GEAR TECHNOLOGY

THE JOURNAL OF GEAR MANUFACTURING

MARCH/APRIL 1991

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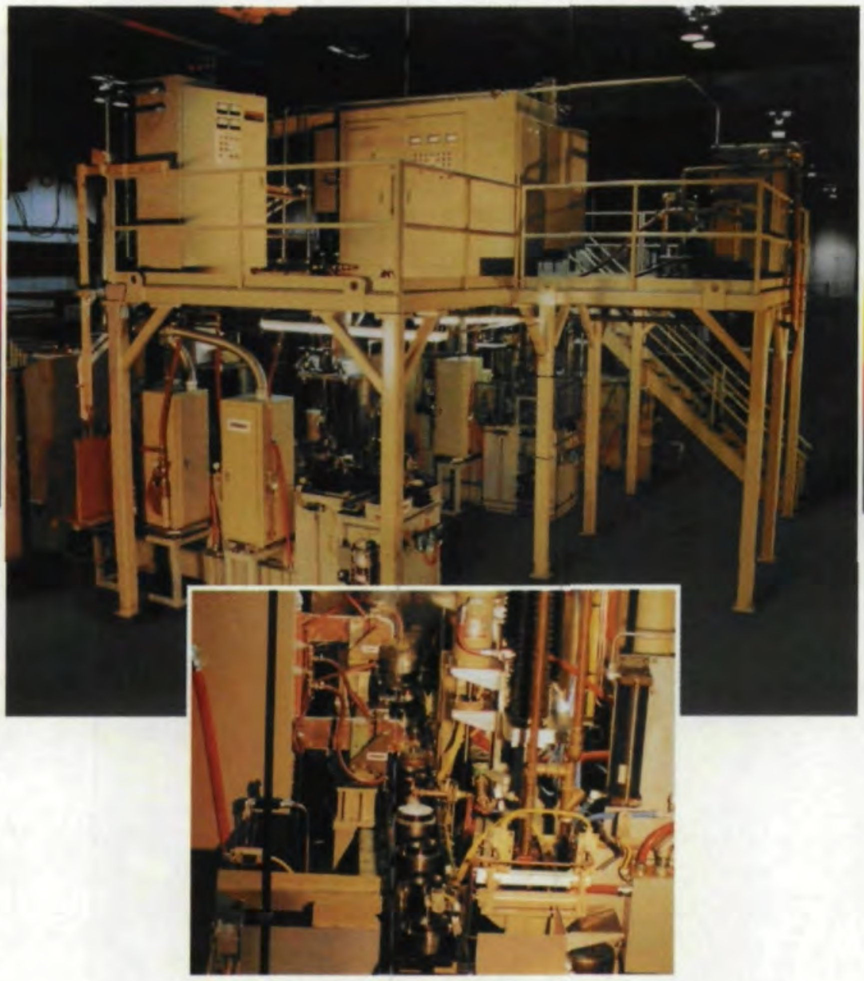
CIRCLE A-3 on READER REPLY CARD

Introducing

TPH

TOCCO Profile Hardening



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CIRCLE A-25 on READER REPLY CARD

* Photographed at TOCCO-Boaz during run-off

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MARCH/APRIL, 1991

FEATURES

Cover photo courtesy of GE Superabrasives.

SPECIAL FEATURES

DEPARTMENTS

ULTIMATE!

The CNC controlled grinder for all Spiral Bevel Gear geometries.

NOW… instead of deciding which gear geometry to use, the Gear Manufacturer may select the Klingelnberg W800CNC (Wiener System) Spiral Bevel Gear grinder which provides precise tolerances and surface finishes for any geometry.

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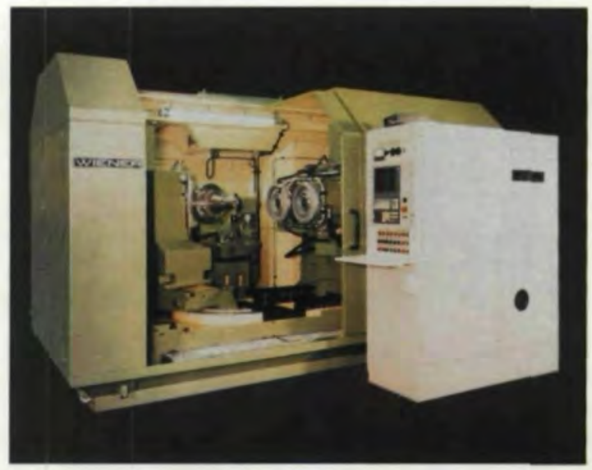

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1401 Lunt Avenue
P.O. Box 1426
Elk Grove Village, IL 60007
(708) 437-6604

VOL. 8, NO. 2

GEAR TECHNOLOGY, The Journal of Gear Manufacturing (ISSN 0743-6858) is published bimonthly by Randall Publishing Inc., 1401 Lunt Avenue, P.O. Box 1426, Elk Grove Village, IL 60007. Subscription rates are: $40.00 in the United States, $50.00 in Canada, $55.00 in all other countries. Second-Class postage paid at Arlington Heights, IL and at additional mailing office.

Postmaster: Send address changes to GEAR TECHNOLOGY, The Journal of Gear Manufacturing, 1401 Lunt Avenue, P.O. Box 1426, Elk Grove Village, IL 60007.

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Part blank and gear cutting tools play critical roles in gear quality control. We offer optional software packages for inspecting gear blanks for circular geometry and gear cutting tools such as hobs, shaper/shaver cutters, and broaches.

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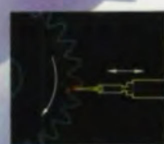

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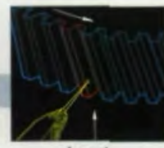
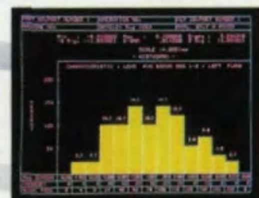


Lead

Involute

Process control can be implemented by analyzing data collected in gear testing. We offer SPC software to evaluate x-bar, R, histogram, and tooth surface topological studies.



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Brave New World

PUBLISHER'S PAGE

Observations while travelling through Hungary last November . . . This is a very ancient country; people have lived and worked here along the Danube River since early times, and change is just another piece of the landscape. Still, the collapse of the old Communist economy is one of the more remarkable phenomena in a land that has seen and lived under different versions of the "new world order" since the first barbarian invasions. The difference is that this time, the people themselves are working the change, and the results are exciting in their variety and effect.

Probably nowhere is the change more evident than in Gyor, where I met my hosts for the visit, Otto Nagy and Laszlo Bilekov, two young men whose vision and hard work are building part of the new Hungary. Formerly technical engineers for a state-owned gear production facility, the two friends formed a multifaceted private company, IHH, several years ago. IHH was started to provide advanced language instruction in the provinces. Nagy stated that previously the only language schools were in the capital, and the young men's decision to be independent and separate from the "mother institute" created quite a "scandal." In the changing Hungary of today, Nagy says, "such an idea is not a 'scandal,' merely a surprise."

Late one evening, I visited the language school, which contained 30 or 40 classrooms for students of all ages. I saw 8-year-olds learning German, and businessmen and engineers studying English. The teachers were young Britons and Germans brought to Hungary by IHH. At lunch another day we observed the eagerness and excitement of these young teachers who were as delighted by the experiment as the Hungarians. They were having a great time practicing their Hungarian, experimenting with native dishes, and learning the culture.

Opening the language school is only the first example of Nagy's and Bilekov's entrepreneurial spirit. Perhaps even more startling is that Nagy and Bilekov are now selling their skills to the state-owned manufacturing facilities in which they were formerly employees! This is part of a bold new experiment that may help transform a state-run economy into private enterprise. Nagy says that IHH will "undertake to raise the quality of gear production" in the state factory. The company has been awarded a six-month contract to oversee gear production without interference from the state.

A tour of the IHH factory was impressive. The bevel gear department was full of American equipment, most of it less than ten years old. Parallel gear manufacturing is done mostly on Russian hobbers and Czech shapers with batteries of both Hungarian and modern Swiss gear grinders. The latest models of bevel generating, sharpening, and testing equipment were neatly arranged in a clean environment, comparable to the best U.S. gear manufacturing plants. According to Nagy, the workers here are meeting and exceeding their goals in every respect, the most difficult problem being the variable quality of Hungarian steel.

Two such projects would seem to be more than enough to fill anyone's plate, but Nagy and Bilekov have other visions for Hungary as well. They have also cofounded the Hungarian chapter of the Jaycees. They hope this chapter will provide another aid to ease the transition to a market economy. Years of living under Communism

PUBLISHER'S PAGE

have left young people with few guidelines or models for working in business. The Jaycee chapter, through contacts with other chapters throughout the world, will open lines of communication and help bridge the gap between cultures and economic systems.

At the same time that Nagy, Bilekov, and the other citizens of Gyor are working tirelessly to bring capitalism to Hungary, many remnants of the old regime are still evident. At present, the *only* organizational infrastructure in place is the Communist one, and it will have to continue to function until something new can be developed. For example, in Budapest I found that most of the restaurants providing the best meals and atmosphere at the best prices are state-run. In Gyor, I also had the interesting experience of staying at a 120-room, state-run hotel with less than two dozen guests. The service, facilities, and attention were up to the best of Western standards, but, as a "guest of the state," I never saw a bill.

The newer, more open economy has had other effects on the people of Gyor. We enjoyed the insights that came from conversations with Klara, our guide. She admitted that she had come to enjoy the convenience of the quick lunch at McDonalds, but not all aspects of the new life are as easy to embrace. I unintentionally flustered her by publicly offering her American currency to make a small purchase for me. She explained that not so long ago having foreign currency was illegal and, even now, is considered a private affair.

Gyor was not the only place in Hungary where the sharp contrasts between old and new remain vivid. Budapest, Hungary's capital, is a divided by the Danube. The river separates the hills of Buda from the plains of Pest. The buildings are large and beautiful, conveying the elegance of an older, statelier past, but the prosperity that gave birth to them in the first place is gone, leaving behind the marks of hard times under Communism. While some restoration is underway, many of the lovely facades are marked by neglect and disrepair and blackened with car exhaust.

On the other hand, signs of the new are everywhere. Prosperity is again taking tenuous root. The shops are full, and Hungarian citizens, not just tourists, can afford to buy from them. An occasional Mercedes or BMW crawls through the narrow, ancient streets, but one mostly still sees battered Trabants, Ladas, and Warburgs.

