis can also be used during all or only during the final part of the cycle to facilitate metal removal and improve surface finish (Fig. 1).

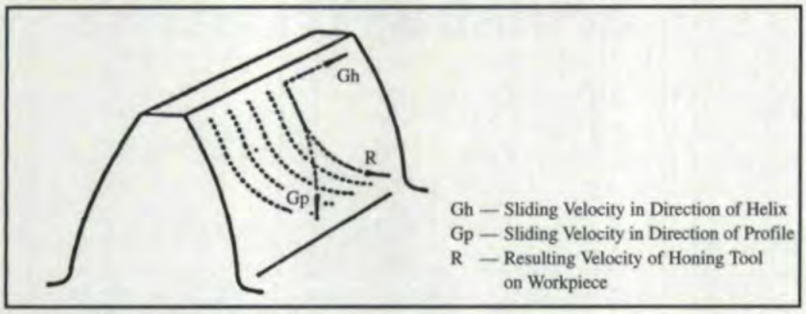

Fig. 1 — Kinematics of machining.

Table I — Technical Situation of Free-Form Honing (AGMA Quality Levels)

	Plunge Shaving	Free-Form Honing (Hob, Ht.tr & Hone)	Gear Grinding
Economical Stock Allowance/Flank	.0012"–.0016"	.0012"–.0024"	.004"–.006"
Usual Precut Gear Quality Grade	Q7–Q8	Q7–Q9	Q6–Q7
Reachable Quality Grade After Finishing	General: Q8–Q9 Accum. Pitch: Q7–Q8	General: Q10–Q11 Accum. Pitch: Q9–Q10	General: Q11–Q13 Accum. Pitch: Q10–Q12
Average Machining Time	25–35 sec.	35–70 sec.	120–240 sec.
Average Investment With Loader System	$0.5 million	$0.7 million	$1.0 million
Factor of the Cost Relationship Per Workpiece	1	2	4

Rotary gear honing was developed to remove nicks and burrs in a timely and 100% efficient manner. Before the development of honing, most gears had to be sound tested and deburred manually or by a pencil type end mill. Obviously these were not sure-fire methods, and costly teardowns would result later if gears with nicks and burrs were discovered in the assembly. However, over time, honing has proved to be not only an effective nick and burr removal system, but also effective for noise reduction and tooth geometry correction. Honing removes stock from the tooth flanks and thus improves runout, lead and profile characteristics. Honing, like shaving, will not dramatically improve the accumulated pitch error level of a gear. This is because the process is a radial pressure setup, and no guidance between the gear and tool is involved.

The honing tool is an internal gear made of either molded ceramic, molded vitrified material or plated with grit of varying quality levels and size. Ceramic tools are required for their stiffness characteristics and are normally used in higher pressure and larger stock removal applications. The tools average about 15" in pitch diameter and 1.58" wide. Grits can range from 50–60 size for coarse roughing to 400–500 grit for the fine polishing work required for aerospace gears. Most honing tools are in the 120–180 grit range.

The honing tool is first molded, and then the helical tooth tool is introduced by means of an internal grinder. Finally it is refined by rolling with a diamond dressing gear. Dressing takes place not only before the first piece is honed, but also after the honing tool exhibits wear and has lost some of its initial geometry. The number of pieces worked before this happens can vary greatly, but it is not unusual to redress every 50–100 pieces for ground gears, 30–50 for shaved gears and 20–40 for hobbed-only gears.

The Dressing Process

First the tip diameter or internal diameter of the honing tool is dressed by the diamond dressing ring. The honing tool usually operates between 500 and 1000 rpm. The dressing roller is a plain cylinder plated with diamond crystals.

Next, the flanks of the gear teeth are dressed by means of the diamond dressing tool/gear. The amount of stock removed during tooth flank dressing is approximately .002" in radial in-feed. The average honing tool can accommodate 5,000–30,000 parts during its usable life.

Normally the movements of the dressing cycle are not the same as for the honing cycle. Usually the diamond dressing tool/gear is identical to the desired geometry of the workpiece after honing. The "free form" or spheric honing process discussed later allows the end user to impart different tooth forms (i.e.; taper, crowning, bias) through machine motions, thus freeing the tool from the limitations of the desired end geometry.

Standard quality for the diamond dressing tool/gear is approximately AGMA 13. AGMA 14 indicates extra quality.

The Honing Process

The honing process uses honing oil applied with high pressure to clean the stone. Honing oil for gearing applications is normally low in viscosity and lubricity. This is necessary so that honing tools with minimum open grain structure can achieve enough abrasive resistance for efficient metal removal. The oil is primarily used just to clean the stone.

Unlike grinding, honing does not increase the tooth surface temperature, produce heat cracks or burn spots or reduce the tooth flank hardness. It also does not cold work or alter the microstructure of the gear material, nor does it generate internal stresses. In fact, the honing process improves the surface characteristics by imparting compressive stresses and refining the surface finish so that higher loads can be carried, since the oil film is not pierced by the more jagged tooth surfaces that result from shaving or grinding. The honing process also creates a more random tooth surface than either shaving or honing, which imparts desirable noise characteristics through a white noise effect (Fig. 2).

When to Hone

Rotary gear honing can be employed for the following applications: after hobbing and heat treatment; after hobbing, shaving and heat treatment; and after heat treatment and grinding.

Honing is now gaining acceptance as a hard finishing method used directly after hobbing and heat treatment. This is possible because of better quality hobs and hobbing machines which allow more accurate control of stock amount and flank scallop depth. The current trend in honing technology is also toward stiffer machine tools and honing tools and improved abrasive technology, all of which allow higher metal removal rates.

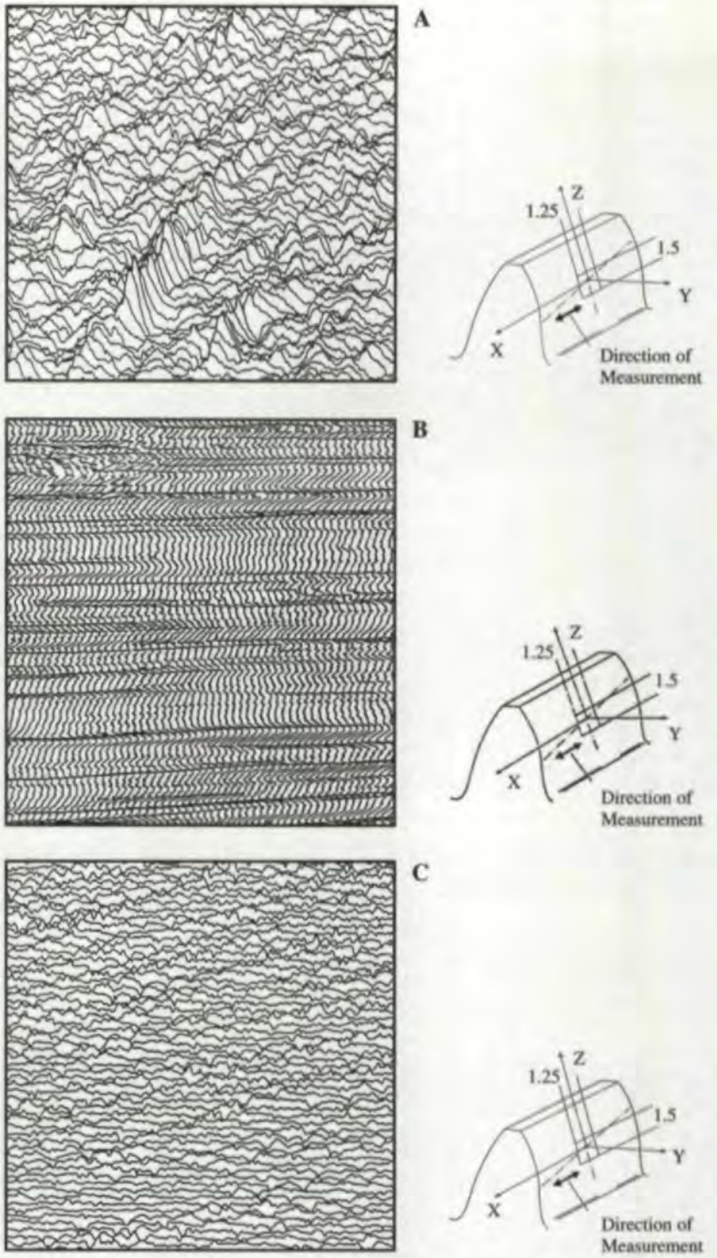

Fig. 2 — A) Surface structure of a shaved flank. B) Surface structure of a ground flank. C) Surface structure of a honed flank.

This technology allows honing to be a direct "after hobbing and heat treatment" operation.

While honing is still employed primarily after shaving and heat treatment or grinding, it has been used successfully to eliminate shaving in gears where the final desired part quality is in the AGMA 10, 11 and, in some cases, to AGMA 12 range (Table I). The honing process operates best where flank scallops are in the .0005"–.0007" range, thus allowing rapid stock removal and quality improvement and making it ideal for "after hob" situations. The honing process requires decent quality (AGMA 8–9) hardened parts in order to be efficient. This cannot be overstated. The free-form honing process is primarily suited for use on "after hobbed and hardened" gears.

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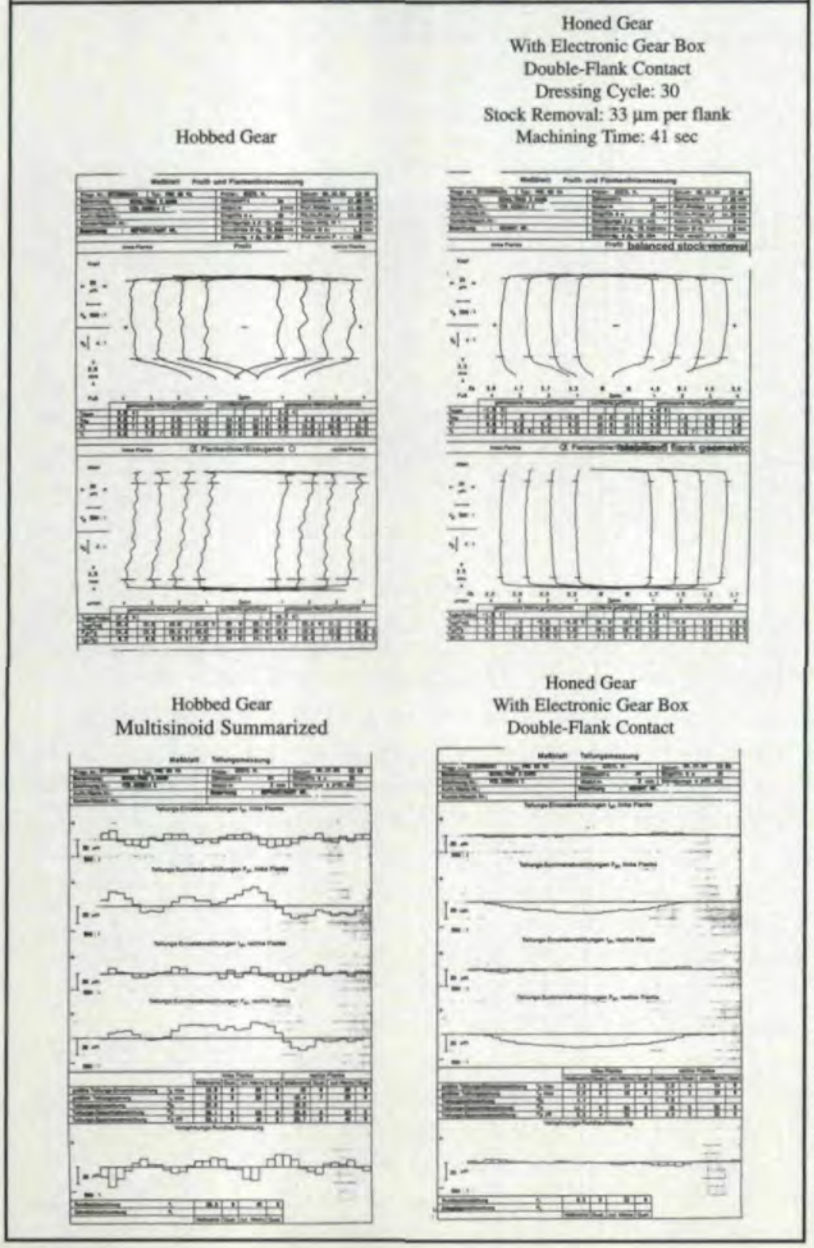
The Advantages of Internal Honing

Internal honing has several advantages over external honing of external gears. The primary benefits are the higher contact surfaces offered by rolling a given gear with an internal gear. These higher contact surfaces provide better equilibrium of the internal contact forces, and this enhances the ability to correct profile errors on smaller diameter gears where fluctuating dynamic forces are a constant problem.

It is not unusual for the honing process to improve an after-hob or after-shave part by two quality grades. An after-grind gear set is less improved—perhaps one class at most. The biggest benefit of honing ground gears, besides noise improvement, is its ability to reduce break-in time and increase load carrying capacities by as much as 30% and wear life by as much as 1,000%.

Before and After Results of Spheric Honing



Most internal type honing machines have a 4.0" wide honing tool capacity. This means that while most honing tools are 1.5" wide, there is still room for a second or possibly third tool. The two tools can be employed as roughing or finishing tools on the same gear section or as two independent tools to be used to hone two distinct gear sections, such as those found on a shaft. The face width of the gear must normally be under 1.25" for cluster honing.

Virtually all of the modern CNC honing machines are of the internal style for use on external gears. This means that the honing tool is actually an internal gear/annulus with either the workpiece or the diamond dressing tool running inside it as the mating member.

The internal style still has limitations, and one of these is honing small diameter gears (1.5" dia. and less) or very large diameter gears, where rolling interference can occur with the honing tool.

CNC Honing

Most honing machines have two linear and one swivel axes. The free form or spheric honing process has three orthogonal kinematic CNC axes. This third axis allows the contact point to be maintained in the center of the tool even if the tool is shifted, or it can create special kinematic effects.

CNC honing offers extensive benefits in addition to fast setup times. These benefits include automatic calculation of new machine axes positions to maintain size after diamond dressing, and calculation of a new, increased crossed-axis angle setting to maintain constant pressure and force distribution between the teeth of the workpiece and the tool during the entire life of the tool.

Some CNC honing machines operate in both rotational directions to balance the tool wear, stock removal and profile errors. However, CNC honing machines that use Electronic Gearboxes (EGBs) typically rotate in only one direction, and the acceleration rates are adjusted, depending on the torque amount measured. Typically free-form honing is done on EGB machines.

A Typical Honing Cycle

A typical honing cycle on a CNC machine with an EGB is as follows:

- The wheel and gear begin rotating.
- An electronic stock divider does rough stock division—accuracy .002".
- The honing tool makes rapid traverse to work.
- The gear is stock-divided to the tool through force measurements using an EGB.
- The honing cycle starts with the EGB engaged to make pitch improvements.

• Modifications to the tooth roughness are then made without the EGB.

The following cycles are also found in older honing machines:

• *Loose backlash.* Here the honing tool and work are in loose mesh. This is used primarily for slight improvement in surface and normally employed on fine pitch or already ground gears.