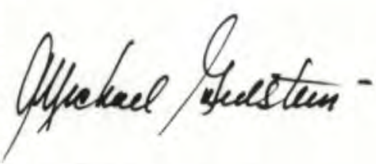
And the signs of freedom appear in more than material ways. Now creative impulses no longer have to be followed with one eye over the shoulder for the censors. At Gyor's new performing arts center, I saw a ballet recital which was as powerful, both politically and emotionally, as any I have ever seen. I doubt such a performance could have occurred a few years back.

One last stop in Hungary only underlined my previous impressions of this exciting place and time. Babolna, a centuries-old horse breeding farm in the countryside, has grown into a gigantic state agricultural company with strong links to that icon of capitalism, McDonald's. Founded in 1789 as a supplier of thoroughbred horseflesh to the wealthy and aristocratic, the blood stock business is still the heart of Babolna. The farm's collection of awards won by its horses at races and shows around the world is cause enough for pride.

However, the managers have taken their skill in horse husbandry and carried it over to poultry, beef, and pig breeding and to extensive work in animal nutrition and sanitation. The "farm" now employs 5000 people and has been chosen as the supplier of beef to the Hungarian McDonald's restaurants, a good indication of the consistent high quality of its products.

Any short tour of a new country is over too soon, and one's impressions are at best kaleidoscopic. The mind is full of brief "snap shots" that can only hint at the state of transition in which countries like Hungary find themselves.

The energy, ambition, and courage of men like Otto Nagy and Laszlo Bilekov will go far in creating a new Hungary. These men and others that we met are hard working people whose goals of quality and growth are not unlike our own. These are hopeful times for an eager citizenry, and one cannot help but share their enthusiasm as they face the challenge of building their brave new world.



Michael Goldstein,
Publisher/Editor-in-Chief

Are You Ready to Choose An Advertising Agency?

Phil Callighan

Countless research studies confirm this fact: COMPANIES THAT ADVERTISE AGGRESSIVELY DURING A RECESSION WILL FLOURISH AFTER THE ECONOMIC TIDE TURNS. Regardless of company size, effective advertising generally requires the services of an agency, and under current economic conditions, you may need one now more than ever. The question is, how do you go about getting the right one for your company.

Perhaps a prior question is in order here. Why should I hire an agency, and what do I get when I hire one? David Knoepp, founder of Concepts for Industrial Marketing in Buffalo, says there is a trend toward using agencies. According to him, ". . . more companies are contracting out what had been staff functions . . . due to administrative cutbacks."

Knoepp also notes as part of the same trend that more companies are shifting advertising and marketing responsibilities to sales managers. Without full time advertising and marketing managers of their own, companies must rely more on agencies. What it comes down to is that many managers have neither the time nor the expertise to do the job effectively.

What you get when you hire an agency will depend on a number of variables, but one can assume some basics. A good advertising agency knows ways to help you stretch your advertising dollar. An agency runs interference between you and all the media banging on your door. An agency uses just the right words and visuals to tell your story.

An agency is creative. An agency contributes good strategic ideas. An agency is cost-effective. An agency is . . .

Well, not all agencies perform in an ideal manner, but those are some of the attributes for which you should be looking.

Whatever your specific needs, consider the following criteria for choosing your new (or first ever) advertising agency: 1) size, 2) location, 3) experience, 4) personality, 5) compensation arrangement, 6) performance test.

Size – both your company's and the agency's – is certainly a critical issue. Just as you cannot serve every customer, neither can an advertising agency. An agency can be too large or too small for your needs.

Unless your advertising budget represents 3% or more of the agency's revenue, don't expect much service. Three percent of an agency's revenue means the agency has 33 other accounts just like yours. To serve 33 accounts, does the agency have sufficient staff? Another factor to consider is whether your work is seasonal. Or is it just project work that can be fitted in with other jobs in progress at the agency, and still give you the service you need?

While you may be impressed with big time presentations, the $25 million agency cannot afford to assign its senior staff to handle a $50,000 account. Likewise, you should be cautious if your account significantly swells the size of the agency. Your account may become pivotal to the future of the agency. Ask yourself if you want to be responsible for that agency, and whether the agency can respond to your growth fast enough.

Recognize, too, that size does not necessarily guarantee better or faster work. David

MANAGEMENT MATTERS

Managing a business in today's volatile economic environment is tough. Let our new column, "Management Matters," lend a hand. From its pages learn about subjects like marketing, overseas trade, labor relations, economic trends, environmental issues, and product liability. Tell us what management matters interest you. Write to Gear Technology at P.O. Box 1426, Elk Grove Village, IL, 60009, or call our staff at (708) 437-6604.

Phil Callighan
is President of the Center for Communications, a division of AdPro, a full-service advertising, promotional, and public relations firm with offices in Sycamore and Batavia, IL. If you have questions for Mr. Callighan, please circle Reader Service No. 46.

Knoepp cites, "I can mobilize more people in half a day than most of the larger agencies."

Dennis Klimko, Marketing Manager, Niagara Gear, Buffalo, NY, says his advertising does not suffer at all with the services of a smaller agency. "What I lose in resources, I gain in personal service," he says.

Location of the agency must also be considered. With facsimile machines, telephones, car phones, and computer modems, location no longer plays as big a role in agency selection as it once did. In fact, an out-of-state client once told me he appreciated the fact that my agency was quite distant from his office. "Because you have to fly in," he said, "my people can't postpone our meetings. It forces us to get our act together and not mix advertising and marketing with other issues."

Nevertheless, there is no universal substitute for face-to-face contact. Certain presentations, ideas, and concerns are much better when related in person. If you are an executive who wants to be involved with your advertising, ask yourself if you have the patience to put your brilliant idea on hold for several days before your agency can see you, or if you want someone to respond within 24 hours or less.

Will the costs of mail, telephone, and travel reduce your budget significantly? Is the risk of losing something in transit worth it?

On the other hand, do you want to work with the closest agency . . . or the best? Or are these the same thing?

No matter how you answer that question, there are other criteria that go into determining which agency is "best" for you.

"Experience" is generally a key factor in agency selection.

If your agency has experience working in your field, so much the better. Frankly, though, experience in gear manufacturing is no substitute for creative thinking, business problem solving, and fresh approaches. An agency with gear manufacturing experience may give you an added sense of security, but weighing this background too heavily may not be in your best interests for the following reasons:

1) Although the agency itself may have experience in your field, the people assigned to your account may not.

2) The agency's familiarity may breed contempt for suggestions you make – after all (they may claim) they know what works better than you do.

3) Innovation may be stifled. You may fall victim to "cookie cutter" strategies and programs that look too much like your competitors'.

Keep in mind that every agency was inexperienced at one time. Rather than industry experience, it is often more judicious to ask the agency to submit evidence of its experience with strategic thinking and creative concepts.

Perhaps the agency's experience in areas other than advertising may be equally important to you. Do you need experience in sales pro-motion? Public relations? Training? Do you prefer an agency with a great deal of production experience in trade show presentations? Meetings? Videotape programs? Once you determine your own needs, you will be better able to ask an agency for proof of experience.

Once you have done that, review the work of the agencies you are considering. Be sure you examine evidence of experience from the people *who will work on your account*, not examples of work from staffers who have since departed the agency.

MANAGEMENT MATTERS

Related to the matter of experience is the sticky question of experience with the competition. Many American companies are so reluctant to deal with an agency that works for one of their direct competitors, that agencies themselves often decline to even consider pitching such accounts. Agencies don't want to spend the time and effort to make a presentation, only to be told, "We won't work with you because you already have ABC Widgets as a client."

Interestingly enough, overseas companies don't share this reluctance. It is common practice in Asia, for example, for competitors to use the same agencies. Questions of breaking confidentiality don't seem to arise. The point for U.S. companies is this: Raise this question early in your discussion with potential agencies. Find out the attitude of the agency and be sure in your own mind how you feel about the matter. That can save everyone a lot of time and hard feelings.

Personality is also critically important in choosing the agency that's right for you. When Robert Turk, Sales Manager, Fairlane Gear, Plymouth, MI, chose an agency to help prepare literature and ads, he found one ". . . willing to listen to how we wanted to express ourselves. And they were flexible – that's what appealed to me."

Does the agency exhibit the same values and integrity as you? Does the agency exhibit enthusiasm for your account? Do you like the people from the agency with whom you will work? Will you still be in love after the honeymoon is over?

Elsewhere in the world, much greater emphasis is placed on knowing the agency people personally. Before being asked to represent a Japanese corporation, I was invited to spend a week with the company executives at their offices so that we could become better acquainted. We spent nearly every hour of every day together, and time was devoted to socializing as well as business. After one week these people had become my friends. I never wanted to disappoint them. The rapport we built enhanced my working relationship with them.

The investment of this amount of time may not be possible for you, but surely the choice of an agency should not be a casual affair. When you consider an agency is to function on your behalf, as a representative of your company, is it not prudent to invest more than a couple of two-hour meetings to acquaint the agency with your company? Frequently, a company's new-employee orientation program is more intense and time-consuming than the time dedicated to the advertising agency; yet the expectations and budget dedicated to the agency may surpass the salaries of several employees.

Another aspect of an agency's personality is its own objectives. Is the agency's growth plan in concert with your own? What kind of work does the agency like to do? Will your account have a place in the agency two years from now? Do you care?

Your agency's compensation must also be addressed. Will the agency insist on buying all your media and receiving the 15% media commission? Will the agency want a monthly retainer fee from you? Will the agency work with you on a project, that is, a job-by-job, basis?

If you are considering asking the agency to do project work, you should be aware that the service you receive from your agency will be in direct proportion to the level of commitment you make to the agency. Companies in such relationships may feel they can always get another agency for a different project; agencies in a project-by-project relationship with you may feel fewer scruples about replacing your account executive or dropping you entirely if a more committed client comes along. Continuity of service and high levels of loyalty are sacrificed in a project relationship.

A retainer arrangement may be better for you. It guarantees the agency will receive a set amount of money regularly to furnish certain services. For example, strategic planning, preliminary concept proposals, and public relations might be consolidated under a monthly retainer. Production of specific material (e.g., advertisement, product brochure, direct mailer, etc.) might be invoiced separately. Retainers generally pay only for the agency's time. Travel and expenses (often including fax transmissions, phone calls, postage, etc.) are additional.