• *Zero backlash.* The honing tool and workpiece are in tight mesh at fixed center distance, providing maximum runout improvement with minimum stock removal.

• *Constant pressure.* The honing tool and workpiece are in mesh at a constant pressure. This method removes nicks and burrs and provides surface finish improvement in minimum time.

Spheric Honing

The automobile industry has long demanded the development of a hard finishing process that is comparable in quality and cost to free shaving unhardened gears. Some attempts at developing such a process were made using CBN coated or ceramic bonded external toothed tools. The basic problem was to maintain tooth quality with this hard fine machining process even though the initial quality parameters were much worse than with green shaving, where distortion caused by hardening added another difficult process. As a rule, the requirement was to raise the pre-cut quality of the teeth, a demand which could not be met.

Meanwhile, various investigations showed that the known capabilities of internal toothed honing tools could be expanded considerably by using different types of kinematics and more powerful machinery, and the idea of applying this expanded capability to the hard finishing process was born. Free-form (spheric) honing with torque-controlled, two-flank action or with electronic guidance was developed.

The word "spheric" refers to the spherical path of the tool relative to the workpiece. It is a kinematic extension of the relative movements—parallel, tangential, diagonal and plunge—familiar to green shaving.

The use of the term "honing" is debatable when referring to the machining of pre-cut teeth with large machining allowances on the flanks and when considering the standard characteristics of the various honing processes.

However, in this case, "honed" refers to the quality of specific properties of surfaces, which is higher than that of the same properties in ground gears. Since the final surface of the tooth flanks machined using the free-form (spheric honing) process has the excellent roughness and undulation characteristics of a honed surface, this process should be distinguished from the other hard finishing methods; therefore, "gear honing" has been used for several decades to refer to gear manufacturing processes which achieve a surface quality better than a ground surface.

The technical difficulties characteristic of gear honing in the past can now be largely avoided using spheric honing because it is sufficiently precise mathematically and technologically. Spheric honing of precut and hardened toothed workpieces represents a new technology that in most respects fills the niche in gear finishing between green shaving and heat treatment and grinding.

As shown in Table I, spheric honing combines the positive features of gear grinding and green shaving. Therefore, this process can be technologically, qualitatively and economically classified between these technologies.

The positive features of gear grinding are

- Precut, hardened workpieces can be processed,
- Precutting quality does not affect final quality, with the possible exception of runout,
- High quality tooth system production,
- Good flexibility in terms of flank modification,
- Low input for adaptations to different workpieces,
- Process can be precisely specified.

The positive features of green shaving are

- Economy,
- Simple machine and reliable peripherals do not require a highly skilled operator,
- Highly suitable for mass production,
- Low noise modifications and flank surface structures for tooth systems,
- Straightforward tool setup and logistics.

Free-form honing can provide some of these features while offering more of the features of grinding and green shaving in others.

Free Form Kinematics

Fig. 3 shows the kinematics of free form honing. The barrel-shaped part of the surface of the workpiece rotates about axis III, and the barrel-shaped part of the surface of the internal toothed tool about axis II. The two pitch surfaces have a tangential contact at point IV. The oscillating sphere for the workpiece pitch surface has its center at I, and the oscillating sphere for the pitch surface of the hollow tool at V. If the rotating partial surface of the workpiece is moved forward on its spherical envelope, which is rotating with it, with the forward feed being specified at will, the pitch surface of the workpiece will be enveloped

Advantages of the Electronic Gear Box Drive System

• Exact dressing of the preshaped honing tool.

• Dressing of wide ranges of the tool diameter with definitely guided spheric motions.

• Improvement of the accumulated pitch deviations up to halving the amplitudes.

• Variations in the technology caused by free running, torque or electronic guided engagement.

• Adaptive control of stock allowance with automatic machining time regulation.

• Balanced stock removal between right and left hand flanks.

• Adaptive control of accumulated pitch deviations with automatic machining time regulation.

by tangential point IV. The pitch body of the hollow tool can also be moved on its oscillating sphere at a specified forward feed, and the tangential point IV will also envelop the pitch body of the hollow.

A straight line g goes through I, intersects II, intersects III, is colinear with the pitch and envelope body normals at IV and goes through V. It describes the regularity with which any crowning or taper of the workpiece helix traces can be produced with the orthogonal feed axes V_x-V_y-V_z, using specific assigned points on the pitch surface of the tool. Here no account is taken initially of the fact that defined helix angles are to be generated on the pitch surface of the workpiece, where the condition is that the helix traces of the tool must be in contact with the helix lines of the workpiece at point IV. It is possible to influence the tangential contact of the helix traces by a small relative rotation about line g without harming the tangential conditions of the pitch surfaces at IV. For the sake of simplicity, the crossing axes angle movement V_A is used for this rotation, though compensation has to be made for the loss of intersection point II through V_x-V_y-V_z. The calculation for these kinematic relationships is made automatically in the controller of the machine, starting from the screen-controlled operating panel.

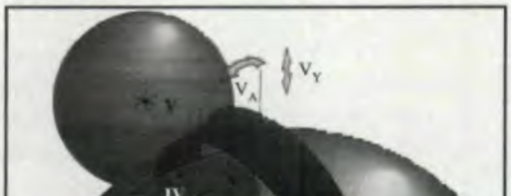


Fig. 3 — Basic kinematics of the spheric honing process.

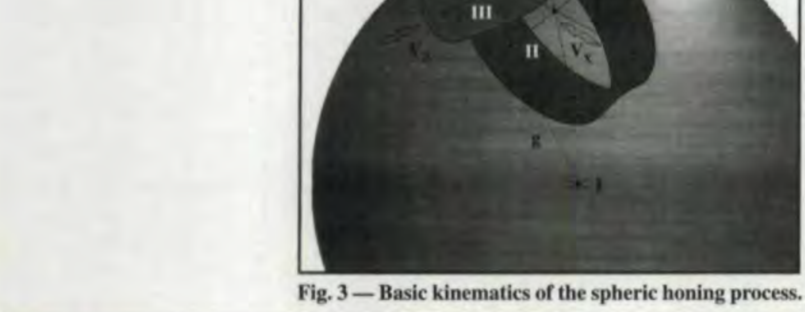


Fig. 4 — Flank modifications with spheric honing.

The advantage of the spheric honing technique, particularly in two-flank contact, is that the contact conditions between the left and right flanks are controllable at every point of contact. This is particularly important if there is flank contact outside the axial intersection when using side tools. Furthermore, the helix trace modification for the dressing wheel does not have to correspond with that of the workpiece, and forward feed strategies can be fluidly transformed into each other. So it is possible to work with a very fast plunge at the start of the cycle, which shortly before reaching the required axial distance, changes without stopping to a spherical feed with which the optional helix trace modification is produced.

Spheric honing can also produce positive and negative twisted flanks (bias) with constant initial conditions for the diamond dresser and the tool. This means that the positive (but also negative) twisted flanks, which are beneficial in noise reduction, can be produced in a simple manner. Negative twist of the flank is important if the mating gear has very large effective twist because it has been manufactured with a negative twist.

Because of the ability to freely configure the system kinematics, spheric honing can mimic all the honing processes currently known, and furthermore, unlike the kinematics of conventional processes, it has the ability to provide spatial feed strategies that are particularly suitable about the equilibrium of forces with meshing teeth (Fig. 4).

The feed strategies can be completely different for dressing with a diamond dresser than when machining the workpieces, allowing the different force conditions applicable when dressing and machining to be appropriately addressed. This is very important when the geometry of the tool flanks has to be changed by increasing internal tool diameter for dressing to make optimum use of the diameter. The equilibrium of forces between left and right flank contact has to be maintained, which is achieved by changing the contact conditions. This task is particularly difficult if the width of the diamond dresser is smaller than that of the honing wheel since, if the helix angle of the honing wheel changes, a relative helical rotation of the tool is necessary. However, the electronic gearbox and the free-form, spheric honing method support these technological requirements in an ideal manner. The machine incorporates a program that simulates all the process conditions and ensures as far as possible that the optimum conditions are provided. With this method, it is possible to increase the number of pieces per tool by a factor of up to 5 compared with conventional methods.

The kinematic axes V_x-V_y-V_z in Fig. 3 are identified with the corresponding machine axes in Fig. 5. Note that the usual swivel table axis for producing the lead modification is not present, since the modification is produced by the simultaneous spheric interpolation of V_x-V_y-V_z and, if necessary, with V_A. The axis V_z is also the loading axis, since the workpiece is taken by the spindle head, moved out to the left and brought into engagement using V_z, while at the same time, the head stock will move into the center of the clamping system.

The axes C_1 and C_2 in Fig. 5 are both driven by water-cooled motors, meaning that they can be controlled either by torque or electronically. The electronically controlled device is advantageous when there are very unfavorable meshing conditions present. Torque control would follow the modulations caused by rotation.

The spheric honing process requires a machine to be fitted with an electronic gearbox as standard, though this can be operated and used in various modes.

The electronic gearbox operation is infinitely variable. This means that the positive drive effect can be varied from inactive to fully active. This enables the operating modes of free running, torque action and positive action to be used. It has often proven beneficial to carry out the initial dressing with full positive action to produce a tool condition of defined quality; then to carry out a few dressing passes with torque action; and then to make a positive action pass again at specified dressing intervals. In this way, the dressing times should be shortened, and tool life will be extended. Furthermore, certain workpieces (e.g. very well ground pieces) are more suited to free running machining than to positive action machining. If workpiece preparation is good and the required quality permits it, torque action machining is more economical than positive action operation. The electronic gearbox, thus, has the capacity to adapt optimally to a variety of technological demands.

The electronic gearbox is also used for the operations of adaptive centering of workpiece flanks, adaptive allowance capability and adaptive cumulative pitch capability.

• Adaptive centering ensures that the metal removal rate is approximately equal from the right and left flanks of the workpiece.

• The adaptive allowance strategy ensures detection of the initial honing wheel/workpiece contact and that the necessary machining time is set.

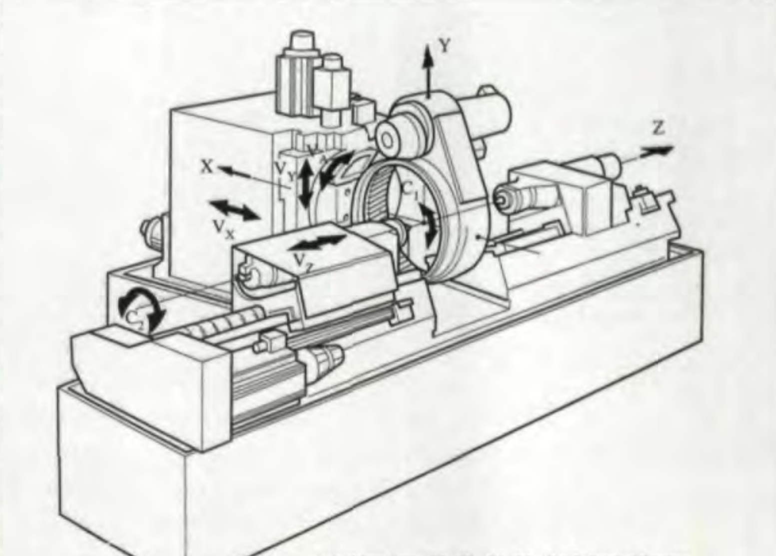
• The adaptive cumulative pitch strategy ensures that cumulative pitch characteristics are evaluated and that the necessary machining time is set.

These measures substantially increase the reliability of the process, since the honing tools only have a limited metal removal capacity, and overloading of the tool results immediately in geometric changes and reduced tool life.

The axes V_z-V_y have a compound slide function which moves the tool along its own axis relative to the workpiece. This makes it possible to carry out rough finish machining or to achieve longer tool life using several tools next to each other, or to machine several different tooth forms in one loading. By using suitable control data related to the workpiece, this function can also be moved automatically to the intersection point of the axes without the need to move the tailstock or spindle head manually.

The compound slide method can also be advantageously used if a repeat series of workpieces that are equally clampable, but have different flank geometries, have to be machined. Different simultaneously mounted honing tools, different diamond dressers and one dressing roller for dressing the inner diameter of the internal gear wheel are then used. This process can be designed such that the control system automatically identifies the workpiece so that, in principle, mixed production can be carried out.

Shifting the tool by moving the Y-Z compound slide amounts to the same as shifting the tool along the axis. This shifting is very important in kinematic terms, since the meshing conditions consequently remain unaffected. The tool is



Machine Axes V_X-V_Y-V_Z-V_A for Spheric Honing

Drive System Axes C_1-C_2 With Electronic Gearbox Drive

Fig. 5 — Machine and drive system axes for spheric honing with an electronic gearbox drive.

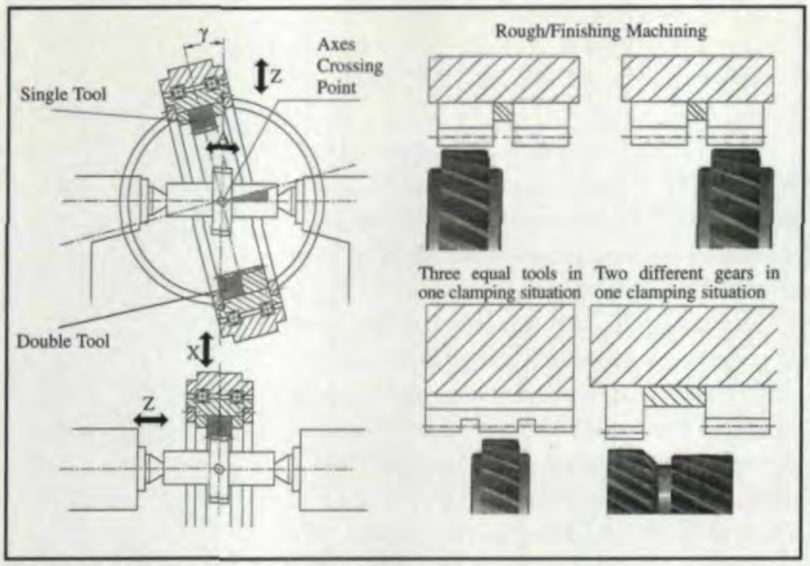


Fig. 6 — Advantages of the compound slide technique.

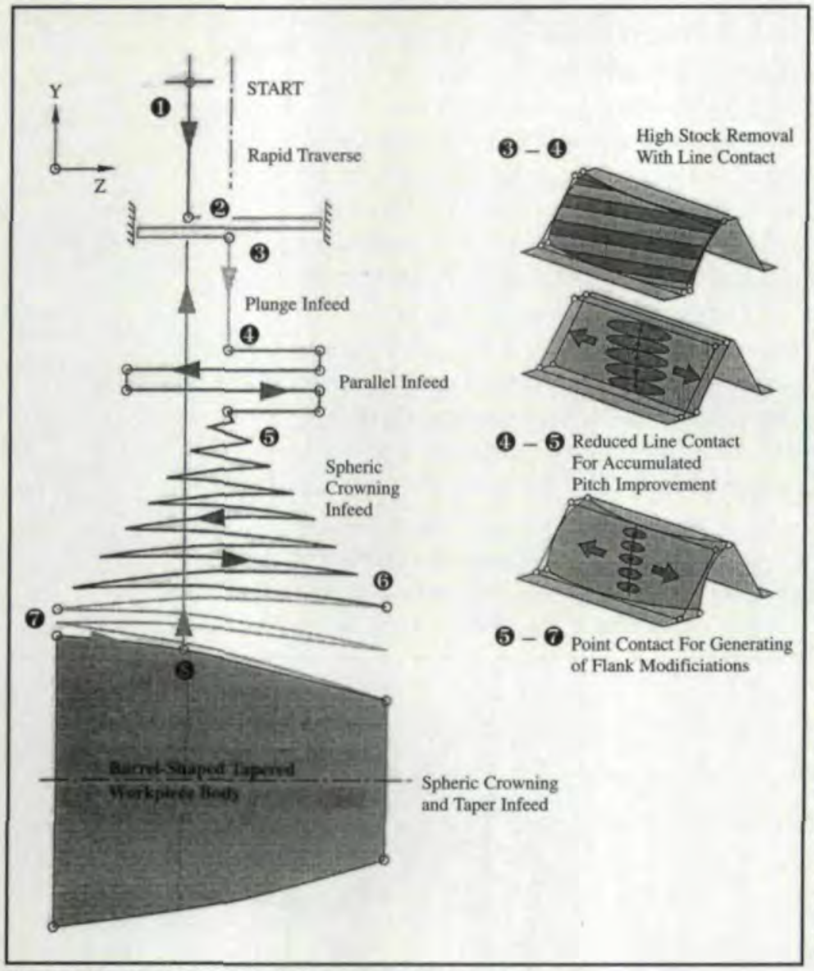


Fig. 7 — Tooth contact behavior between tool and workpiece.

always in the same position in spatial kinematic terms relative to the workpiece. If the tool is displaced only along the V_z axis, the tool/workpiece contact is shifted into the tool's hyperbolic edge zones. This should be avoided to maintain the simplicity of the process (Fig. 6).

The tooth contact between the honing wheel flanks and the workpiece is very important in achieving good geometric and economic results. Double flank contact is always used. This results in contact forces that are very high because of the limited cutting capacity as a consequence of the relatively low effective cutting speeds balancing each other out within the meshing teeth. The electronic gearbox action has no effect on these internal contact forces, since the frequency of the contact force fluctuations can be on the order of several kilohertz and, thus, a counter oscillation of the same high frequency by the drive system would be necessary to compensate for the force fluctuations. Therefore, the rigidity of the contact between the right and left flank should be designed such that an approximate equilibrium of forces exists in every meshing position. In this regard, the possibilities offered by the kinematics of spheric honing play a substantial role, as does the sizing of the geometric parameters of the honing tool and the diamond dresser (Fig. 7).

The feed strategies can be specified completely freely with spheric honing (Fig. 8). Advantageous feed strategies for certain tasks have emerged, and these have been included as standard programs in the process.

The structure of the surface is responsible for the surface noise quality of a flank. Fig. 2a shows the diffuse surface structure of a shaved hardened flank with an Ra value of 0.4 microns (16μ" Ra). Since no orientation of a periodic undulation in or near the direction of the line of contact to the gear and its mating gear in the transmission exists, no periodic surface noise will be audible.

Fig. 2b shows the surface structure of a ground flank with an Ra value of 0.3 microns (12μ" Ra). A distinct micro-undulation pattern can be seen near the line of contact, and this is symptomatic of the typical metallic noise characteristics of ground flanks. Normally an Ra value of 0.3 microns would suffice to avoid metal-to-metal contact due to the formation of a hydrodynamic oil film. With this type of undulating structure, either microvibrations break down the oil film or they interfere with the film's formation.

Fig. 2c shows the surface structure of a spheric honed flank with an Ra value of 0.2 microns (8μ" Ra). The orientation of the structure runs in the direction of the vector of the honing sliding velocity on the flanks. This structure, however, has a low roughness, so that the effect is the same as for a diffuse surface. Micro-undulations on the flanks are avoided due to the large contact areas and the tip-to-root orientation of the path of contact during honing, and this has a very beneficial effect on the noise characteristics.

When examining the tooth contact properties, consideration must be given as to how many teeth of the tool and workpiece are simultaneously in mesh. The fact that double-flank contact is being used, the relationship between the type of flank contact and the tooth height and width, and the flank microcontact all must be considered. These correlations highlight the intricate and complex nature of honing and the fact that only a process which is versatile in adapting to these conditions has any chance of success.

Conclusion

The test charts on page 28 show results after precutting and heat treatment and after spheric honing. In all the machining carried out so far, spheric honing could meet the target of achieving the same quality as green shaving before heat treatment. With torque-controlled spheric honing, at least the same strengths and weaknesses which are characteristic of green shaving show up:

• Good form stability of the flanks, but with a tendency to deviations due to wobble, depending on the pre-machining of the teeth and the clamping conditions.

• Good results for individual pitch deviations, concentricity and lead, but less control of the cumulative pitch deviations.

If all flanks with all deviations are considered generally, there is a systematic collective deviation caused by the process. In the assembled state with the mating gear, however, this acts like a random collective deviation which permanently suppresses narrow banded resonant excitation. With the characteristics of the surface, this effect is largely responsible for the quiet running of green shaved or honed gears.

The machining quality grades after hobbing, hardening, bore grinding and surface grinding for the car industries are listed in Table II. ○

References:

1. Dugas, John. "Rotary Gear Honing," The 16th annual AGMA Gear Symposium, April 10-12, 1988.

2. Wunderlin, Willy. "Hard Finishing of Gear Tooth Flanks by Means of the Honing Process," Third World Congress on Gearing, February 12-14, 1992.

3. Schriefer, Herbert. "Spheric Honing," Hurth, 1995.

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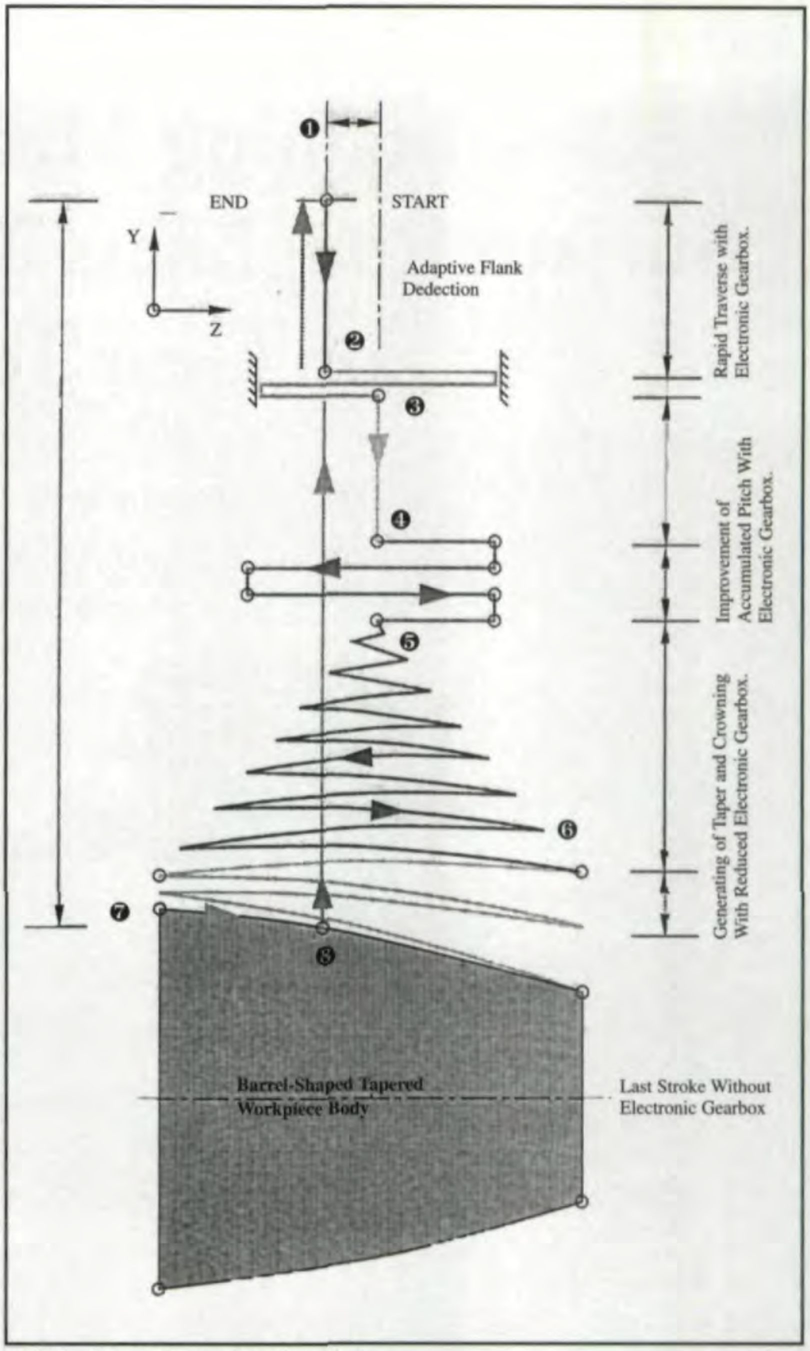


Fig. 8 — Spheric honing infeed strategies.

Table II — Quality Grades Before and After Spheric Honing

Criterion (DIN Symbols)	After Hobbing and Hardening AGMA Tol./Class	After Honing AGMA Grade Tol./Class
1. Pressure angle deviation $f_{H\alpha}$ 2. Profile form deviation $f_{f\alpha}$	(+/- .0007") (.0008"–9") 8	(+/- .00035") (.0004") 10
3. Lead deviation $f_{H\beta}$ 4. Lead form deviation $f_{f\beta}$	(+/- .0007") (.0006") 8–9	(+/- .0005") (.00035") 10
5. Adjacent Pitch Deviation f_u 6. Accumulated pitch deviation F_p	(.0007") (.0022") 8–9	(.0005") (.0016") 9–10
7. Pitch Variation f_p	(.0005–6") 9	(.0004") 10
8. Runout F_r	(.0022") 8	(.0016") 10

(Deviation figure for workpiece in thousandths of an inch, NDP = 12.7 to 7.3, diameter 2.0" to 5.0", face width up to 1.60", utilization of tolerance 100%).

Obtaining Meaningful Surface Roughness Measurements on Gear Teeth

Ronald A. Lavoie

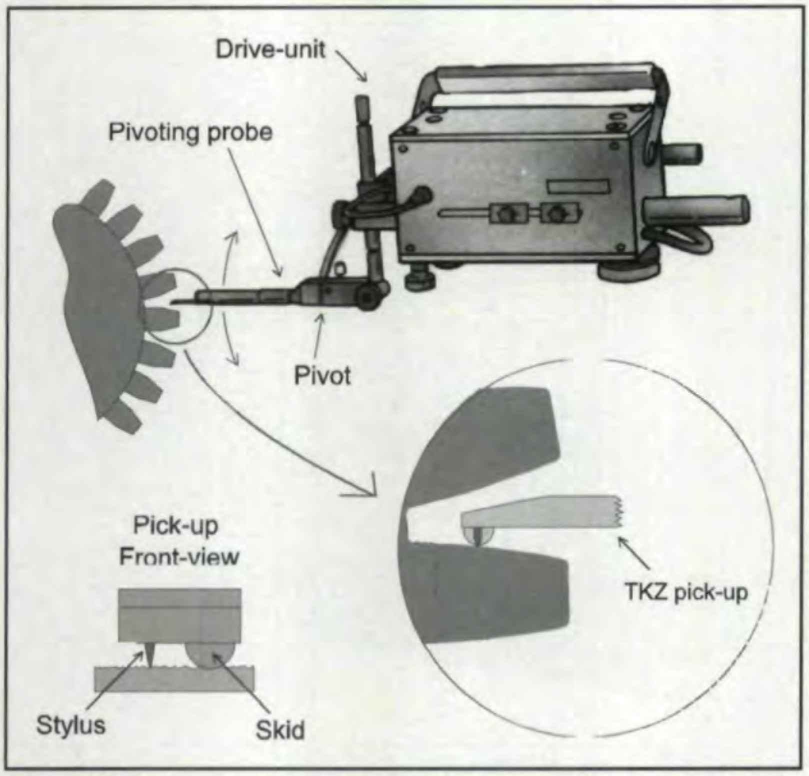


Fig. 1 — The involute form on gear teeth, in most cases, necessitates the use of a skid-type pickup. Gear tooth pickups differ from general purpose pickups in two key areas. The skid is located alongside the stylus instead of having the skid located either before or after the stylus. Also, the skid radius on gear tooth probes is a much smaller radius, typically .8 mm vs. 30 mm. The combination of a smaller skid radius with the side-by-side orientation results in a superior tracking of the involute form.

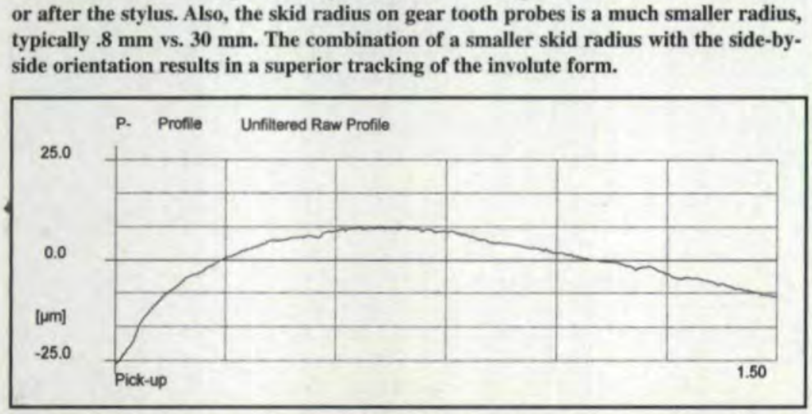


Fig. 2 — The unfiltered profile generated by the signal from the pickup shows the significant amount of curvature that results from the interaction of the skid and the involute form. Also, the roughness signal is hardly discernable.

Surface roughness measuring of gear teeth can be a very frustrating experience. Measuring results often do not correlate with any functional characteristic, and many users think that they need not bother measuring surface roughness, since the teeth are burnished in operation. They mistakenly believe that the roughness disappears in a short amount of time. This is a myth! The surface indeed is shiny, but it still has considerable roughness. In fact, tests indicate that burnishing only reduces the initial roughness by approximately 25%.

This article deals with the key issues that must be addressed if we are to obtain a meaningful surface roughness measurement. We will see that close attention to detail is necessary.

The following areas need to be addressed: equipment, particularly probe selection, filtering and roughness parameters.

Surface Finish Measuring System

A surface finish measuring system consists of a probe that is moved across the involute surface of a gear tooth by a drive system. Signals from the probe are sent to a computer-based system for filtering and evaluation (Fig. 1). The probe usually consists of a skid and a stylus. The skid is used to support the probe on the surface to be evaluated, and as the probe moves across the surface, the skid tracks the overall curvature of the surface. The stylus, the sensitive portion of the measuring system, consists of a very fine diamond with a tip radius of 5µm. The stylus measures the microvariations in the surface, which make up the "roughness." The involute curve of the gear teeth, as well as the limited space between teeth, particularly on fine pitch gears, requires a special type of probe designed specifically for gear tooth measurement (Fig. 1).