In order to cut costs, some companies consider buying media themselves in order to save the 15% commission to which the agency would be entitled. To do this, they incorporate their own in-house advertising agencies. If you are considering this strategy, ask yourself if your company has the necessary *time* and *expertise* to run your own ad campaigns well. For example, time is needed to discuss rates, special issues, and promotions. And there's more to it than just picking a couple of likely magazines at random in which to place an ad. Do you know enough to create an advertising schedule that will optimize your expenditure? Have you included the media that reach your audience best – highest number of gross impressions, best effective cost per thousand, in an editorial environment that fosters credibility? In other words, do you know when the book you have always used is no longer the best way to reach your target?

Going it alone without an agency has other disadvantages. Will you, as a single media account, be able to exert the same kind of clout as the agency with multiple accounts? Will a magazine be as anxious to accommodate your company-placed ad within the first five pages of its next issue, when an agency (with three accounts advertising twice as much as you) is putting similar pressure on the magazine? If you are asking an agency to generate editorial coverage for your company, will they be as helpful, knowledgeable, and effective as they need to be, when they are unfamiliar with your advertising plans and your relationship with the media?

Dennis Klimko of Niagara Gear believes his agency has earned its commission by ". . . reducing our rates using sister publications that would give us discounts, bringing us publicity that I don't have the time to pursue, and making us aware of other publications, which we don't receive in-house, but which will be important as we prepare to penetrate a new market."

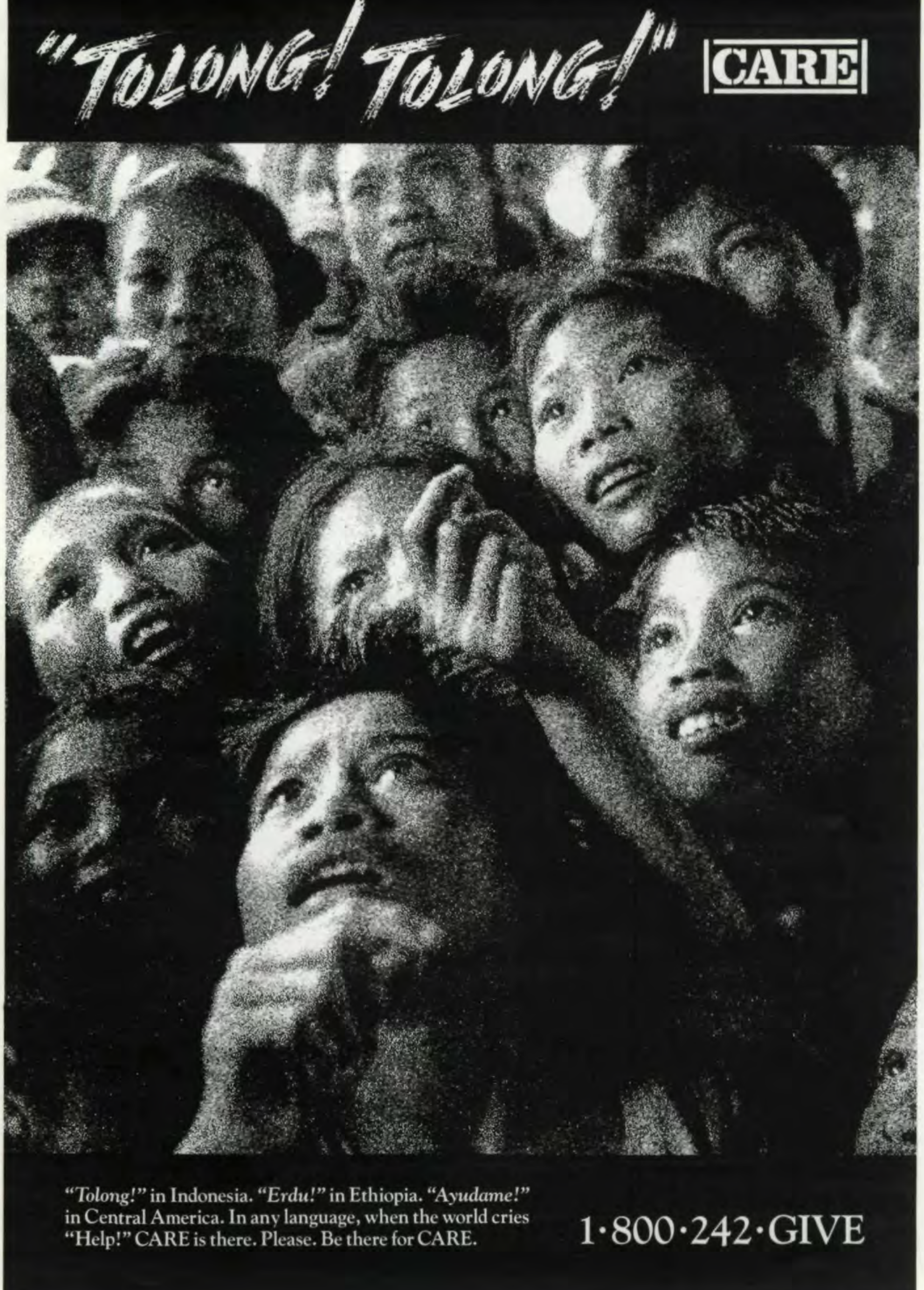
If you are lucky enough to find more than one agency that fits all your requirements, perhaps you should see what each agency could specifically do to help you – but do not expect to receive anything worthwhile for free. The services and expertise an agency provides are as valuable and worthy of compensation as the products and services you sell to your customers, and, like you, they cannot afford to give this expertise away. If you really want to see what agencies can do for you, contribute some dollars to each agency to defray their expenses (and some of their time) and ask them to develop some preliminary work for you.

Many executives say that hiring the right people is the key to their success. The same is true when you choose your advertising agency. The right-sized agency, experienced in the areas you deem important, with an attractive personality and reasonable compensation requirements can help your business survive and grow.

Take time to make your choice. And give your choice time to serve you appropriately. You both need to learn about the other's expectations.

Obviously, you want your agency to serve you well for many years. David Knoepp advises that a company should reassess its relationship with an agency every three years, ". . . if only to give each 'partner' the opportunity to address shortfalls and perceived shortfalls."

Hiring an agency is in one sense no different than hiring any key employee for your company. You need to look for a good match, a solid commitment to your company goals, and a fair compensation package. Then you can look forward to a rewarding relationship that works well for both you and the agency. ■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CALENDAR

AGMA Programs/Meetings/Seminars. For more information on AGMA programs, contact AGMA headquarters, 1500 King St., Suite 201, Alexandria, VA, 22314. (703) 684-0211.

MARCH 18-19
Gear Rating Committee (Bevels), Alexandria, VA. Begin work on revision of AGMA 2003-BXX, Rating Pitting Resistance and Bending Strength.

MARCH 20-21
AGMA Technical Education Seminar. Gear Drive Lubrication. Chicago, IL. 2-day seminar on enclosed drive lubrication.

APRIL 7-8-9
19th Annual AGMA Gear Manufacturing Symposium. Embassy Suites O'Hare. Chicago, IL.

APRIL 17
ANSI/AGMA TAG to ISO/TC60/WG6. Bevel Rating Subgroup will review the draft of ISO/CD 10300 for bevel gears.

APRIL 18
ANSI/AGMA TAG to ISO/TC60. This committee will review all current proposals for international gear rating standards.

APRIL 18-19
Metellurgy and Materials Committee, Alexandria. VA. Resolve comments on AGMA 2007-BXX on surface temper inspection.

APRIL 22-23
Fine Pitch Gearing Committee, Albany, NY. Review comments on AGMA 1003-GXX and continue work on fine pitch design manual.

APRIL 30

Cylindrical Worm Gearing Committee, Detroit, MI. Resolve comments on AGMA 6034-BXX for enclosed cylindrical worm gears, speed reducers, and gear motors.

MAY 1-2

Flexible Couplings Committee, Pittsburgh, PA. Continue work on draft of AGMA 9004-AXX, Flexible Couplings – Mass Elastic and Other Properties.

MAY 8-9

Gear Motors and Shaft Mounts Committee, Alexandria, VA. Continue work on revision of AGMA 6019-FXX and 6021-HXX.

MAY 14-15

Vehicle Gearing Committee, Indianapolis, IN. Begin work on next revision of design manual for vehicle gears, AGMA 6002-CXX.

MAY 21-22

Technical Education Seminar. Tapered Roller Bearings. Indianapolis, IN.

MAY 23

Acoustical Technology Committee, Indianapolis, IN. Review of next revisions of AGMA gear unit sound and vibration standard.

JUNE 5-6

Small Business Manufacturer's Committee. The Breakers, West Palm Beach, FL.

JUNE 6-9

AGMA 75th Anniversary Annual Meeting. The Breakers, West Palm Beach, FL.

JUNE 19

Technical Education Seminar Worm Gear Design Cincinnati, OH.

SEPTEMBER 16-17

Bevel Gearing Committee, Alexandria, VA. Continue work on next revision of design manual for bevel gears, AGMA 2005-CXX.

OCTOBER 21-23

Gear Expo '91. The World of Gearing. Biennial trade show devoted exclusively to gear and gearing products. Cobo Conference and Exhibition Center, Detroit, MI.

Fall Technical Meeting. Held in conjunction with Gear Expo '91, the conference will feature gear experts from around the world presenting technical papers on design, analysis, manufacturing, applications, drives and related products, and other gear-related subjects.

APRIL 8-11

National Design Engineering Show/ASME workshops. McCormick Place North, Chicago, IL. Some 850 companies showing computerized design engineering tools and OEM products will be at the show. The concurrent workshops, run by ASME, will cover designing with plastic parts, metal fatigue, design reliability, and more. Contact Show Manager, National Design Engineering Show, 999 Summer St., Stamford, CT. (203) 964-8287.

JUNE 11-13

SME Superabrasives '91 Conference & Exposition. O'Hare Exposition Center/Hyatt Regency O'Hare, Rosemont (Chicago) IL. This is the largest event on applications for superabrasive, diamond, and cubic boron nitride (CBN) products ever staged. For more information, contact SME Event Public Relations, One SME Drive, P.O. Box 930, Dearborn, MI, 48121-0930. PH: (313) 271-0777.

JUNE 24-27

AIAA, SAE, ASME, ASEE Joint Propulsion Conference. Sacramento, CA. Special Gear System Technology Session. For more information, contact: Douglas A. Wagner, Allison Gas Turbine, P.O. Box 420 S-48, Indianapolis, IN, 46206-0420. PH: (317) 230-4170.

NOVEMBER 24-26

International Conference on Motion and Power Transmissions. Hiroshima, Japan. The conference covers all aspects of the theory and application of motion and power transmission systems. For more information, contact: 606 Japan. FAX: (Japan) 75-771-7286. TELEX: 5423115 ENG KU J.

The Lubrication of Gears – Part 1

Robert Errichello
GEARTECH, Albany, CA

Introduction

This is a three-part article explaining the principles of gear lubrication. It reviews current knowledge of the field of gear tribology and is intended for both gear designers and gear operators. Part 1 classifies gear tooth failures into five modes and explains the factors that a gear designer and operator must consider to avoid gear failures. It defines the nomenclature and gives a list of references for those interested in further research. It also contains an in-depth discussion of the gear tooth failure modes that are influenced by lubrication and gives methods for preventing gear tooth failures.

The second part gives an equation for calculating the lubricant film thickness which determines whether the gears operate in the boundary, elastohydrodynamic, or full-film lubrication regime. Also given is an equation for Blok's flash temperature, which is used for predicting the risk of scuffing. Finally, a recommendation for selecting lubricant type, viscosity, and application method and a case history, which demonstrates many of the principles of gear lubrication, are given.

Gear Tribology

Because gears are such common machine components, they may be taken for granted. Not generally appreciated is that they are complex systems requiring knowledge from all the engineering disciplines for their successful design. Gear design is a process of synthesis where gear geometry, materials, heat treatment, manufacturing methods, and lubrication are selected to meet the requirements of a given application. The designer must design the gearset with adequate strength, wear resistance, and scuffing resistance. To do this, he or she must consider gear tribology. The choice of lubricant and its application method is as important as the choice of steel alloy and heat treatment. The interrelationship of the following factors must be considered:

- Gear tooth geometry
- Gear tooth motion (kinematics)
- Gear tooth forces (static and dynamic)
- Gear tooth material and surface characteristics (physical and chemical)
- Lubricant characteristics (physical and chemical)
- Environment characteristics (physical and chemical)

Gear Tooth Failure Modes

To obtain optimum, minimum-weight gearsets the gear designer must be aware of the intricate details of many competing modes of failure. In its nomenclature publication,[1] the American Gear Manufacturers Association (AGMA) has classified 20 modes of gear failure under the broad categories of wear, surface fatigue, plastic flow, breakage, and associated gear failures. References 2 through 6 also give gear failure modes. For our purposes, the basic categories are overload, bending fatigue, Hertzian fatigue, wear, and scuffing.

Table 1 subdivides the five basic failure modes. Many gear failures are known by several names and/or qualifying terms, such as initial, moderate, destructive, etc. These names and terms are included in the lists in parentheses. The term "scoring" has been used in the past in the U.S.A., while the term "scuffing" is used in Europe to describe the severe form of adhesive wear which involves the welding and tearing of the surfaces of gear teeth. To agree with current usage, the term scuffing will be used in this article when referring to

TABLE 1

Basic Failure Modes

Overload
- Brittle fracture
- Ductile fracture
- Plastic deformation
  - cold flow
  - hot flow
  - indentation (rolling, bruising, peening, brinelling)
  - rippling (fish scaling)
  - ridging
  - bending, yielding
  - tip-to-root interference

Bending Fatigue
- Low-cycle fatigue (<1000 cycles to failure)
- High-cycle fatigue (<1000 cycles to failure)

Hertzian Fatigue
- Pitting (initial, superficial, destructive, spalling)
- Micropitting (frosting, grey staining, peeling)
- Sub-case fatigue (case crushing)

Wear
- Adhesion (normal, running-in, mild, moderate, severe, excessive)
- Abrasion (scoring, scratching, plowing, cutting, gouging)
- Corrosion
- Fretting – corrosion
- Cavitation
- Electrical discharge damage
- Polishing (burnishing)

Scuffing
- Scuffing (scoring, galling, seizing, welding, smearing, initial, moderate, destructive)

this failure mode. The term scoring implies scratching, and it will be used to describe abrasive wear rather than scuffing.

Lubrication – Related Failure Modes

These articles are concerned with gear tooth failures that are influenced by lubrication. Pitting or scuffing may cause the gear teeth to deteriorate and generate dynamic forces, which in turn cause the gear teeth to fail by bending fatigue. In these cases the bending failure is secondary and not directly related to lubrication, while pitting or scuffing are the primary failure modes, and both are definitely influenced by lubrication. The failure analyst must discern the difference between primary and secondary failure modes because the wrong corrective action is likely to be recommended if a secondary failure mode is mistaken for the primary failure mode. For example, increasing the size of the gear teeth to prevent reoccurence of the above-mentioned bending failure would only make the situation worse by lowering the pitting and scuffing resistance. Godfrey[7] gives a good description of lubrication-related failure modes.

With the above considerations, overload and bending fatigue are judged to be unrelated to lubrication and are eliminated from further discussion together with sub-case, Hertzian fatigue. Although corrosion, fretting-corrosion, cavitation, and electrical discharge damage are influenced by lubrication, they are not discussed because these failure modes occur relatively rarely in gear teeth. Hence, the following failure modes are included in the scope of this article: Hertzian fatigue, including pitting and micropitting; wear, including adhesion, abrasion, and polishing; and scuffing.

Hertzian Fatigue – Pitting. Pitting is a common failure mode for gear teeth because they are subjected to high Hertzian contact stresses and many stress cycles. For example, through-hardened gears are typically designed to withstand contact stresses of approximately 100,000 psi, while the contact stresses on carburized gears may reach 300,000 psi. In addition, a given tooth on a pinion that is revolving at 3600 rpm accumulates over 5 million stress cycles every 24 hours.

Pitting is a fatigue phenomenon[8] which occurs when a fatigue crack initiates either at the surface of the gear tooth or at a small depth below the surface. The crack usually propagates for a short distance in a direction roughly parallel to the tooth

Robert Errichello
is the principal in GEAR-TECH, a gear consulting firm in Albany, CA. His article reprinted here has won the STLE's 1990 Wilber Deutch Memorial Award for the best article on the practical aspects of lubrication. Mr. Errichello is a member of ASME, AGMA, and is a Registered Professional Engineer in the State of California.

Nomenclature Table

Symbols

Symbol	Description	Units
B_M	– thermal contact coefficient	lbf/[in $s^{0.5}$ °F]
b_H	– semi-width of Hertzian contact band	in
c	– constant (See Table 3.)	hp/gpm
c_M	specific heat per unit mass	lbf in/[lb °F]
d	– operating pitch diameter of pinion	in
E_1, E_2	– modulus of elasticity (pinion, gear)	lbf/in²
Er	– reduced modulus of elasticity	lbf/in²
h_{min}	– minimum film thickness	in
L_{min}	minimum contact length	in
n	– pinion speed	rpm
P	– transmitted power	hp
q	– oil flow rate	gpm
S	– average surface roughness, rms	μin
Tb	– bulk temperature	°F
Tb, test	– bulk temperature of test gears	°F
Tc	– contact temperature	°F
Tf	– flash temperature	°F
Tf, test	– maximum flash temperature of test gears	°F
Ts	– scuffing temperature	°F
V	– operating pitch line velocity	ft/min
Ve	entraining velocity	in/s
Vr_1, Vr_2	– rolling velocity (pinion, gear)	in/s
W_{Nr}	– normal operating load	lbf
w_{Nr}	– normal unit load	lbf/in
X_W	– welding factor	– –
X_r	– load sharing factor	– –
α	– pressure-viscosity coefficient	in²/lb²
λ	– specific film thickness	– –
λ_M	– heat conductivity	lbf/[s °F]
μ_m	– mean coefficient of friction	– –
μ_o	– absolute viscosity	Reyns (lbs/in²)
ν_1 ν_2	– Poisson's ratio (pinion, gear)	– –
ν_{40}	– kinematic viscosity of 40°C	cSt
ϱ_1 ϱ_2	– transverse radius of curvature (pinion, gear)	in
ϱ_M	– density	lb/in³
ϱ_n	– normal relative radius of curvature	in
σ	– composite surface roughness, rms	μin
σ_1, σ_2	– surface roughness, rms (pinion, gear)	μin
ψ_b	– base helix angle	deg
ω_1, ω_2	– angular velocity (pinion, gear)	rad/s

surface before turning or branching to the surface. When the cracks have grown to the extent that they separate a piece of the surface material, a pit is formed. If several pits grow together, the resulting larger pit is often referred to as a "spall." There is no endurance limit for Hertzian fatigue, and pitting occurs even at low stresses if the gears are operated long enough. Because there is no endurance limit, gear teeth must be designed for a suitable, finite lifetime.

To extend the pitting life of a gearset, the designer must keep the contact stress low and the material strength and lubricant specific film thickness high. There are several geometric variables, such as diameter, face width, number of teeth, pressure angle, etc., that may be optimized to lower the contact stress. Material alloys and heat treatment are selected to obtain hard tooth surfaces with high strength. Maximum pitting resistance is obtained with carburized gear

Methods for Preventing Pitting

1. Reduce contact stresses by reducing loads or optimizing gear geometry.
2. Use clean steel, properly heat treated to high hardness, preferrably by carburizing.
3. Use smooth tooth surfaces produced by careful grinding or honing.
4. Use an adequate amount of cool, clean, and dry lubricant of adequate viscosity.

teeth because they have hard surfaces, and carburizing induces beneficial compressive residual stresses which effectively lower the load stresses. The drawbacks to using them are that they are relatively expensive to produce and that they must be finished by grinding. The details for obtaining high lubricant specific film thickness will be explained later when elastohydrodynamic (EHD) lubrication is discussed, but general recommendations are to use an adequate supply of cool, clean, and dry lubricant that has adequate viscosity and a high pressure-viscosity coefficient.

Pitting may initiate at the surface or at a subsurface defect, such as a nonmetallic inclusion. With gear teeth, pits are most often of the surface-initiated type because the lubricant film thickness is usually low, resulting in relatively high metal-to-metal contact. The interaction between asperities of contact at defects, such as nicks or furrows, creates surface-initiated, rather than subsurface-initiated cracks. For high-speed gears with smooth surface finishes, the film thickness is greater, and subsurface-initiated pitting, rather than surface-initiated, may predominate. In these cases, pitting usually starts at a subsurface inclusion, which acts as a point of stress concentration. Cleaner steels, such as those produced by vacuum melting, prolong the pitting life by reducing the number of inclusions.