The position of the skid relative to the stylus on a standard surface roughness probe will almost always produce unsatisfactory measurement results on a gear tooth. The special gear tooth probe is designed to fit into relatively small spaces. It also has a stylus skid orientation that is designed to minimize the distortion that would result from the involute curve.

Filter Selection

Selecting the correct type of filter and the correct filter setting is imperative. A great deal of ignorance exists in this area of surface roughness measurement. Misapplication of filtering often results in measurements that are worthless.

The raw, unfiltered profile that is the output of the probe must be filtered if we are to have meaningful roughness information. Fig. 2 shows the large curvature resulting in the raw, unfiltered profile. This curvature is the result of the interaction between the skid and the involute profile. If we did not filter this curvature out of the profile, it would so dominate our parameter calculations that we would never measure the actual roughness of the surface. Fig. 3 shows the roughness of the surface after filtering. Note the absences of any curvature.

There are two types of surface roughness filters in common use today. They are the RC, resistor capacitor filter and the M1 filter that is a digital phase, corrected, Gaussian filter. The RC filter is the original filter found in surface roughness equipment dating back to the 1960s. It is still available on modern surface roughness instruments to allow correlation with measurements on older instruments. The M1 filter was introduced when computers became commonplace within surface roughness instruments. The M1 filter is much more efficient than the RC filter and produces more accurate results. The RC filter is notorious for produce distortions, particularly when the raw, unfiltered profile has excessive curvature, as is almost always the case when measuring gear teeth. When measuring gear teeth, RC filters may produce distortions resulting in roughness readings twice the actual roughness of the surface. Therefore, it is highly recommended that only M1 filters be used when measuring gear teeth.

Using the right filter setting, referred to as the cutoff, is critical. Unfortunately, most surface roughness measuring equipment defaults to a particular cutoff, based on stroke length (cutoff equals 1/6 of stroke length). The cutoff may not produce accurate results. Fig. 4 shows that the average roughness value, R_a, will change continuously with different cutoff settings.

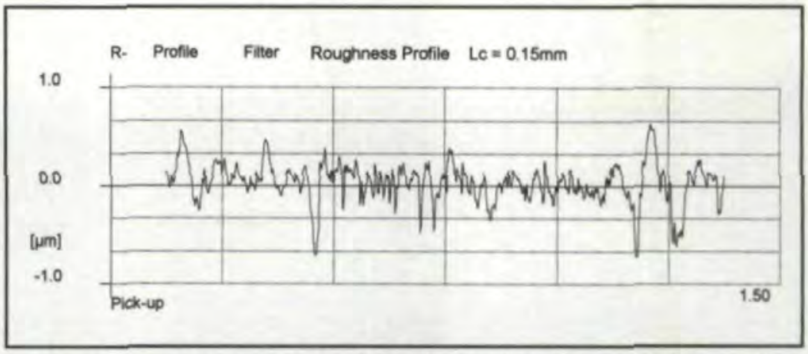


Fig. 3 — The roughness profile is the signal after filtering with a cutoff of .15 mm. Note that the amplification of this chart is 25 times greater than that of the unfiltered profile. Also, the profile is centered down the middle of the chart and shows no residual curvature, indicating that the cutoff was small enough to remove any residual curvature from the unfiltered profile.

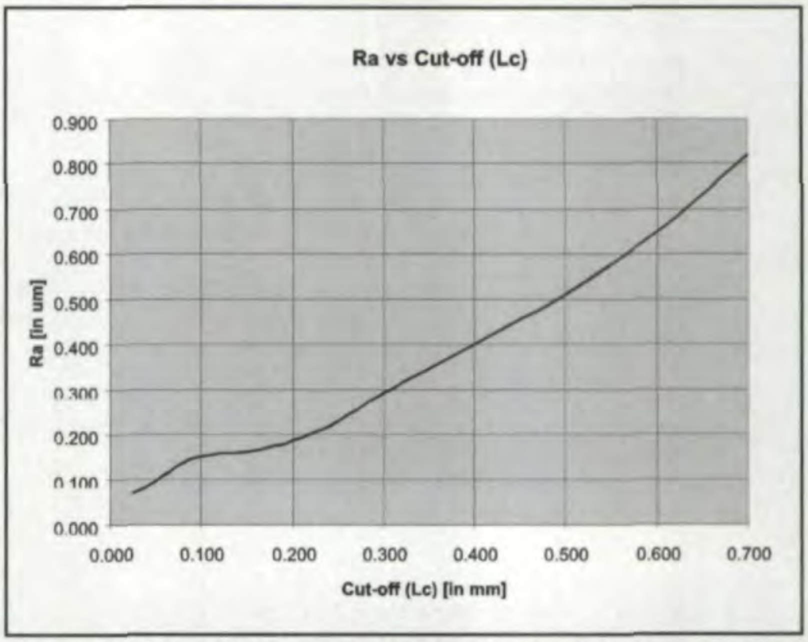


Fig. 4 — It can be seen that the roughness on a gear tooth profile continues to increase as the cutoff increases. This graph is typical of surfaces where there is a high degree of curvature in the measured surface. Note the inflection point that incurs at approximately a .15 mm cutoff. The point where the inflection occurs is usually at the optimum cutoff value. The roughness continues to increase in value after the optimum cutoff value because the cutoff is too large, and residual curvature is becoming a part of the roughness calculation.

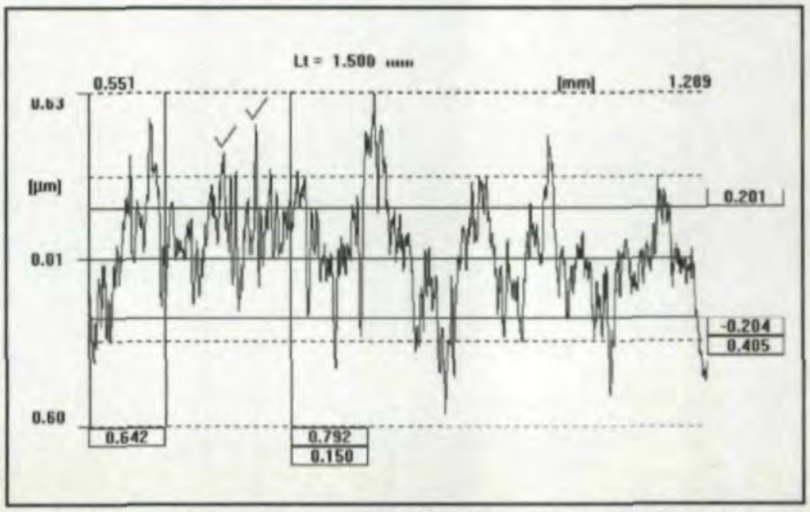
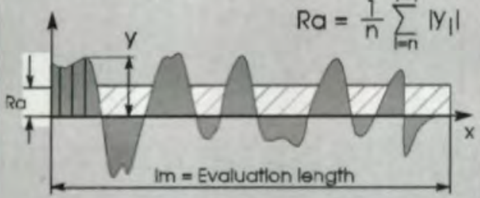


Fig. 5 — An approximate method for establishing the proper cutoff involves zooming on the unfiltered profile and determining the spacing between 2 1/2 major peaks of the surface profile. Repeating this process at different areas of the profile will result in an average cutoff value.

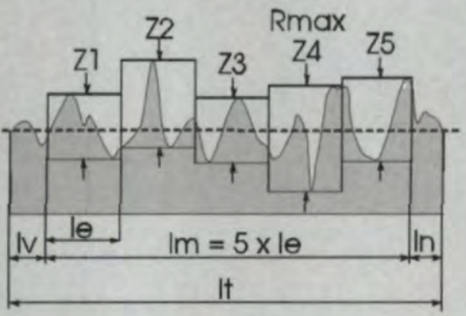
POPULAR ROUGHNESS PARAMETERS

Ra - Arithmetric mean roughness value The arithmetric average value of the filtered roughness profile determined from deviations about the center-line within the evaluation length Lm.

$$Ra = \frac{1}{n}\sum_{i=n}^{i=1} |y_i|$$



Rmax - Maximum individual peak-to-valley height: The maximum peak-to-valley dimension obtained from the five sampling lengths Le within the evaluation length Lm.

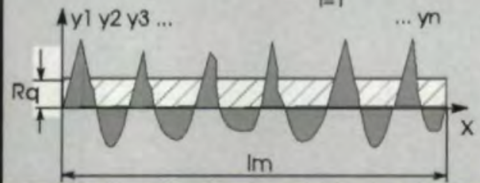


RzDIN - Mean peak-to-valley height The arithmetic average maximum peak-to-valley height of roughness value Z1 to Z5 of 5 consecutive sampling lengths Le over the filtered roughness profile.

$$R_z = \frac{1}{5}\,(Z1 + Z2 + Z3 + Z4 + Z5)$$

Rq (RMS) - Root mean square roughness value: The RMS value obtained from the deviations of the filtered roughness profile over the evaluation length Lm.

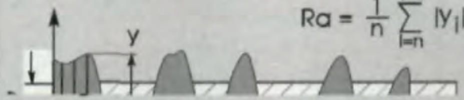
$$R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{i=n} y_i^2}$$



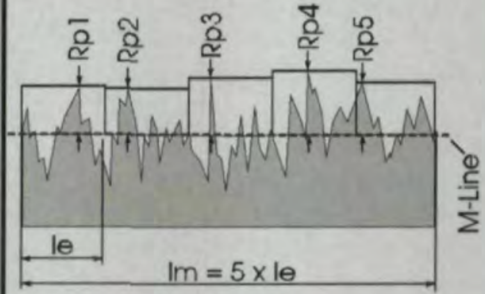
Popular roughness parameters

Ra - Arithmetric mean roughness value The arithmetric average value of the filtered roughness profile determined from deviations about the center-line within the evaluation length Lm.

$$Ra = \frac{1}{n}\sum_{i=n}^{i=1} |y_i|$$



Rp - Single highest peak above the mean-line: The value of the single highest peak above the center line of the filtered *profile as obtained from Rpm.*



Pc - Peak count: A peak count taken over a standard length of 10 mm of the filtered roughness profile. Whereby a peak is only read after the profile has passed through both a lower and an upper variable preset threshold C1 and C2. Both threshold lines are set parallel to the 'center-line'.

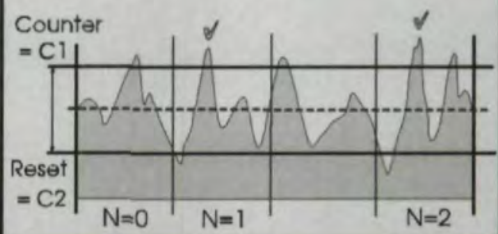


Fig. 6 — Popular roughness parameters.

So what is the appropriate cutoff value? A very small cutoff will insure the elimination of any curvature resulting from the involute of the gear tooth, but it will also eliminate virtually all the roughness. A very large cutoff will include all the roughness, but also a great deal of the involute curvature. The optimum cutoff value is that one that is small enough to eliminate the involute curvature and at the same time large enough so that it is not attenuating the actual roughness profile. Once this cutoff value is found for a particular process, it need not change and will probably be adequate for any measurements on gear teeth made from that process.

THE OPTIMUM CUTOFF IS SMALL ENOUGH TO ELIMINATE THE INVOLUTE CURVATURE AND AT THE SAME TIME LARGE ENOUGH TO NOT ATTENUATE THE ACTUAL ROUGHNESS PROFILE.

Obtaining the proper cutoff setting requires a surface roughness system which is capable of producing a profile of the unfiltered signal. Zooming on this profile will allow the inspector to determine the spacing between the dominant peaks of the surface. Generally speaking, the optimum cutoff value will be a distance which is equal to 2 1/2 peaks. (See Fig. 5.) Also, another indication of proper filter selection is a roughness trace that runs straight down the middle of the chart with no residual curvature evident. For example, in the measurement shown in Fig. 2, the default setting for the cutoff would have been .25 mm. However, careful study of the unfiltered profile, as well as the roughness profiles at various cutoff settings, indicated that a more appropriate cutoff would be .15 mm. Note that the default cutoff setting would have produced a roughness value 50% higher than the correct value.

Parameter Selection

Surfaces are digitally and objectively characterized by roughness parameters. There are many roughness parameters, each intended to describe a particular feature of a surface. If a surface roughness parameter cannot predict the functionality of a gear surface, it is worthless. For example, the average roughness parameter R_a may be a useful production monitoring tool, but it cannot differentiate between significantly different surfaces and, therefore, may be of little value in predicting functionality. Discussing all of the various roughness parameters is beyond the scope of this article. However, a good understanding of the 25 core roughness parameters in common use is critical if a designer is going to be able to select the proper parameter for a particular application. The most popular of these core parameters are described in Fig. 6.

Even the material of the gear will affect surface roughness parameter selection. For example, sintered gears or gears manufactured from cast iron are highly porous. This produces a roughness profile with many deep valleys. These valleys may have little effect on function, yet they will have a dramatic effect on the magnitude of any roughness parameter that involves data from the valley portion of the profile. For example, the R_z parameter, average peak to valley, would be very much affected by these pores. In this situation, if one is trying to measure the efficacy of a manufacturing process, a parameter such as R_{pm}, the average peaks above the mean line of the profile, would be far more relevant than the R_z parameter.

Parameter selection is not as difficult as it may seem. A good understanding of how the parameters are calculated and an understanding of the functional requirements of the surface will facilitate the selection of parameters that can indeed predict functionality.

Accurate surface roughness measurements on gear teeth can be a valuable quality analysis tool. Attention to the basic requirements of surface finish analysis such as proper equipment, correct filtering and the use of surface roughness parameters that will predict the functionality of the gear are key to successful implementation of surface finish discipline. ○

Acknowledgement: *A version of this material was presented at the SME Advanced Gear Processing and Manufacturing Conference, June 3–5, 1996.*

Ronald A. Lavoie

is the president of Hommel America Inc. of New Britain, CT, a manufacturer of gear inspection equipment. He is the author of several articles on inspection subjects.

Hoechst Technical Polymers to Gather Plastic Gear Materials Data

Hoechst Technical Polymers has expanded its interests in plastic gears with the introduction of the new Plastic Gear Evaluation and Research machine P-GEAR™ The machine is the centerpiece of the company's continuing efforts to promote and develop the use of plastic gears in higher-powered applications.

Other efforts include the development of new grades of plastics for gear manufacturing use, a special company team devoted to plastic gear research, the support of university-based research into the uses of plastics for gears and the future publication of a plastic gear design manual.

Plastic Gear Advantages

Plastic gears have some advantages over metal parts in some applications. Used as-molded, they do not require expensive finishing operations. They can cost as much as one-half to one-fourth as much as stamped, machined or powder metal gears, and they can weigh as much as 75% less. They can be self-lubricating and can run quieter than metal gears one or two AGMA quality classes higher in accuracy. However, one powerful drag on the increasing use of plastic gears in industrial applications has been the lack of available engineering data. "We can't get people to use our materials without having the data to enable designers to assess how the materials will work in their applications," says Maribeth Fletcher, leader of the HTP Gear Team.