Contamination from water in the lubricant is believed to promote pitting through hydrogen embrittlement of the metal, and abrasive particles in the lubricant cause pitting by indenting the tooth surfaces, causing stress concentrations and/or disrupting the lubricant film. At present, the influence of lubricant additives on pitting is unresolved.

Hertzian Fatigue – Micropitting. On relatively soft gear tooth surfaces, such as those of through-hardened gears, Hertzian fatigue forms large pits with dimensions on the order of millimeters. With surface-hardened gears, such as carburized, nitrided, induction-hardened, and flame-hardened, pitting may occur on a much smaller scale, typically only 10μm deep. To the naked eye, the areas where micropitting has occurred appear frosted, and "frosting" is a popular term for micropitting. Japanese researchers[9] have referred to the failure mode as "grey staining" because the light-scattering properties of micropitting gives the gear teeth a grey appearance. Under the scanning electron microscope (SEM) immediately evident is that micropitting proceeds by the same fatigue process as classical pitting, except the pits are extremely small.

Many times micropitting is not destructive to the gear tooth surface. It sometimes occurs only in patches and may stop after the tribological conditions have improved by running-in. The micropits may actually be removed by light polishing wear during running-in, in which case the micropitting is said to "heal." However, there have been examples[9-11] where micropitting has escalated into full-scale pitting, leading to the destruction of the gear teeth.

The specific film thickness is the most important parameter that influences micropitting. Damage seems to occur most readily on gear teeth with rough surfaces, especially when they are lubricated with low viscosity lubricants. Gears finished with special grinding wheels to a mirror-like finish[12] have effectively eliminated micropitting. Slow-speed gears are prone to micropitting because their film thickness is low.

Methods for Preventing Micropitting

1. Use smooth tooth surfaces produced by careful grinding or honing.
2. Use an adequate amount of cool, clean, and dry lubricant of the highest viscosity permissible.
3. Use high speeds if possible.
4. Use carburized steel with proper carbon content in the surface layers.

To prevent micropitting, the specific film thickness should be maximized by using smooth gear tooth surfaces, high-viscosity lubricants, and high speeds. Experiments[10] have shown that flame-hardened and induction-hardened gears have less resistance to micropitting than carburized gears of the same hardness. This is probably due to the lower carbon content of the surface layers of the flame-hardened and induction-hardened gears.

Wear – Adhesion. Adhesive wear is classified as "mild" if it is confined to the oxide layers of the gear tooth surfaces. If, however, the oxide layers are disrupted, and bare metal is exposed, the transition to severe adhesive wear usually occurs. Severe adhesive wear is termed scuffing and will be discussed later. Here we assume that scuffing has been avoided through proper design of the gears, selection of the lubricant, and control of the running-in process.

When new gear units are first operated, the contact between the gear teeth is not optimum because of unavoidable manufacturing inaccuracies. If the tribological conditions are favorable, mild adhesive wear occurs during running-in and usually subsides with time, resulting in a satisfactory lifetime for the gears. The wear that occurs during running-in is beneficial if it smooths the tooth surfaces, increasing the specific film thickness, and if it increases the area of contact by removing minor imperfections through local wear. To ensure that the wear rate remains under control, run in new gearsets by operating for at least the first ten hours at one-half load.

The amount of wear considered tolerable depends on the expected lifetime for the gears and requirements for control of noise and vibration.

Methods for Preventing Adhesive Wear

1. Use smooth tooth surfaces.
2. If possible, run in new gearsets by operating the first ten hours at one-half load.
3. Use high speeds if possible. Otherwise, recognize that highly loaded, slow-speed gears are boundary lubricated and are especially prone to excessive wear. For these conditions, specify nitrided gears and the highest permissible lubricant viscosity.
4. For very slow-speed gears (<10 fpm), avoid using lubricants with sulphur-phosphorous additives.
5. Use an adequate amount of cool, clean, and dry lubricant of the highest viscosity permissible.

Wear is considered excessive when the tooth profiles wear to the extent that high dynamic loads occur or the tooth thickness is reduced to the extent that bending fatigue becomes possible.

Many gears, because of practical limits on lubricant viscosity, speed, and temperature, must operate under boundary-lubricated conditions where some wear is inevitable. Highly loaded, slow speed (<100 fpm), boundary-lubricated gears are especially prone to excessive wear. Tests with slow-speed gears[10] have shown that nitrided gears have good wear resistance, while carburized and through-hardened gears have similar, but lower wear resistance. Reference 10 concluded that lubricant viscosity has the greatest influence on slow-speed, adhesive wear, and that high – viscosity lubricants reduce the wear rate significantly. The same authors found that sulphur-phosphorous additives can be detrimental with slow-speed (<10 fpm) gears, giving very high wear rates.

A few gear units operate under ideal conditions with smooth tooth surfaces, high pitch line speed, and high lubricant film thickness. For example, turbine gears that operated almost continuously at 30,000 fpm pitch line speed still had the original machining marks on their teeth, even after operating for 20 years. Most gears, however, operate between the boundary and full-film lubrication regimes, under elastohydrodynamic (EHD) conditions. In the EHD regime, with the proper type and viscosity of lubricant, the wear rate usually reduces during running-in and adhesive wear virtually ceases once running-in is completed. If the lubricant is properly maintained (cool, clean, and dry), the gearset should not suffer an adhesive wear failure.

Wear – Abrasion. Abrasive wear on gear teeth is usually caused by contamination of the lubricant by hard, sharp-edged particles. Contamination enters gearboxes by being built-in, internally generated, ingested through breathers and seals, or inadvertently added during maintenance.

Many gear manufacturers do not fully appreciate the significance of clean assembly; it is not uncommon to find sand, machining chips, grinding dust, weld splatter, or other debris in new gear boxes. To remove built-in contamination, drain and flush the gearbox lubricant before start-up and again after the first 50 hours of operation, refill with the recommended lubricant, and install a new oil filter.

Methods for Preventing Abrasive Wear

1. Remove built-in contamination from new gearboxes by draining and flushing the lubricant before start-up and again after the first 50 hours of operation. Refill with the recommended lubricant and install a new filter.
2. Minimize internally generated wear debris by using surface-hardened gear teeth, smooth tooth surfaces, and high-viscosity lubricants.
3. Minimize ingested contamination by maintaining oil-tight seals and using filtered breather vents located in clean, non-pressurized areas.
4. Minimize contamination that is added during maintenance by using good housekeeping procedures.
5. For circulating oil systems, use fine filtration.
6. For oil bath systems, change the lubricant at least every 2500 hours or every six months.
7. Monitor the lubricant with spectrographic and ferrographic analysis together with analysis of acid number, viscosity, and water content.

Internally generated particles are usually wear debris from gears or bearings due to Hertzian fatigue pitting or adhesive and abrasive wear. The wear particles are especially abrasive because they become work-hardened when they are trapped between the gear teeth. Internally generated wear debris can be minimized by using accurate, surface-hardened gear teeth (with high pitting resistance), smooth surfaces, and high viscosity lubricants.

Breather vents are used on gearboxes to vent internal pressure, which may occur when air enters through seals, or when air within the gearbox expands (or contracts) during the normal heating and cooling of the gear unit. The breather vent should be located in a clean, non-pressurized area and should have a filter to prevent ingress of airborne contaminants. In especially harsh environments, the gearbox can be completely sealed, and the pressure variation can be accommodated by an expansion chamber with a flexible diaphragm.

All maintenance procedures which involve opening any part of the gearbox or lubrication system must be carefully performed to prevent contamination of the gearbox system.

Abrasive wear due to foreign contaminants, such as sand or internally generated wear debris, called three-body abrasion, is a common occurrence. Two-body abrasion also occurs when hard particles or asperities on one gear tooth abrade the opposing tooth surface. Unless the tooth surfaces of a surface-hardened gear are smoothly finished, they will act like files if the mating gear is appreciably softer. This is the reason that a worm pinion is polished after grinding before it is run with a bronze worm wheel. Manufacturers of computer disk drives have found that stainless steel pinions mated with anodized aluminum racks have excessively high wear rates. The anodized layer of the aluminum rack is extremely thin and brittle, and it breaks up and impregnates the relatively soft stainless steel pinion. The aluminum oxide particles then act like emery paper and wear the teeth of the rack very quickly.

The lubrication system should be carefully maintained and monitored to ensure that the gears receive an adequate amount of cool, clean, and dry lubricant. For circulating-oil systems, fine filtration removes contamination. Filters as fine as 3 μm have significantly increased gear life. For oil-bath gearboxes, the lubricant should be changed frequently to remove contamination. Under normal operating conditions the lubricant should be changed at least every 2500 operating hours or six months, whichever occurs first. For critical gearboxes a regular program of lubricant monitoring can help prevent gear failures by showing when maintenance is required. The lubricant monitoring should include spectrographic and ferrographic analysis of contamination, along with analysis of acid number, viscosity, and water content.

Polishing wear. If the extreme pressure (EP) additives in the lubricant are too chemically reactive, they may cause polishing of the gear tooth surfaces until they attain a bright, mirror finish. Although the polished gear teeth may look good, polishing wear is undesirable because it generally reduces gear accuracy by wearing the tooth profiles away from their ideal form. EP additives used in lubricants to prevent scuffing, such as sulfer and phosphorous, will be covered when scuffing is discussed. They function by forming iron sulfide and iron phosphate films on areas of the gear teeth where high temperatures occur. Ideally, the additives should react only at temperatures where there is a danger of welding. If the rate of reaction is too high, and there is a continuous removal of the surface films caused by very fine abrasives in the lubricant, the polishing wear may become excessive.

Polishing wear can be prevented by using less chemically active additives. As an alternative to sulfur-phosphorous additives, anti-scuff lubricants are available with dispersions of potassium borate[13] which deposit EP films without chemically reacting with the metal. Removing the abrasives in the lubricant by using fine filtration or frequent oil changes is helpful.

Methods of Preventing Polishing Wear

1. Use less chemically active anti-scuff additives, such as borate.
2. Remove abrasives from the lubricant by using fine filtration or frequent oil changes.

Scuffing. Scuffing is defined as localized damage caused by solid-phase welding between sliding surfaces. It is accompanied by transfer of metal from one surface to another due to welding and tearing. It may occur in any sliding and rolling contact where the oil film is not thick enough to separate the surfaces. The symptoms are microscopically rough, matte, torn surfaces. Surface analysis that shows transfer of metal from one surface to the other is proof of scuffing.