The P-Gear Tester

The P-Gear Tester, built by Lewis Research, Inc. of Lewes, DE, is part of the answer to that problem. It is a computer-controlled wear and fatigue tester that should provide much useful data about the gear working environment and the way plastics behave in it.

The tester enables researchers to test plastic gears in a range of conditions, with and without lubrication, and to collect data automatically. It has a precision dynamometer and drive to run gear sets of mixed materials under loads of 5.5 hp and at speeds to 3,600 rpm. Gear set center distances can range up to 5", and parallel shaft gear sets can include a third idler gear. The drive assembly also swings 90° to accommodate worm gears and other cross-action drives. P-GEAR provides ambient environments from room temperature to +200°C initially and will go down to -40°C with future modification.

HTP's P-GEAR™ plastic gear tester.

System Strengths

The system uses a Pentium®-based PC with Strawberry Tree™ data collection software. It uses precision rotary encoders to monitor the relative position of meshing drive and driven gears under programmed loads. Gears run at constant speed and torque for a set period and are then stopped and oscillated slowly to measure their relative positions in order to assess backlash.

P-GEAR has non-contact infrared temperature sensors for unlubricated gears and fluid temperature sensors for lubricated gears. According to Hoechst, temperature measurements taken on different materials at changing loads and speeds will provide researchers their first accurate picture of the gear tooth environment, leading to predictive measurement of tooth temperature and ultimately to the selection of the best candidate gear material for each specific design and application.

Researchers also hope the P-GEAR tester will enable them to run static bending tests to measure mesh stiffness. It will also monitor gear noise and document the effect of material mixes and resin additives on noise reduction.

P-GEAR's data collection capability will allow the machine to chart the gear environment and help generate predictive equations for estimating the fatigue life of plastic gears.

Initially the tester will be used to validate existing data on HTP resins in plastic gears. These preliminary measurements on familiar materials will help formulate test protocols for developing gear life cycle curves related to bending strength and contact stress and wear. Subsequent work will establish protocols for predicting tooth operating temperature and provide wear constants for predictive life cycle equations.

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M & M Precision, Penn State & NIST Team Up For Gear Metrology Research

In 1993, M & M Precision Systems was awarded a three-year, partial grant from the Advanced Technology Program of the Department of Commerce's National Institute of Standards and Technology (NIST). Working with Pennsylvania State University, M&M embarked on a technology development project to advance gear measurement capabilities to levels of accuracy never before achieved.

Responding to industry concerns about the measurement uncertainties associated with gear manufacturing process control and the competitive position of U.S. gear manufacturers worldwide, M & M contributed over $1 million of its own funds to significantly improve gear measurement accuracies and provide a proven methodology for verifying these accuracies.

Project Goals

The goals of the project included:

- Develop and implement a rational methodology for analytically representing all points on the running surfaces of all teeth on a generic gear, necessary information for transmission error prediction, analysis of heat treat distortion, etc.;
- Model the accuracy of generative gear measurement machines as a function of accuracy of the components of the system;
- Determine the accuracy of state-of-the-art generative gear measurement machines by use of the above model and comprehensive gear measurements;
- Enhance measurement machine and controls architecture and sensor hardware and software technologies to achieve submicron level accuracies in gear measurements;
- Develop statistical methods using measurement redundancies and replications to enhance measurement accuracies and to estimate measurement uncertainties;
- Develop computation algorithms and software to compensate for systematic machine-component errors and minimize final measurement inaccuracies;
- Develop procedures and artifacts adequate to verify submicron level accuracies in precision gear measurement;
- Verify the achieved level of gear measurement accuracy by implementing the above developments into an enhanced generative gear measurement machine.

Progress

A number of developments in hardware and software were necessary to achieve these goals.

Environmental Chamber. An environmental chamber was installed in the first year of the project. This room has been certified traceable to NIST to control temperature within .1°F and humidity under 45%. It has been used both to determine current day gear measurement machine accuracies and to provide the necessary environment to achieve project goals.

Enhanced Accuracy for Linear and Rotary Axes. M & M and Penn State worked together to develop models to characterize the systematic machine and component errors throughout the entire system. Software to enhance probe locations in the light of these errors (slide path, yaw, and distance errors) were integrated into the M & M 9000 gear measurement program. Rotary axis errors were derived from a set of index measurements on a set of master gears. Software separated the gear index errors used in the measurements from the rotary axis errors. The M&M 9000 can calibrate index errors on a master gear to better than 15 microinches of measurement uncertainty.

Laser Linear Measuring System. A laser linear measuring system was also developed. This system was evaluated by the Mid-Scale & Complex Form Metrology Group at NIST and shown to achieve a .2 micrometer (2 sigma) uncertainty for 800 mm displacement.

Gear Artifacts. To evaluate the enhanced measuring system with the lowest measurement uncertainties possible for profile, index and tooth alignment (lead), artifacts were designed and calibrated. NIST and the Oakridge Metrology Center Y-12 Plant measured a pin master, a 1" sphere master (under 2 microinch form errors), a lead master and an involute master. Procedures are currently being documented along with mathematical estimates of the final measurement uncertainties for all artifacts.

M&M HAS CONTRIBUTED OVER $1 MILLION TO THE GEAR METROLOGY RESEARCH PROJECT.

Final results of the research are currently being documented for NIST. Integration of this new technology into available products is underway at M & M.

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Detroit in 97—the
BIGGEST GEAR EXPO EVER

"A Decade of Performance" is the theme of the American Gear Manufacturers Association Gear Expo 97, to be held October 19–22 at Detroit's Cobo Hall. Products and services related to every aspect of the gear manufacturing process, from turning and grinding the blanks to coating and inspection of the gears, will be represented at the show.

According to the show's managers, early indications are that it will be the biggest and most successful show in the expo's 10-year history. With more than 40,000 sq. ft. of exhibition space sold by the end of March, the show is already 10% larger than the 1995 Gear Expo. AGMA has added an additional 10,000 sq. ft. to its original 40,000 sq. ft. of available space to accommodate additional exhibitors.

AGMA is predicting record attendance levels, with visitors from all over the U.S. and 25 other countries.

Photo by Bill Pugliano.

Detroit skyline.

Photo by Vito Palmisano.

Freedom fireworks display.

Photo by Vito Palmisano.

Detroit People Mover.

SHOW BASICS

Who? Everyone with an interest in gears and gear manufacturing.
What? AGMA's Gear Expo 97, "A Decade of Performance."
Where? Cobo Hall, Detroit, MI.
When? October 19–22, 1997.
Why? To see the only international trade show devoted exclusively to the gear industry.
How? Contact AGMA headquarters 703-684-0211.

For more information, see Show Central, *Gear Technology*'s electronic look at Gear Expo 97 (*http://www.geartechnology.com*).

WHERE TO STAY

Three hotels near Cobo Hall are offering special rates for Gear Expo 97 visitors and exhibitors. They will be holding blocks of rooms until September 23.

Westin Renaissance Hotel
Renaissance Center
Near Cobo Hall.
The "Headquarters" Hotel
Ph: 313-568-8000
Fax 313-568-8116
Single/Double — $122.00 per night

The Atheneum Suite Hotel
1000 Brush Avenue
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TECHNICAL CALENDAR

AGMA GEAR SCHOOL & HOB SHARPENING CLINICS

The AGMA Training School for Gear Manufacturing is held at Daley College, Chicago, IL. This one-week course is designed for employees with at least six months' experience in setup or machine operation, and it covers setup, gear inspection, gear calculations and basic gearing principles. The curriculum includes both classroom and hands-on training in hobbing, shaping and inspection. The remaining sessions for 1997 will be held **Sept. 22–26 and Nov. 17–21**.

The Hob Sharpening Workshop is also held at Daley College. It is a two-day course with both classroom and hands-on training in hob sharpening basics, grinding and wheel dressing, setup, inspection and sharpening helical flute hobs. The last session of 1997 will be **Aug. 7–8**. For more information, contact Susan Fentress at AGMA. Phone 703-684-0211, fax 703-684-0242, e-mail *agma@clark.net.*

OTHER EVENTS OF INTEREST

August 27. Gear Research Institute Annual Meeting. Penn State University Applied Science Building, State College, PA. Business and technical sessions. Contact National Center for Advanced Drivetrain Technologies (NCADT) at Penn State for more information. Ph: 814-863-9749; Fax: 814-863-1185.

Sept. 4–5. Metalworking Software Expo '97. Chicago Marriott O'Hare, Chicago, IL. This exhibition will display the latest software and hardware for job shops involved in production machined parts, screw machine parts, dies and molds, fabricated parts and assemblies, stampings, castings, die castings, forgings, fasteners, springs, metal finishing and heat treating. Software applications include CAD/CAM and engineering systems, integrated management systems, office automation, data collection, CNC machine control systems, quality management systems and special application software. Contact Michelle Jenkins at Gardner Management Services, 1-800-950-8977 or fax 513-527-8950.

Sept. 9–11. Detroit '97 Advanced Productivity Exposition. Cobo Hall, Detroit, MI. The Midwest's largest machine tool and manufacturing event for the automotive industry and suppliers. Sponsored by SME, AMTDA and AMT. For more information, contact SME at 313-271-1500 or fax 313-271-2861.

Sept. 22–24. Technology 2007 Convention & Exposition. Hynes Convention Center, Boston, MA. Sponsored by NASA, *NASA Tech Briefs* and The Technology Utilization Foundation, this convention is for engineers, scientists, managers, developers and entrepreneurs who need to stay on the cutting edge of technology development and/or who are looking for commercial partners. For more information, call 212-490-3999 or check the convention Web site at *www.nasatech.com/t2006.*

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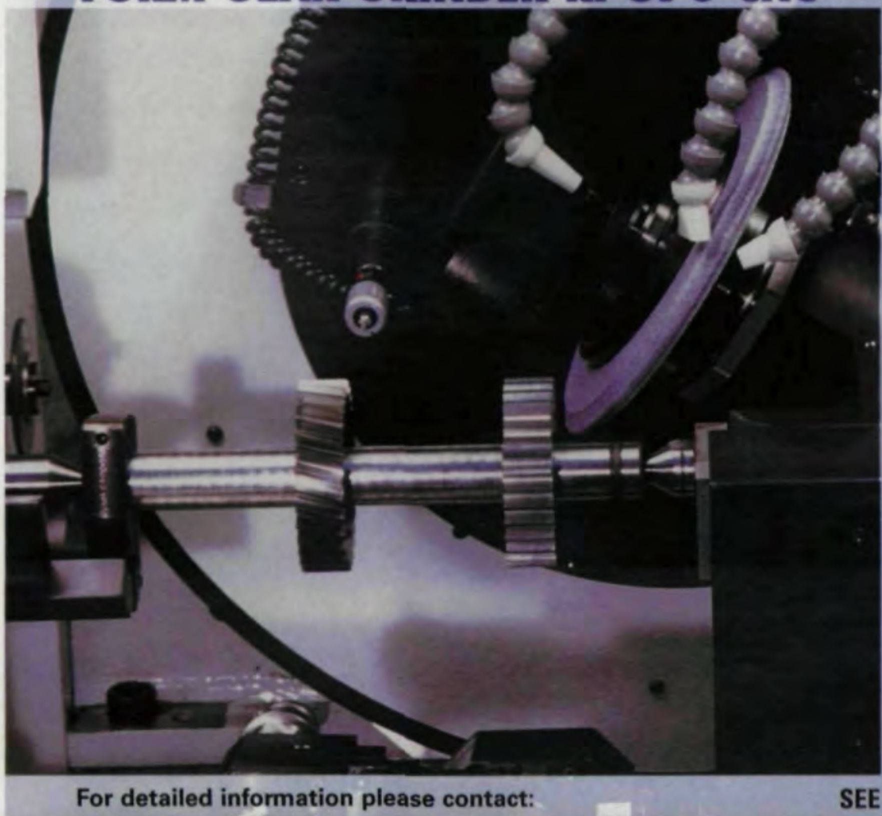

Involute Inspection Methods and Interpretation of Inspection Results

Yefim Kotlyar

Introduction

What is so unique about gear manufacturing and inspection? Machining is mostly associated with making either flat or cylindrical shapes. These shapes can be created by a machine's simple linear or circular movements, but an involute curve is neither a straight line nor a circle. In fact, each point of the involute curve has a different radius and center of curvature. Is it necessary to go beyond simple circular and linear machine movements in order to create an involute curve? One of the unique features of the involute is the fact that it can be generated by linking circular and linear movements. This uniqueness has become fertile soil for many inventions that have simplified gear manufacturing and inspection. As is the case with gear generating machines, the traditional involute inspection machines take advantage of some of the involute properties. Even today, when computers can synchronize axes for creating any curve, taking advantage of involute properties can be very helpful. It can simplify synchronization of machine movements and reduce the number of variables to monitor.

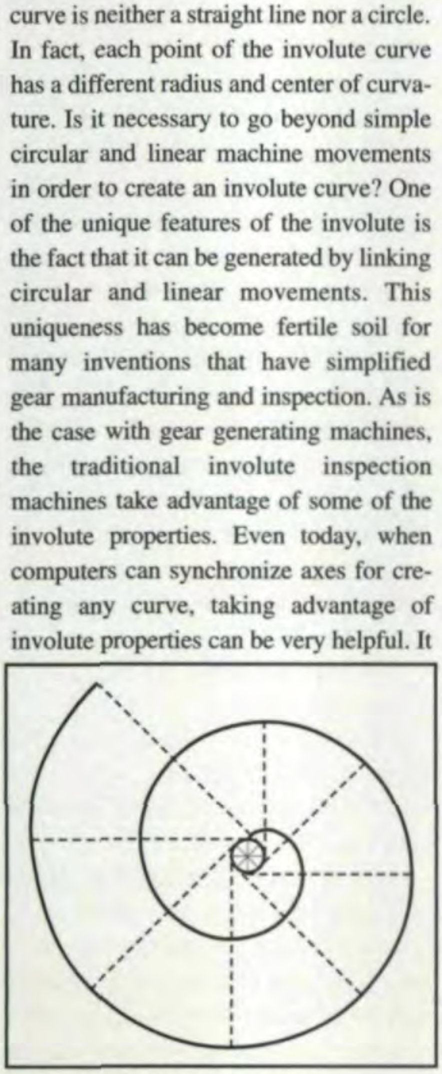

Fig. 1 — The basic involute curve.

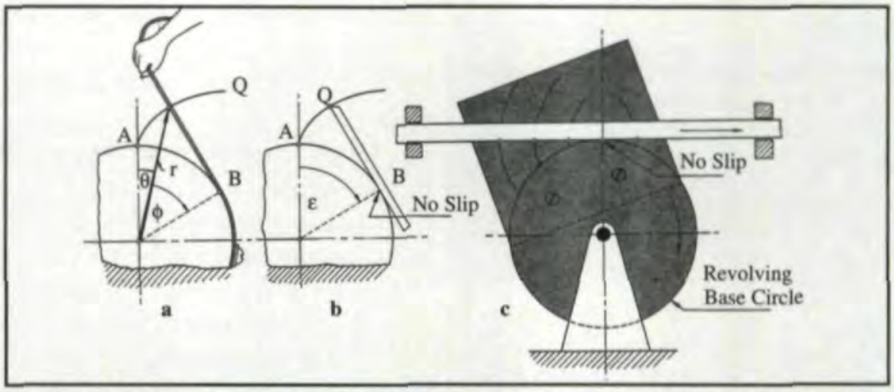

Fig. 2 — Methods for generating an involute curve: a) the string method; b) a beam rolling around a fixed base circle; c) beam and base circle rolling with each other without slip.

Involute Definition, Geometric Properties and Involute Function

The involute curve is a spiral beginning at the base circle and having an infinite number of equidistant coils (Fig. 1). Only a small portion of the innermost coil has been utilized in practical applications. The easiest way to visualize this is by describing the way it can be generated. The involute curve can be generated by a point on a tightly held, inextensible and extremely thin thread that is unwound from a fixed circle, called the base circle (Fig. 2a). This method is called the string method. An involute can also be generated by a beam rolling around a fixed base circle (Fig. 2b) or by a beam and base circle rolling with each other without slip (Fig. 2c). All these principles are used in gear generating and inspection machines.

Important geometric properties of the involute curve can be derived from its generation. Some of these properties are used either for the inspection machine movements or referenced in the inspection results.

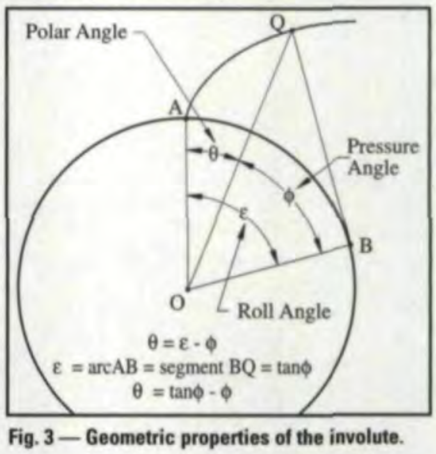

Fig. 3 — Geometric properties of the involute.

• The line tangent to the base circle, drawn from any point of the involute, is always perpendicular to the involute curve (see Fig. 3).

• The segment of the tangent line, *QB*, is the radius of curvature of the involute for the point *Q*. Points where the string separate from the base circle are instantaneous centers of the involute curvature.

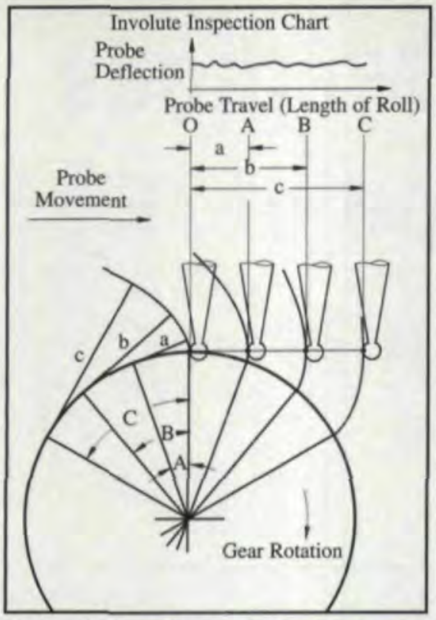

Fig. 4 — Basic mechanics of an involute inspection process using a probe.

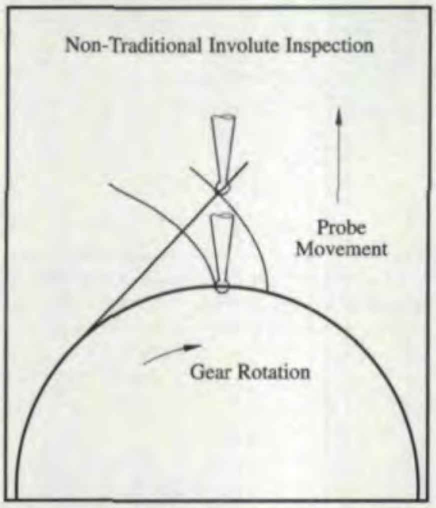

Fig. 5 — Mechanics of non-traditonal involute inspection.

• For any point on the involute, arc length AB, contained by the beginning of the involute and the point of tangency, is equal to the length of the line segment QB tangent to the base circle.

Involute Function

Let the involute or polar angle be θ, the pressure angle be ϕ and the roll angle be ε. Then let us assume for simplicity that the base radius equals 1 unit of linear measurement. In this case, the length of an arc equals the angular measurement using radians as measuring units. Therefore, $\theta = \varepsilon - \phi$, where $\varepsilon = \text{arc}AB$ = segment $BQ = OB \bullet \tan\phi = 1 \bullet \tan\phi = \tan\phi$. The involute function can be derived by replacing ε with its function of ϕ: $\theta = \tan\phi - \phi$.

Most analytical gear inspection machines use these involute geometry properties:

• Length of roll QB equals the length of arc of roll AB.

• The line tangent to the base circle is always perpendicular to the involute curve.

Principles of Traditional Mechanical or CNC Involute Inspection and Resulting Charts

The Mechanics of Machine Movement. Traditional involute inspection concepts are based on combining the linear motion of the probe carrier and the rotational motion of the gear. This combined movement generates an involute path for the probe relative to the gear profile. While the probe moves along the path that is tangent to the base circle, the distance equals the length of roll a, and the gear rotates the angle A (Fig.4).

One important beneficial distinction of the traditional involute inspection method is the unchanging probe contact point throughout the entire probe travel (Fig. 4). This unchanging contact point simplifies the inspection process by reducing the number of variables that need to be monitored.

The probe deflection represents a deviation of the gear profile from the involute curve. If the gear profile is a perfect involute, the probe deflection would stay constant throughout the entire movement, and the resulting inspection chart would be a straight horizontal line. A deviation from this straight line would constitute the profile error.

Involute Inspection Charts. An involute inspection chart is scaled proportionately to the length or angle of roll. The X coordinate (probe travel) represents length or angle of roll. The Y coordinate represents profile deviation from the perfect involute in the direction normal to the involute curvature.

It is important to reiterate that the traditional involute inspection chart is not proportional to the diameter, nor is it proportional to the length of involute curve.

Non-Traditional Involute Inspection

With the proliferation of coordinate measuring machines, other involute inspection methods have come into being. Some CMMs use the traditional method, but some don't. Nevertheless, the inspection results are presented in the old fashioned way—profile tracing is scaled proportionately to the length of angle of roll, as shown in the upper section of Fig. 4.

Machines that do not use the traditional method include

• CMMs without rotary tables. The probe contours a fixed gear.

• CMMs with rotary tables, but without tangential slides.

The principle difference between non-traditional and traditional machines is the fact that non-traditional machines have three axes instead of four. A fewer number of axes makes one part of the machine less expensive; however, it also creates an additional burden in

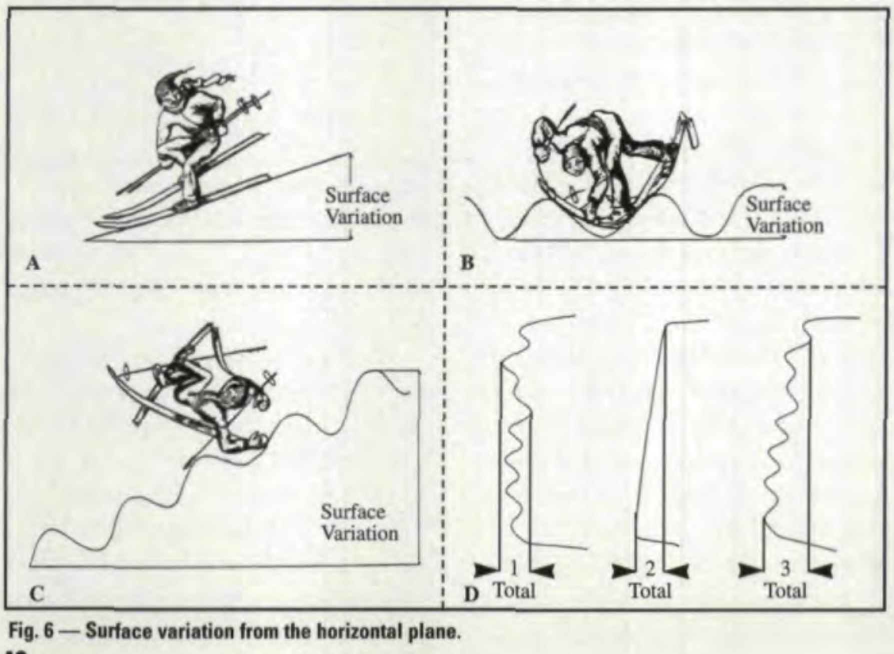

Fig. 6 — Surface variation from the horizontal plane.

another area of the machine. In both non-traditional cases, in addition to two moving machine axes, the system has to keep track of one extra variable—the contact point of the probe. Thus, the machine cannot take full advantage of involute properties for reducing the number of variables to monitor during involute inspection.

Fig. 5 depicts the involute inspection principle for the machine without a tangential slide. *X* & *Y* coordinates of the probe contact are continuously changing as the probe moves from root to tip (See Fig. 5). To make matters worse, in the case of helical gears, *X*, *Y* and *Z* coordinates of the probe contact are continuously changing.

The advantages of non-traditional machines are that they have fewer axes, and their 3-dimensional probes give them the potential for adding non-gearing inspection capabilities to the machines.

The disadvantages of using these non-traditional machines include the need to monitor the extra variables during involute inspection, which can make the systems either less accurate or more expensive to develop, and the requirement for 3-dimensional probes, which add a significant cost to the apparatus.

Some Common Principles of Surface Evaluation

How do people analyze, qualify and quantify the surface deviation from desired conditions? What do we mean by "profile error"? Is this the amount of error or the shape of the error or both? There are situations in which one number for defining involute error is not sufficient to quantify and qualify the error.

Let's introduce three definitions: slope error, form error and total error. The drawings in Fig. 6 help to illustrate the differences between these three concepts. Fig. 6a shows surface variation from the horizontal plane. Is it a lot or a little? For a farmer it may be lot, but for a skier, it may not be enough. Fig. 6b shows a different type of surface variation. Even for some skiers, it may be too much. In reality however, people frequently deal with a combination of the kinds of surface errors shown in a and b. The situation is more like the one shown in Fig. 6c. The errors may have the same value, but a different appearance, as shown in the Fig. 6d.

Determination of Total, Slope and Form Errors

The total surface deviation from an ideal condition can be broken down into slope and form errors (Fig. 7). There are various techniques for isolating these errors. The most popular, and probably the most accurate, is the "least squares" method. This method is based on determining the "best fit" line that segments the curve into two approximately equal areas on either side of that line (see Fig. 7). Deviation of the best fit line from the ideal position (the vertical in Fig. 7), is called the slope error. Deviation of the inspection curve from the best fit line is called the form error.

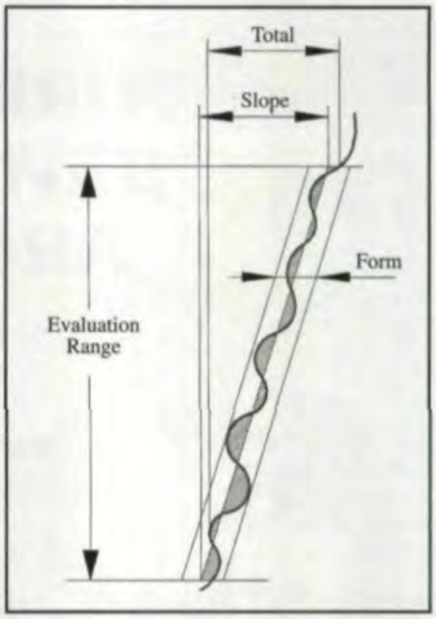

Fig. 7 — Total, slope and form errors.

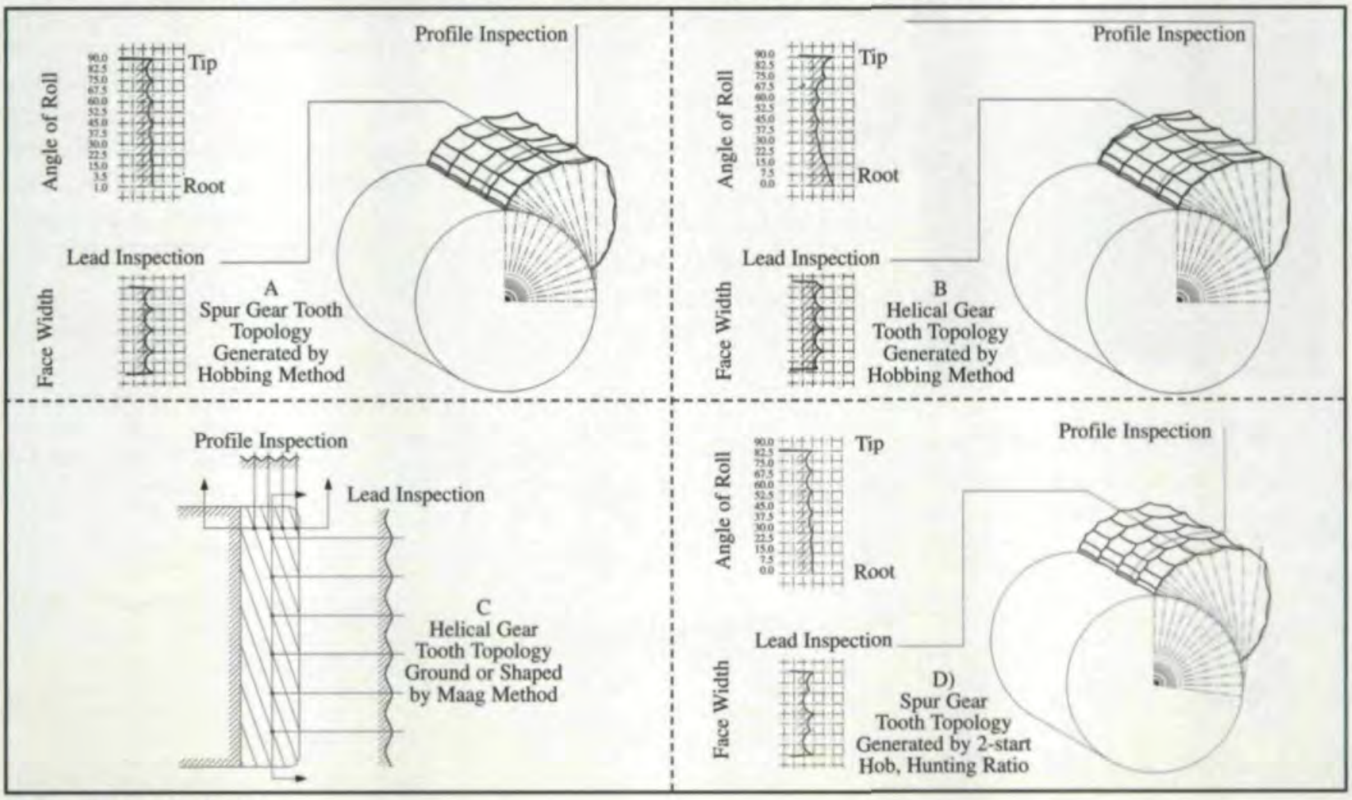

Fig. 8 — Spur gear tooth topology.