Scuffing can occur in gear teeth when they operate in the boundary lubrication regime. If the lubricant film is insufficient to prevent significant metal-to-metal contact, the oxide layers that normally protect the gear tooth surfaces may be broken through, and the bare metal surfaces may weld together. The sliding that occurs between gear teeth results in tearing of the welded junctions, metal transfer, and catastrophic damage.

In contrast to pitting and bending fatigue, which only occur after a period of running time, scuffing may occur immediately upon start-up. In fact, gears are most vulnerable to scuffing when they are new, and their tooth surfaces have not yet been smoothed by running in. For this reason, it is wise to run in a new gearbox under one-half load for at least ten hours to reduce the surface roughness of the teeth before applying full load. The gear teeth can be coated with iron manganese phosphate or plated with copper or silver to protect them from scuffing during the critical running-in period.

The basic mechanism of scuffing is not understood clearly, but by general agreement, it is believed to be caused by intense frictional heating generated by the combination of high sliding velocity and intense surface pressure. Blok's[14] critical temperature theory is believed to be the best criterion for predicting scuffing. It states that scuffing will occur in gear teeth that are sliding under boundary-lubricated conditions, when the maximum contact temperature of the gear teeth reaches a critical magnitude. For mineral oils without anti-scuff/EP additives, each combination of oil and rubbing materials has a critical scuffing temperature which is constant, regardless of the operating conditions.[15] The critical scuffing temperatures are not constant for synthetic lubricants and lubricants with anti-scuff additives; they must be determined from tests which closely simulate the operating conditions of the gears.

Today, most anti-scuff additives are sulfur-phosphorus compounds, which form boundary lubricating films by chemically reacting with the metal surfaces of the gear teeth at local points of high temperature. Anti-scuff films help prevent scuffing by forming solid films on the gear tooth surfaces and inhibiting true metal-to-metal contact. The films of iron sulfide and iron phosphate have

Methods for Preventing Scuffing

1. Use smooth tooth surfaces produced by careful grinding or honing.
2. Protect the gear teeth during the critical running-in period by coating them with iron manganese phosphate or plating them with copper or silver. Run in new gearsets by operating the first ten hours at one-half load.
3. Use high viscosity lubricants with anti-scuff additives, such as sulfur, phosphorous, or borate.
4. Cool the gear teeth by supplying an adequate amount of cool lubricant. For circulating-oil systems, use a heat exchanger to cool the lubricant.
5. Optimize the gear tooth geometry by using small teeth, addendum, and profile modification.
6. Use accurate gear teeth, rigid gear mountings, and good helix alignment.
7. Use nitrided steels for maximum scuffing resistance. Do not use stainless steel or aluminum for gears.

high melting points, allowing them to remain as solids on the gear tooth surfaces even at high contact temperatures. The rate of reaction of the anti-scuff additives is greatest where the gear tooth contact temperatures are highest. Because of the rubbing action of the gear teeth, the surface films are repeatedly scraped off and reformed. In effect, scuffing is prevented by substituting mild corrosion in its place. Occasionally, anti-scuff additives, such as sulfer, are too chemically active, causing polishing wear and necessitating a change to less aggressive additives. Lubricants with anti-scuff additives of potassium borate do not cause polishing wear because they deposit glass-like boundary films without reacting with the metal.

For mineral oils without anti-scuff additives, the critical scuffing temperature increases with increasing viscosity, and ranges from 150°C to 300°C. The increased scuffing resistance of high viscosity lubricants is believed to be due to differences in chemical composition rather than increases in viscosity. However, a viscosity increase also helps to reduce the risk of scuffing by increasing the lubricant film thickness and reducing the contact temperature generated by metal-to-metal contact.

Scuffing is controlled by the total contact temperature Tc, which consists of the sum of the gear bulk temperature Tb, and the flash temperature Tf; i.e.,

$$Tc = Tb + Tf$$

The bulk temperature is the equilibrium temperature of the surface of the gear teeth before they enter the meshing zone. The flash temperature is the local and instantaneous temperature rise that occurs on the gear teeth due to the frictional heating as they pass through the meshing zone.

Anything that reduces either the bulk temperature or the flash temperature will reduce the total contact temperature and lessen the risk of scuffing. Higher viscosity lubricants or smoother tooth surfaces help by increasing the specific film thickness, which in turn reduces the frictional heat and, therefore, the flash temperature. Also, the lubri-

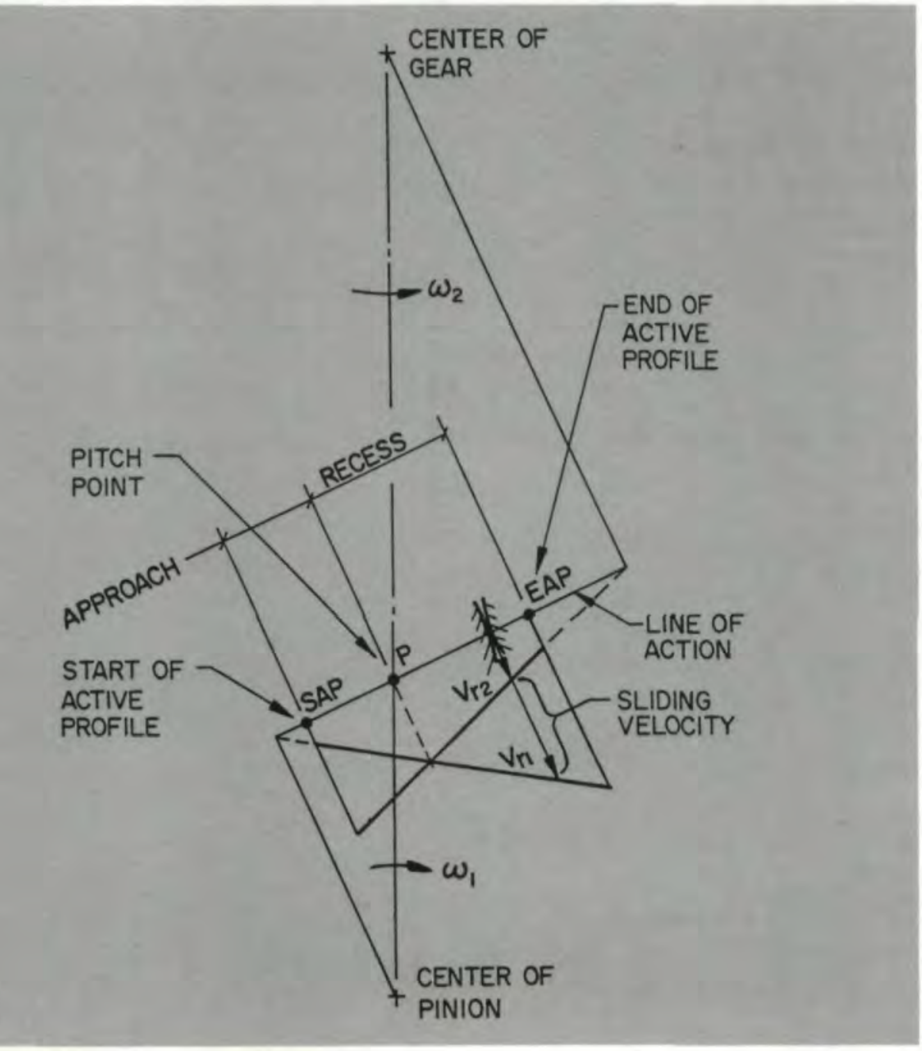

Fig. 1

cant performs the important function of removing heat from the gear teeth. It must be supplied to the gear teeth in such a way that it removes heat rapidly and keeps a low bulk temperature. A heat exchanger can be used with a circulating oil system to cool the lubricant before it is sprayed at the gears. The gear designer can maximize scuffing resistance by optimizing the gear geometry so that the gear teeth are as small as possible, consistent with bending strength requirements, to reduce the temperature rise caused by sliding. Fig. 1 shows that the rolling velocities, Vr_1 and Vr_2, linearly increase from zero at the interference points to a maximum at each end of the path of contact. The sliding velocity is represented by the distance between the Vr_1 and Vr_2 lines. The amount of sliding is proportional to the distance from the pitch point, P, and is zero when the gear teeth contact at the pitch point, and largest at the ends of the path. Addendem modification can be used to balance and minimize the temperature rise that occurs in the addendum and dedendum of the gear teeth. The temperature rise may also be reduced by modifying the tooth profiles with slight tip and/or root relief to ease the load at the start and end of the engagement path where the sliding velocities are the greatest. Also, the gear teeth must be accurate and held rigidly in good alignment to minimize tooth loading and, therefore, the temperature rise.

Gear materials should be chosen with their scuffing resistance in mind. Nitrided steels, such as Nitralloy 135M, are generally found to have the highest resistance to scuffing, while stainless steels are liable to scuff even under near-zero loads. The thin oxide layer on stainless steel is hard and brittle, and it breaks up easily under sliding loads, exposing the bare metal, thus promoting scuffing. Anodized aluminum has a low scuffing resistance similar to stainless steel. Hardness does not seem to be a reliable indication of scuffing resistance.

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Bevel Gear Manufacturing Troubleshooting

Robert L. Sebetic
Rockwell International, Newark, Ohio

BASIC GEARING DEFINITIONS*

- GEAR – The member with the larger number of teeth.
- PINION – The member with the smaller number of teeth.
- PITCH LINE RUNOUT is the total variation between high and low indicator readings of the amount of pitch line error as observed from a fixed reference point perpendicular to the axis of gear rotation. Runout readings include eccentricity and out-of-roundness of the pitch line.
- PITCH VARIATION is the difference between the pitch and the measured distance between the corresponding points on any two adjacent teeth.
- TOOTH CONTACT is the area on a tooth surface from which marking compound is removed when the gears are run together in a test machine.
- LAME CONTACT is a condition existing when the tooth contact pattern on one side of a tooth is nearer the top (or flank) than is the tooth contact pattern on the opposite side of the same tooth.

*(GLEASON WORKS, Testing and Inspecting Bevel and Hypoid Gears, 1979)

Abstract:

The quality of gearing is a function of many factors ranging from design, manufacturing processes, machine capability, gear steel material, the machine operator, and the quality control methods employed. This article discusses many of the bevel gear manufacturing problems encountered by gear manufacturers and some of the troubleshooting techniques used.

Introduction

A goal of all gear manufacturers is to have the ability to set up several different bevel machines, accurately duplicate a "production reference," and meet all quality requirements with a minimum amount of labor and scrap. This is true for cutting, lapping, and hard finishing of tooth profiles.

Some manufacturers have taken a major step in accomplishing this goal by the addition of today's new CNC cutting, lapping, skiving, and grinding equipment. However, the manufacturers that still use predominantly old mechanical bevel gear manufacturing equipment are much more susceptible to and likely to struggle with a wide variety of manufacturing problems.

The manufacturing of a desired quality level bevel gear set is a function of many factors, including, but certainly not limited to, design, manufacturing processes, machine capability, gear materials, the machine operator, and the quality control methods employed. In this article we will make some basic assumptions about the bevel gear design, engineering specifications, and the basic processes and concentrate mainly on the problems found in bevel cutting, heat treating, and hard finishing operations.

Assumptions

We want to concentrate primarily on bevel gear manufacturing problems that are encountered by manufacturers that frequently set up and produce a variety of bevel summaries on a repetitive basis. Therefore, we have made the following assumptions.

1. The bevel set design is good, tooth contact analysis programs have been run, and motion curves and displacement values are within desired parameters.

TABLE 1 – HYPOID/SPIRAL BEVEL GEAR & PINION SET PROCESSING

GEAR	PINION
FORGING	FORGING
PRE-TREATMENT NORMALIZE	PRE-TREATMENT NORMALIZE
BLANKING • Profile Turning • Broaching • Hole Drilling • Identification	BLANKING • Profile Turning • Splining • Green Grinding • Threading • Identification
TOOTH CUTTING • Machine Setup	TOOTH CUTTING • Machine Setup
GREEN TEST • Cutting Setup Approval • Size and Contact Comparison to Production "Ref." • Inspection	GREEN TEST • Cutting Setup Approval • Size and Contact Comparison to Production "Ref." • Inspection
BURRING, CHAMFERING	BURRING, CHAMFERING
HEAT TREAT • Carburize and Quench • Bore Size • Gear Geometry	HEAT TREAT • Carburize and Quench • Induction Anneal • Straightening
HARD GRIND • Bore I.D.	HARD GRIND • Bearing Journals

MATCH AND LAP OR HARD FINISH • *Refine Tooth Surfaces for Acceptable Tooth Contacts and Noise Level*

HARD TEST • Monitor Finishing Operation

PROTECT • Phosphate Coating for Break In, Rust Proofing, and Identification

SHIP • Assembly Line or Customer

2. The bevel set development has been completed, "production references" made, and finished gear set testing has been completed and found acceptable.
3. Engineering standards for bevel gear accuracies and tooth contact patterns have been set according to design and testing requirements.
4. The manufacturer has the gear set manufacturing processes to meet the engineering standards for bevel gearing.
5. In general, the gear manufacturing equipment is capable, and the work holding tooling is in good shape and to specifications.
6. Both pinion and gear blanks meet process specifications and are free of damage.
7. Material handling of pinions, gears, and gear sets throughout the manufacturing process is accomplished without damage.

General Bevel Set Processing

A general flow diagram of hypoid and spiral bevel gear processing is shown in Table 1. It lists the steps in the process and in what general order they normally would follow.

The Bevel Gear and Pinion Cutting Operations

Bevel gear and pinion cutting operations are by far the most critical of the bevel processing operations. When performed to meet the manufacturer's engineering specifications for tooth contact position and analytical tolerances, it will minimize the time and labor impact of all other post operations and maintain the highest level of intended gear set quality. This is also true for bevel sets that are processed for hard finishing operations. No matter what gear cutting system you use the majority of what is shown in Tables 2-7 should apply.

The Heat Treatment Operation of Gears and Pinions

Generally, most manufacturers experience a decrease in quality levels as their gears and pinions pass through the heat treat operations. On the

Robert Sebetic
is manager of the Automotive Operations Gear Lab at Rockwell International. He received his Bachelor's Degree from the University of Wisconsin and has an MBA from Ohio University. He serves as committee member on the AGMA Gear Manufacturing Committee and is a member of SME and ASQC.

average, the carburization and press quench process will decrease at least two levels in the AGMA rating tables.

The nature of the heat treat operation alters the geometry and microstructure of the "green" material. The areas of concern generally include flatness, roundness, taper, warpage, pockets, and straightness. The deterioration of gear accuracies has a negative impact on general gear quality, lapping, and hard finishing cycle times, and may cause potential warranty problems.

Hard Finishing of Gear and Pinion Tooth Profiles

These processes consist of grinding or hard carbide cutting the gear or pinion tooth profiles after the heat treat operations. This post heat treat operation offers us the ability to remove any heat treat distortions that may have occurred, as well as improves the gear tooth accuracy.

The Lapping Operation Of The Bevel Gear Set

The lapping of a bevel gear set should be no more than a minimal refining of the gear tooth surfaces for tooth contact shape, length, and noise level. In general, we should take a good quality gear set and make it even better.

Finish Grinding of Gears and Pinion Locating Surfaces

The hard grinding of critical mounting dimensions and bearing journals are as important to gear quality and life as the cutting operation itself. Engineering tolerances for runout, size, concentricity, and perpendicularity must be met.

Conclusion

We have attempted, in these few pages, to discuss the hypoid and spiral bevel gear set manufacturing process and to provide a general checklist that can be used to troubleshoot manufacturing problems when they occur.

Understanding the root causes of gear manufacturing problems is good prevention and also contributes to improved quality and productivity.

Acknowledgement: *Presented at the SME Gear Clinic, Nashville, TN, Oct. 16-18, 1990. Reprinted with permission.*

TABLE 2 – THE GEAR CUTTING OPERATION

Problem	Checklist
• TOOTH CONTACT DUPLICATION	
• Vertical Position/Cross	• Improper Machine Settings • Arbor Dimension Error
• Vertical Position/Both Sides Heel or Toe	• Improper Machine Settings • Arbor Dimension Error
• Lameness	• Improper Cutter Sharpening • Wrong Pressure Angle Cutter • Cutter Gaging Error • Arbor Dimensions Error
• PITCH LINE RUNOUT	• Dirt/Chips • Improperly Mounted Workholding Equip. • Improperly Mounted Cutter • Clamping Pressure • Clamping Spring Size • Hydraulic Pressure • Work Piece Not Seated Properly • Overhead Bracket Support on Some Machines • Clamping Plate Size and Rigidity • Locating Plate/Expandisc Size
• PITCH VARIATION	• Index Plate Worn • Index Lock-up Pawl Worn • Stock Division Error by Operator • Mechanical Index Counter Error • Amount of Stock Left for Finish Cut • Bore Locator Undersize • Finish Cutter Cutting in Roughing Rootline • Drive Key Used

TABLE 3 – THE PINION CUTTING OPERATION

Problem	Checklist
• TOOTH CONTACT DUPLICATION	
• Vertical Position	• Machine Settings • Machine Difference • Wrong Cutter Point Diameter • Not Generated Out of Cut
• Pinion Cone	• Machine Center to Back • Ratio Roll Gear • Modified Roll Gearing • Tilt Setting • Wrong Pressure Angle Cutter • Improperly Ground Cutter • Cutting Collar Length
• PITCH LINE RUNOUT	• Arbor Not Seated • Arbor Not Built Properly • Blank Locating Surfaces • Cracked Collet or Oversize Nose Piece • Runout in Pinion Blank Locating Surfaces • Sliding Base Stop • Chucking Pressure
• PITCH VARIATION	• Collet Cracked • No Backlash in Mechanical Gearing • Sliding Base Positive Stop • Cradle Brake Needs Adjustment • Lubrication on Machine Gears • Too Much Stock Left from Rougher • Root Line Too Shallow and the Finish Cutter is Cutting in the Root • Finish Cutter is Too Deep and Cutting in the Rootline • Return Roll Centering Not Working Properly • Very Rough Surface Finish

TABLE 4 – HEAT TREAT CHECKLIST

Problem	Checklist
MAINTAINING GEAR GEOMETRY THROUGH HEAT TREAT	• Size is a Function of Case Depth and Gear Material • Quench Oil Temperature • Time from Furnace to Press Quench and Table Speed • Handling Equipment • Load Pattern Height, Stack Weight, and Spacers • Quench Oil Flow Rates • Dishing Cam "Zeroed" • Quench Ring Pattern and Alignment Key • Cleanliness of Oil • Type of Gear Steel • Nicks and Bumps on Gears • Lower Die Parallelism • Inner, Outer Ring, and Expander Pressure
MAINTAINING PINION GEOMETRY THROUGH HEAT TREAT	• Loading Pattern/Vertical Versus Horizontal • Straightening • Center Size • Cleanliness • Quench Oil Temperature

(continued on p. 32)

TABLE 5 – GEAR & PINION FINISH GRINDING CHECKLIST

Problem	Checklist
GRINDING GEAR LOCATING SURFACES	
• Runout	• Pitchline Locators • Bore Size
GRINDING PINION LOCATION SURFACES	
• Runout	• Centers Damaged • Bearing Diameter Undersize • Concentricity
• Pinion Cone Position	• Amount of Grind Stock Removed From Thrust Surface

TABLE 6 – GEAR & PINION HARD FINISHING CHECKLIST

Problem	Checklist
• TOOTH CONTACT POSITION, LAMENESS, PITCH LINE, RUNOUT, AND PITCH VARIATION	• Refer to Cutting List and Substitute the Word Grinding Wheel for Cutter
• INTERFERENCE, GRINDING BURN	• Whole Depth of Wheel • Speeds, Feeds, and Grit Size • Amount of Coolant

TABLE 7 – LAPPING OPERATION CHECKLIST

Problem	Checklist
• TOOTH CONTACT	
• Vertical Position and Lameness	• Gear Set Spot Prior to Lapping • Machine Settings • Oscillation Speeds • Toe/Heel Cam Setting • Tester Setup • Lapping Backlash
• Interference Lines and Hard Spots In Tooth Contact Area, Scoring	• Pinion Rootline/Sliding Base • Toprem • Position of Compound Pipe • Lapping Grit Size • Contamination of Vehicle • Undersize Gear or Pinion Tooth • Nicks and Bumps
• PITCH LINE RUNOUT	• Workholding Tooling • Mounting of the Workholding Tooling • Gear or Pinion Locating Surfaces • Runout Cut into Gear or Pinion • RPM of Lapping Machine • Brake/Torque During Lapping • Tester Tooling and Setup
• PITCH VARIATION	• Not Likely to Occur

Synthesis of Spiral Bevel Gears

Faydor L. Litvin
University of Illinois
Chicago

There are different types of spiral bevel gears, based on the methods of generation of gear-tooth surfaces. A few notable ones are the Gleason's gearing, the Klingelnberg's Palloid System, and the Klingelnberg's and Oerlikon's Cyclo Palliod System. The design of each type of spiral bevel gear depends on the method of generation used. It is based on specified and detailed directions which have been worked out by the mentioned companies. However, there are some general aspects, such as the concepts of pitch cones, generating gear, and conditions of force transmissions that are common for all types of spiral bevel gears.