The breakdown of total error into form and slope components is applicable to both involute and lead inspection. Because slope and form errors come from different sources, isolating and assigning a value to each error component is very helpful for finding the largest contributor to the tooth surface inaccuracy.

Slope error sources include

• Lead. The wrong machine settings for the helix angle.

• Involute. Wrong hob pressure angle or wrong rake angle induced during hob sharpening.

Form error sources include

• Lead. Excessive feed rate.

• Involute. Excessive hob runout or hob gash index error or excessive hob lead error or insufficient number of hob gashes.

The breakdown of the total error into the slope and form error components can be invaluable for determining exact machine or tool adjustments, thus eliminating time-consuming trial and error techniques. For example, lead or taper adjustment on a CNC hobbing machine can be determined accurately with the average lead slope errors.

Tooth Surface Patterns Created by Various Manufacturing Processes

Every gear manufacturing method creates a certain gear topology that, during the inspection, translates mostly into form errors. Some examples of tooth topology are shown in Figs. 8a–d. Note that all these examples display involute and lead errors despite the fact that these gears were manufactured under ideal conditions of machine, tool, fixture and blank. These errors are referred to as inherent errors introduced by the process principle.

Even the most accurate hobs and machines can create greater than allowed lead and involute errors. Understanding the tooth topology helps to differentiate between the inherent errors introduced by the process principle and errors induced by the process variables (machine, cutting tool, fixture and blank inaccuracies). Frequently, determining the error source is a bigger challenge than the elimination of that source.

Common Profile Modification

Commonly gears are designed with tip and/or root relief (Fig. 9). The numerical evaluation of such profiles becomes more complicated. There are various computerized techniques available for evaluation of profile modifications. Some people use a comparison with an ideal curve. Some evaluate various portions of the tracing separately; some evaluate crown; some evaluate hollow;

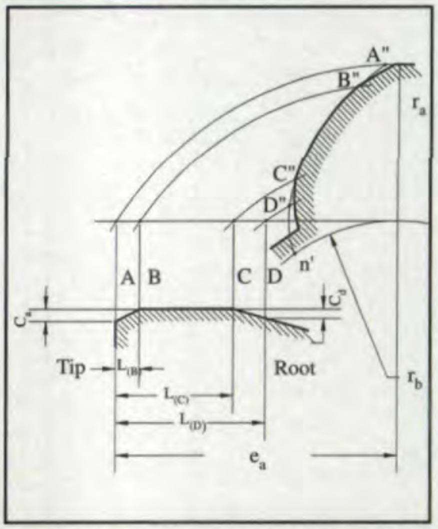

Fig. 9 — Involute geometry of a gear designed with tip and root relief.

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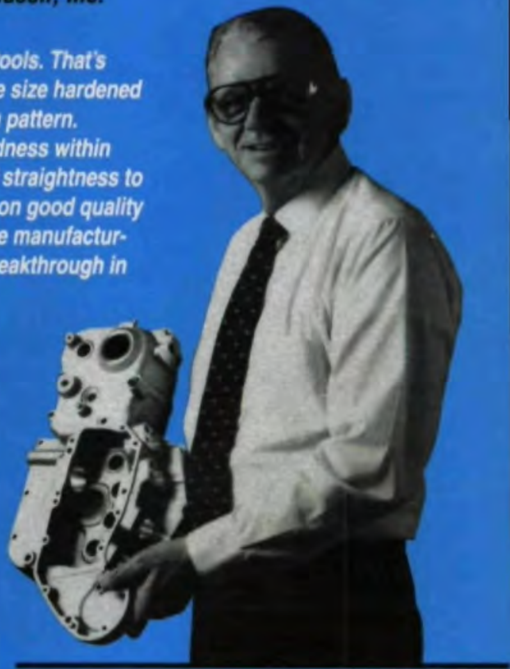

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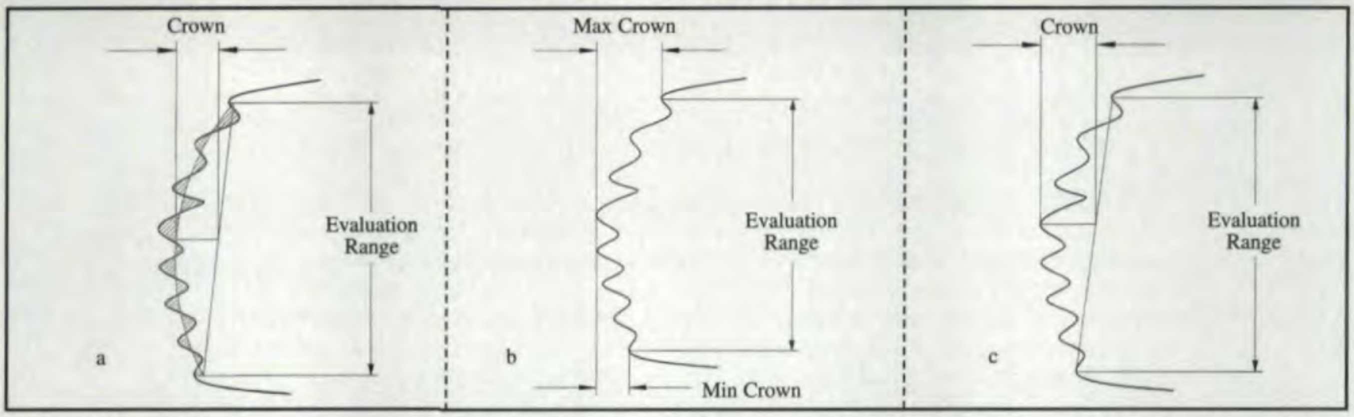

Fig. 10 — Computized techniques for crown evaluation: a) best fit curve method; b) comparison of both ends of tracing with high point; c) comparison of a line connecting tracing ends with high point.

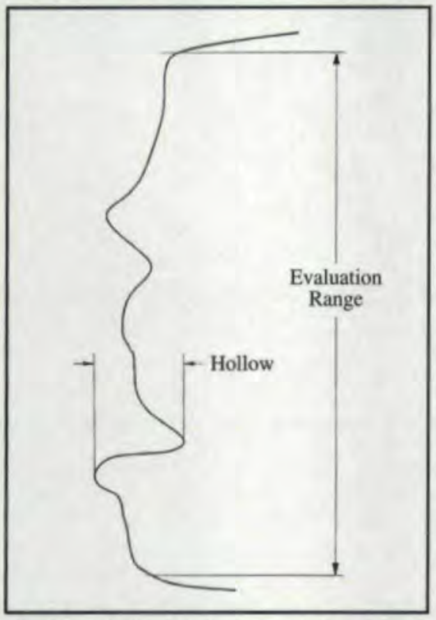

Fig. 11 — "Hollow" is the reversal of curvature.

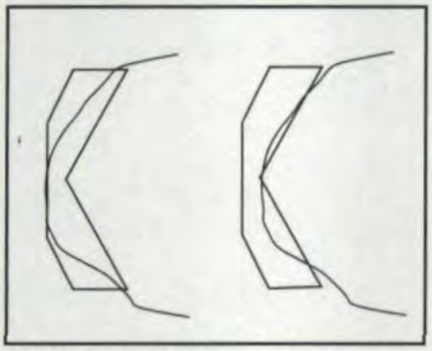

Fig. 12 — A basic K-chart evaluation.

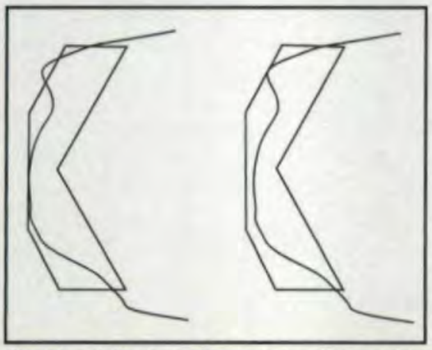

Fig. 13 — A K-chart with more than three points.

and some use the K-chart technique. Most people use some kind of combination of these methods.

Crown of the Surface. There are various computerized techniques available for crown evaluation. Some use a best-fit curve (Fig. 10a). Some compare both ends of the tracing with a high point (Fig. 10b), and some compare a line connecting tracing ends with the highest point (Fig. 10c).

Hollow. Hollow is the reversal of the curvature, as shown in Fig. 11. One can look at hollow as a variation of the form error. This characteristic is widely monitored for evaluation in the automotive industry.

The K-Chart Method of Profile Evaluation

The K-chart is probably the most widely used technique for qualifying or disqualifying a gear. The K-chart is a simple appraisal for deciding whether or not the gear profile is within the specification. However, it is important to note that the K-chart is not a good tool for analyzing the source of a problem. It is only a go/no-go gage which tells whether the profile is good or bad. When a gear does not fit the K-chart, a more detailed analysis must be conducted in order to find and eliminate the source of the problem; e.g., total error must be broken down into the slope and form components.

Despite its seeming simplicity, the K-chart can become a matter of controversy. Many companies—and sometimes different people within the same company—differ about how to interpret a K-chart. For example, is the tracing in Fig. 12 inside or outside the K-chart tolerance?

The answer depends on which interpretation method is used. An inspection tracing could be justified to a "plus" material condition as shown on the left of the figure or a "minus" as shown on the right. Sometimes, K-chart bands are defined with more than three points. This opens up a further proliferation of evaluations. Some people may justify the high point located anywhere between SAP and EAP, as shown on the right of Fig. 13. But some may use a specific range of roll angle for justifying the high point. An example is shown in Fig. 13 on the left, where a middle portion of the tracing is used for justifying a high point of the involute. As a result, the same tracing could be considered as outside (left) or inside (right) a K-chart.

Conclusion

Basic principles of gear inspection have not changed during the last 30 to 40 years. But there has been a dramatic proliferation of gear inspection standards, evaluation techniques and inspection machines. Computers certainly have contributed a great deal to this proliferation.

While the proliferation of gear inspection machines was a welcome sign for gear manufacturers, the current variety of home-grown gear evaluation standards and techniques have had both positive and negative effects. On one hand, it has opened up choices and provided fertile soil for creativity. But on the other hand, especially for people without a strong background in gear geometry, this proliferation of standards and techniques has become a very confusing matter.

AGMA standards for involute and lead evaluation are by no means comprehensive and conclusive. For example, AGMA does not classify form and slope error components. Perhaps that is one of the reasons why many American gear manufacturers have created their own, more detailed, but frequently contradicting standards and techniques. Examples of these contradictions are the aforementioned K-chart and crown varieties of evaluations. These varieties are wide open for different interpretations and resulting disagreements.

To avoid these disagreements, it is helpful to recognize these varieties and, if necessary, develop or adapt, document and communicate the company's policy regarding profile evaluation methods and interpretations of the K-chart or crown.

In contrast, the European gear inspection standards are more comprehensive and adopted widely. As a result, these standards are much more effective in helping gear companies find common ground when dealing with one another. These standards can also be more effective for debugging gear manufacturing processes, for example, by applying slope and form error components.

Regardless of where one stands on the merits of home-grown standard and evaluation proliferation, understanding the basics can help one navigate in this sea of inspection standards and evaluation techniques. ○

Acknowledgement: *The article is based on paper presented at the SME Gearing Conference, Feb. 3, 1997, Chicago, IL.*

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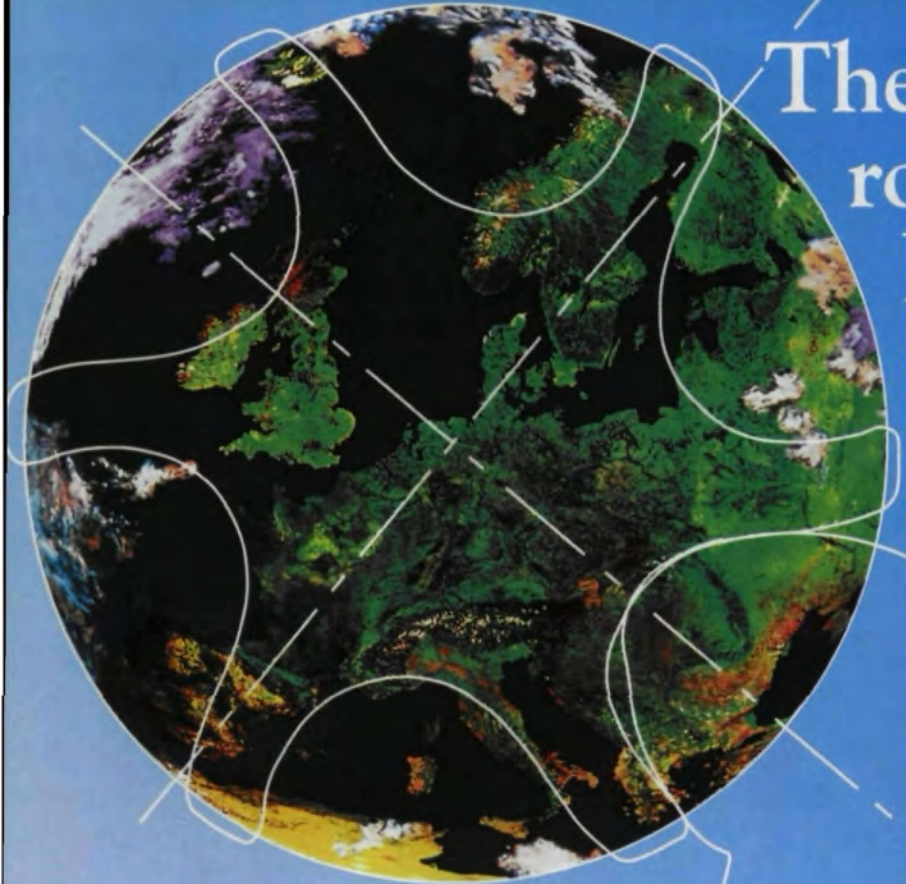

Welcome to our Product News page. Here we feature new products of interest to the gear and gear products markets. To get more information on these items, please circle the Reader Service Number shown. Send your new product releases to: *Gear Technology*, 1401 Lunt Avenue, Elk Grove Village, IL 60007, Fax: 847-437-6618.

Mobile Parts Cleaner

The Graymills Model TL1 Tempest® Series Jet Spray Parts Cleaner is designed specifically to provide parts cleaning in a compact cabinet. It is designed for job shops and other facilities where space is at a premium. It has an optional caster kit, which makes it easily portable from one location to another. The TL1 has dimensions of 40"L x 33"W x 50"H and a tank capacity of 18 gallons. It will handle parts up to 250 lbs. It has a 3/4 hp pump which produces 20 GPM at 30 psi and is available with a choice of power sources: 115V or 230V, single phase or 230V or 460V, 3 phase.

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Citrus Degreaser

Environmental Chemicals & Lubricants introduces its Orange It Degreaser. This natural citrus, water-based degreaser will break down the toughest oils, including No. 6 oil, as well as tar and asphalt from virtually any surface. It can be used in hot or cold pressure washers and will not attack painted surfaces, according to the manufacturer. It is completely biodegradable, non-flammable, non-corrosive, contains no petroleum distillates and will not irritate the skin.

Circle 302

Brown & Sharpe Chameleon CMM

Chameleon from Brown & Sharpe combines single-point measurement and multi-point scanning technology in what the company describes as a fast, accurate and affordable CMM. Chameleon uses the DATOS dimensional analysis technology to support high accuracy data evaluation at very high speed analog opened and closed loop scanning, with data transfer up to 120 points per second. The machine comes with a patented on-board temperature compensation system and all-aluminum machine construction. It has V_2 accuracy of 4.2 μm at a scanning speed of 20 mm/sec. It can be equipped with a touch trigger probe, a laser probe and an analog scanning probe. It has a 750 mm x 650 mm x 500 mm measuring range and QUINDOS® software.

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Manufacturers' Liability Insurance

The Hartford insurance company is offering a commercial liability insurance package designed for small to medium-sized manufacturing businesses. The Tripak is targeted to manufacturers of products with moderate to severe liability exposure. It contains three coverages: repair and replacement; manufacturers' errors or omissions and product recall-advertising expense. The package is meant to be a supplement to commercial general liability or product liability coverage. The coverage usually comes with standard limits of $100,000, but higher limits are available. The package is not designed for manufacturers of high-tech or medical products and is available in most states.

Circle 304

Chip-Mist Collector

The Aget chip-mist collector is designed to remove wet dust, oily chips and other contaminants generated by metal cutting operations such as machining, drilling, boring and wet grinding, and by screw machines and aluminum cut-off saws. The two-stage system consists of a Dustkop cycle separator which receives the moisture-laden chips and oil dust, removes the solids from the air stream and deposits them into a waste container. The second stage is a Mistkop filter that separates the remaining moisture from the air and carries it by tube to a waste container or returns it to the sump of the equipment. Clean air is returned to the workplace through the outer mesh wall of the filter. Available in capacities from 400 to 5500 cfm.

Circle 305

Vdraft CAD System

SoftSource™ introduces Vdraft, its AutoCAD-drawing-based CAD system for all types of architecture, design, drafting, engineering and Internet applications. The new system runs on Windows 95/NT, and the company says it is the first program produced by any company outside of Autodesk® that can create and edit AutoCAD drawings and DXF files in their native format. Each drawing (including externally referenced ones) opens in its own window, with cut, copy and paste between drawings within Vdraft and between AutoCAD and Vdraft. It also supports long filenames, direct e-mail of drawings and ActiveX automation. It reads and writes AutoCAD drawings, ASCII DXF and Binary DXF formats for Auto CAD from Release 12 back to Release 2.5. AutoCAD R13 can be supported by using the AutoCAD Save As Release 12 command.

Circle 306

Combination Data Collector, Waveform & Spectrum Analyzer

Ono Sokki introduces the new CF-1200 hand-held single channel FFT analyzer. It is a lightweight, portable single channel FFT analyzer specifically designed for field and on-site measurements. The CF-1200 operates continuously for 8 hours on 4 AA batteries and also comes with an AC adapter. It measures 9 1/2" x 4 3/4" x 2" for maximum portability. It is capable of either 100 or 400 lines of resolution, and comes with a built-in power supply for ICP accelerometers, RS-232C port, 12-bit A/D converter, and a PCMCIA type II port. It can automatically convert to English or metric units. The CF-1200 has three display modes: time domain, frequency domain, and overall list for simple data collection and spot checks. It also comes with an optional filter/vibrometer and a Windows-based program which enables the user to download information to a PC or laptop.

Circle 307

Virtual Inspection Process™ Software from ICAMP

ICAMP has announced the expansion of its independent dimensional inspection and analysis software to work with all brands and types of CMMs. The company says the software can be used in the inspection lab, on the manufacturing floor and at the engineer's desk. It provides all GD & T

(ASMEY14.5M-1994) measurements, including true position at MMC and profile of the entire part. The system is available for Windows 3.1, Windows '95 and Windows NT.

Circle 308

Solveware's MATHANSR Software

Designed to provide quick and easy solutions to shop floor mathematical calculations, MATHANSR is calculation software that works in a variety of machine shop environments. The designers say the system is simple and easy to learn and can be mastered in 30 minutes to an hour. Problems are entered in red and answers appear in black. All calculations work in the same manner, making mastering the system easier. Solveware also offers SPEEFEED®,a program for making twelve different speed and feed calculations.

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New Update of an Old Standard

Nancy Bartels

Machinery's Handbook 25 by Erik Oberg, Franklin D. Jones, Holbrook L. Horton & Henry H. Ryffel. Robert E. Green, ed., Industrial Press Inc., New York, NY, 1996 ISBN 0-8311-2424-5, $75.00 (Large Print Version, $95.00).

By the time a book gets to its twenty-fifth edition, you have to figure someone is doing something right. In the case of *Machinery's Handbook*, the collective work of various authors and editors have made the volume a standard reference in engineering offices, job shops, libraries and on factory floors, and with good reason. The basic formulas, equations, definitions, charts, tables, and diagrams needed to address almost any manufacturing design or engineering problem are incorporated in one squat volume. If an engineer had to choose only one reference manual to be trapped on a desert island with, this might be the one.

Coming out with a new edition of such an old standby is not without its problems. As the editors suggest in their preface, "Reference works . . . cannot carry the same information [in every edition] if they are to justify the claim that new or updated material is always presented." They must be aware of "what subjects have less and what have more usefulness to the majority of users. At the same time, material that is of proven worth must continue to be included . . ."

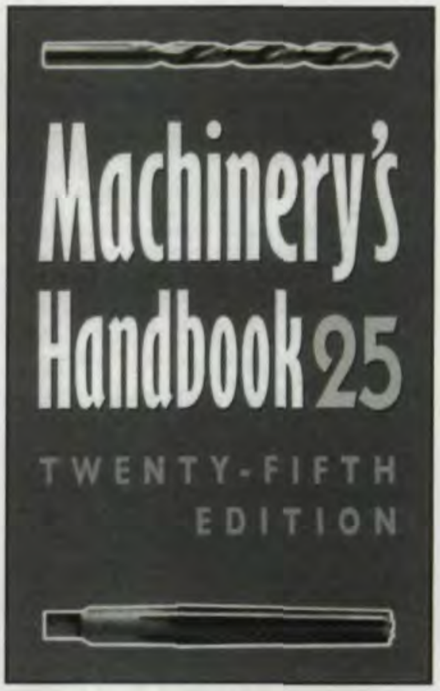
In an attempt to walk this tightrope, the editors have both added much new material and rethought some earlier editorial decisions. Tables of logarithms and trig functions have been included in this edition after being omitted from earlier ones, and some new material on these subjects has been added. Material on straight-sided splines, British Whitworth, Fine, Association and other threads has also been restored.

More material also has been added on numerical control and CAD/CAM, and there is updated information on speeds, feeds, depths of cut and tool life for a wide range of materials. Other new or updated sections of the *Handbook* include: methods of joining, including several kinds of welding; principles and applications of lasers for cutting, welding, drilling, heat treatment and marking of metals; EDM; motion control; quality; circles in rectangles; and drill sizes for tapping Acme threads; break-even analysis aimed at assisting investment in plant and equipment; the properties of woods, ceramics, plastics and alloys used in investment casting and powder metallurgy; ISO 9000 standards; CNC tapping and milling machine indexing; and flat belts, O-rings, adhesives and sealants.

The bad news (at least for those of us interested in gear applications) is that part of the price paid for the addition of this material is a significant reduction in the amount of material included on gearing. In the 24th edition of the *Handbook*, 305 pages were devoted to gear subjects. The 25th edition uses only 184. The editors cite the recent development in the use of computer programs in gear design to explain their omissions, and while there is certainly something to be said for that point of view, many gear engineers will miss some of this material.

Perhaps the most significant loss will be in the sections on bevel and worm gearing. Both of these were gutted. All the detailed material on the Gleason bevel gear system is gone, and worm gearing gets only four pages compared to the 23 devoted to it the 24th edition.

Still, there is much to be said for 25th edition. The book is thumb-indexed as a



matter of course, making it much more convenient to use. Another nice editorial touch is the detailed list of the subjects covered printed at the beginning of each section. Finally, the editors have addressed the issue of the print size in a book that attempts to cover the mechanical engineering world in 2,500 pages. A new large print version of the *Handbook* is available for the first time.

As for the issue of the missing gear material, perhaps the best solution until the editors rethink that section for the 26th edition is to keep your older version as a supplement to the 25th. That way you can have the best of both worlds.

Nancy Bartels
is Gear Technology*'s Senior Editor.*

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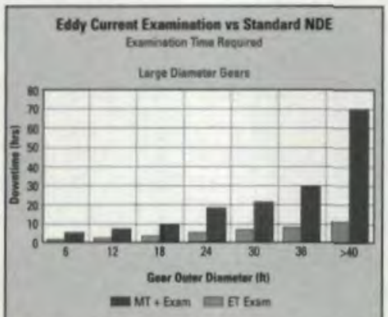
The chart below from "Eddy Current Examination of Gear Systems," which appeared in our last issue contained an error in labelling. The correct version is printed below. We regret any inconvenience this error may have caused.



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Ironclad Gears

Gear Technology's bimonthly aberration — gear trivia, humor, weirdness and oddments for the edification and amusement of our readers. Contributions are welcome.

This issue of Addendum is dedicated to gears that have served their country. There have been many, but among the most significant are surely those at work during the Civil War, when their application changed the nature of naval warfare forever. It's time to recall that role, namely, powering the revolving turret of the *U.S.S. Monitor*, one of the first "ironclad" vessels.

Before we get a lot of angry letters, please note that the Addendum staff wishes to remain neutral in any disagreements which still attach themselves to "The Late Unpleasantness." We have loved and respected ancestors on both sides of the conflict (though, contrary to office rumor, we are not old enough to have personally participated).

For the record, the Confederate Navy was first out of the blocks with an ironclad, the *Manassas*. *C.N.S. Virginia* (the *Merrimack* to those of the Yankee persuasion) destroyed much of the Union fleet in Hampton Roads, VA, and it was in response to this action that the *Monitor* was rushed to the scene. The *Monitor* and the *Virginia* fought to a draw there on March 9, 1862. The ironcladding on both ships was equally effective; the seaworthiness of both equally deplorable.

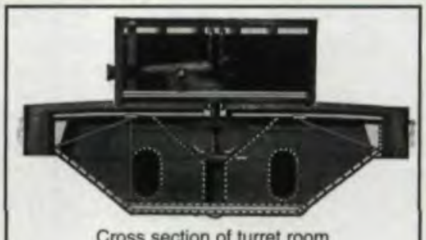
Having said that, Addendum has taken a special interest in the *Monitor* because of its unique revolving gun turret, which held heavy guns mounted on a revolving floor that would bring them to bear over 360°. While the idea needed much refining later, it marked the beginning of modern naval gunnery and warfare.

The *Monitor* was built by Swedish engineer John Ericsson, who claimed ownership of the entire design, including the turret, although later historians have argued that the real credit for the turret goes to New Yorker Theodore Timby, who had been working on the idea of a revolving gun battery since 1841. (See *Civil War Times Illustrated*, June, 1997, for all the juicy details.)

But the fact remains that Ericsson took the praise when the Monitor, which resembled "a cheese box on a raft," left the New York Navy Yard in early 1862.

The turret (the cheese box) was basically a revolving turntable that held two 11" Dahlgren guns, which were capable of firing 166-lb. solid shot a distance of one mile. At rest, the turret sat on a brass ring set into the raft deck. In combat, the crew screwed in a wedge-shaped "key" that jacked up the turret shaft, resting its entire 160 tons on the central spindle. Steam power from the ship's main boilers drove the donkey engine that moved the turret mechanism, a gear assembly which could rotate the turret at $2\,^1/_2$ rpm.

Addendum hasn't been able to see detailed drawings of the gear assembly, but according to Mark F. Jenkins, Webmaster of the Civil War Ironclad Page on the World Wide Web (*http://members.aol.com/MaxDemon88/ironclad.html*), the assembly consisted of "a short vertical crankshaft attached to the turret engine aft of the central spindle," which drove a four-gear assembly, the largest gear of which was mounted around the spindle itself. Jenkins estimates that this spindle gear was about 6.5' in diameter. The turret itself had an exterior diameter of 21.5'.



Cross section of turret room of *U.S.S. Monitor.*

The *Monitor*'s turret revolved once every 24 seconds, but was very difficult to stop on a precise bearing. In fact, during the engagement with the *Virginia*, the turret was left stationary. On the other hand, another ironclad, the *Neosho*, had a turret of very similar design which was said to revolve every 13 seconds, and her commander claimed to have "found no difficulty in stopping her on any object . . . and even when revolving fast, I could stop her so that the slightest turn either way would bring the guns to bear where I wished."

Martha Stewart Revisited

Tom Spenner, M.E., of Racine, WI, has an alternative approach to preserving your back issues. Concerned about punching holes in the magazine (our office puncher worked fine, but perhaps a smaller model would not), he suggests putting each issue in a C-Line #62018 Non-Glare sheet protector. He also recommends a 3" D-ring binder, which holds at least one more year than a 2" model.

Mercifully, no one has shared their pattern for crocheted binder covers yet. Thanks.

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The Addendometer: If you've read this far on the page and enjoyed it, please **circle 225**.


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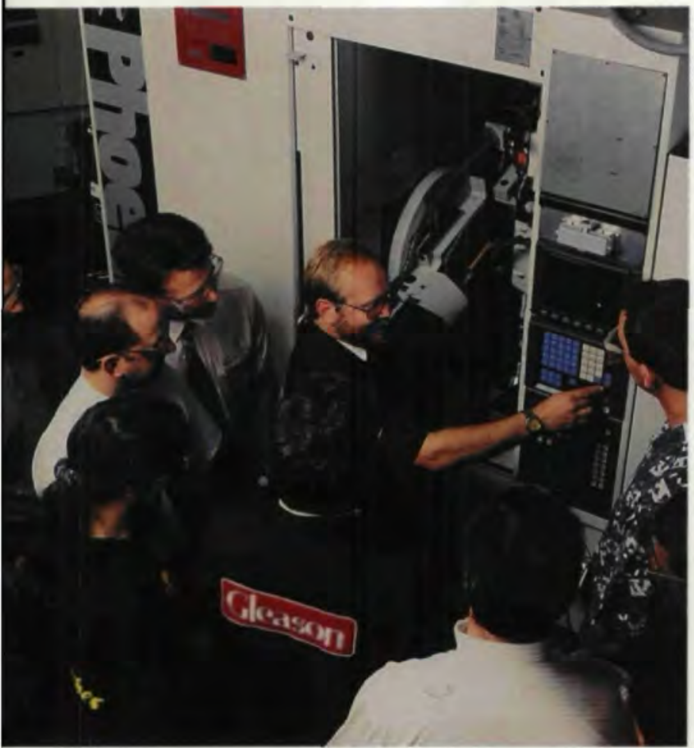

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