Pitch Cones

Consider that rotation is transformed between two intersected axis, Oa_1 and Oa_2, which make an angle γ (Fig. 1). The angular velocities in rotation about these axes are $\omega^{(1)}$ and $\omega^{(2)}$. The instantaneous axis of rotation (OI) is the line of action of the relative angular velocity

$$\boldsymbol{\omega}^{(12)} = \boldsymbol{\omega}^{(1)} - \boldsymbol{\omega}^{(2)} \qquad (1)$$

or

$$\boldsymbol{\omega}^{(21)} = \boldsymbol{\omega}^{(2)} - \boldsymbol{\omega}^{(1)} \qquad (2)$$

The instantaneous axis of rotation is the line of tangency of the pitch cones that roll over each other without slipping. The apex angles of the pitch cones γ_1 and γ_2 are represented by the following equations:

$$\cot \gamma_1 = \frac{m_{12} + \cos \gamma}{\sin \gamma} \qquad (3)$$

$$\cot \gamma_2 = \frac{m_{21} + \cos \gamma}{\sin \gamma} \qquad (4)$$

Here

$$m_{12} = \frac{\omega^{(1)}}{\omega^{(2)}} = \frac{N_2}{N_1} \text{ and } m_{21} = \frac{\omega^{(2)}}{\omega^{(1)}} = \frac{N_1}{N_2}$$

are the gear ratio; N_1 and N_2 are the number of gear teeth.

For the most common case when $\gamma = 90°$, we obtain

$$\cot \gamma_1 = m_{12} \qquad \cot \gamma_2 = m_{21} \qquad (5)$$

Plane II is a tangent plane to the pitch cones (Fig. 1). We may imagine that plane II rotates about axis Oa_g with angular velocity $\omega^{(g)}$, while the pitch cones rotate with angular velocities $\omega^{(1)}$ and $\omega^{(2)}$ about axes Oa_1 and Oa_2, respectively. Plane II, limited with the circle of radius OI, may be considered as a particular case of a pitch cone surface having an apex γ_i, which approaches 90° and has an outer cone distance equal to OI.

Generating Gear: Types of Spiral Bevel Gearing

Consider that a generating surface Σ_g is rigidly connected to the pitch plane II. Surface Σ_g rotates with the pitch plane II about Oa_g (Fig. 1) while gear blanks rotate about Oa_1 and Oa_2, respectively. Surface Σ_g generates tooth surfaces Σ_1 and Σ_2 on gears 1 and 2. Such a generating process provides conjugate gear-tooth surfaces Σ_1 and Σ_2 which contact each other along a line at every instant. The instantaneous line of contact moves over surfaces Σ_1 and Σ_2. Gears 1 and 2, having surfaces Σ_1 and Σ_2, will transform rotation about axes Oa_1 and Oa_2 with the prescribed gear ratio. The type of spiral bevel gearing depends on the type of generating surface Σ_g.

The generating surface for Gleason's spiral bevel gearing is a cone surface. The head cutter that cuts the gear carries blades with straight-lined profiles. Consider a coordinate system S_c that is rigidly con-

FAYDOR L. LITVIN
is Professor of Mechanical Engineering at the University of Illinois at Chicago. In addition, working in conjunction with NASA, Dr. Litvin has developed many new and important ideas for the mathematical formulation and theoretical understanding of spur, helical, and spiral bevel gears. The material in this article is taken from a much larger work, The Theory of Gearing, by Dr. Litvin, which explains the most general problems of gearing theory.

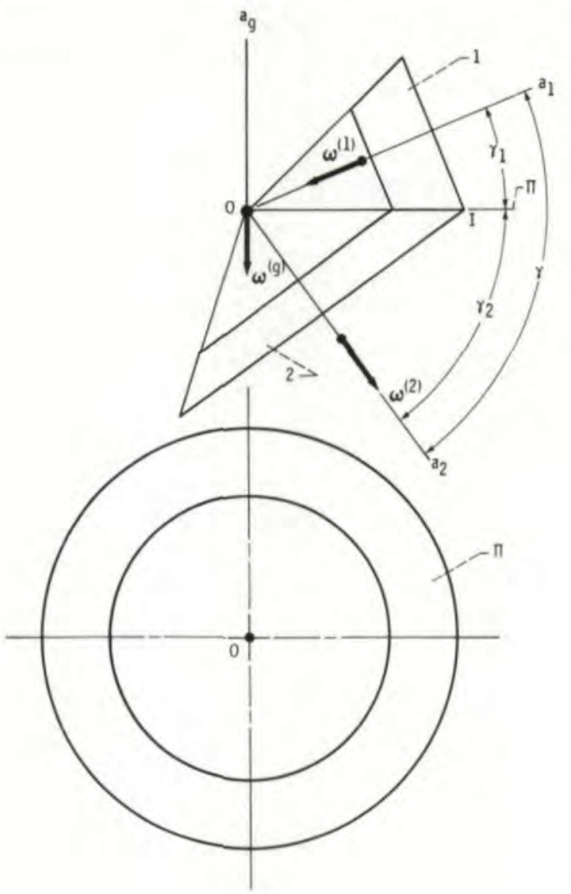


Fig. 1

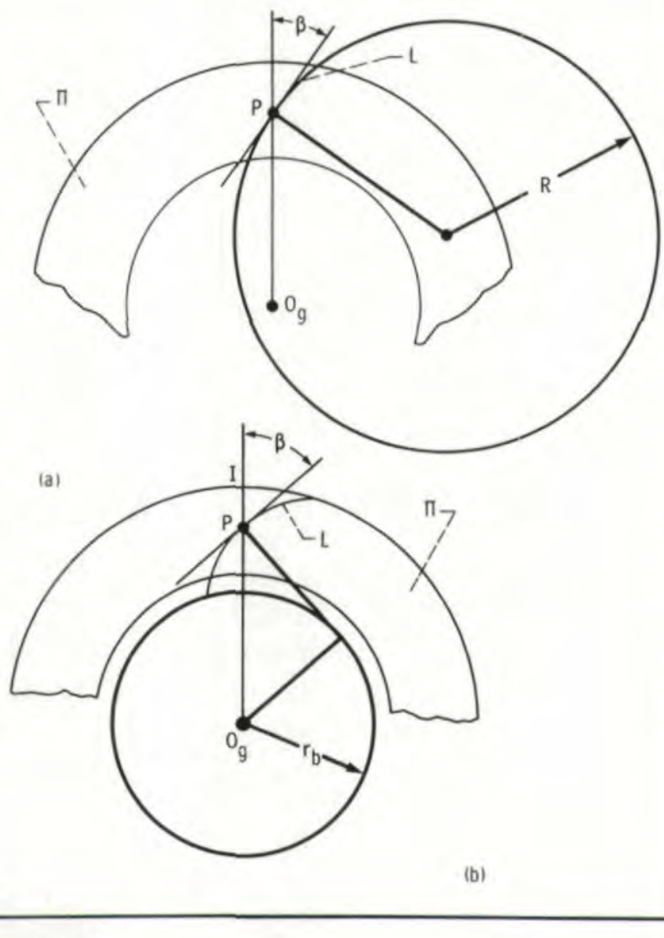


Fig. 2

nected to the head cutter and rotates with it about the *C-C* axis. The head-cutter blades, being rotated about *C-C*, generate a cone in the coordinate system S_c. The angular velocity of rotation about *C-C* does not depend on the generating motions and provides the desired velocity of cutting only.

To generate the gear tooth surface the head cutter has to go through two motions:

(1) Rotation about Oa_g while the generated gear rotates about Oa_{ij}

(2) Rotation about *C-C*.

Rotations of the generating gear and the gear being generated are related since the instantaneous axis of rotation is *OI*. The rotation of the head cutter about *C-C* may be ignored by considering that a generating cone surface is rigidly connected to plane Π (with axis *C-C* of the cone) (Fig. 1) and rotates about axis Oa_g. The motion of the generating gear (rotation about Oa_g) is simulated by the rotation of the cradle of the cutting machine which carries the head cutter.

Consider the line of intersection *L* of the generating surface with the pitch plane Π. In the case of Gleason's gearing, *L* is a circular arc of radius *R* (Fig. 2a). Line *L* generates a spatial curve on the gear pitch cone that is more like a helix rather than a spiral although the gears are called spiral bevel gears.

The type of spiral bevel gears is related to the type of the longitudinal shape of the gear. We differentiate between the following types of spiral bevel gears.

(1) The Gleason's gearing (Fig. 2a): where the longitudinal shape is a circular arc of radius *R*.

(2) The Palloid System of Klingelnberg (Fig. 2b): where the longitudinal shape is approximately an involute curve for a base circle of radius r_b. The generating surface of the Palloid System of Klingelnberg is generated by a conical worm. The tool is a conical hob which simulates the conical worm.

(3) The Cyclo-Palloid System of Klingelnberg and Oerlikon System (Fig. 3) where the longitudinal shape is an extended epicycloid, traced out by point *P* of the finishing blade of the head cutter. The blade and circle of radius ϱ are rigidly connected and represent a rigid body. The circle of radius ϱ rolls over the gear circle of radius *r*. Thus these circles are centrodes of the head-cutter and of the generating gear. The head cutter rotates about O_c and the generating gear rotates about O_g. Unlike the generation of Gleason's gearing, the rotations of the head-cutter and the generating gear in the case of the Cyclo-Palloid System are related: point *I* is the in-

stanteous center of rotation in the relative motion of the head cutter with respect to the generating gear.

In reality the methods of generation discussed are more complicated because they have to provide a localized contact of gear-tooth surfaces. It is for this reason that two generating surfaces are used instead of one.

Henceforth, we will designate the direction of the tangent to the longitudinal shape at point P by β. Point P is the point of intersection of the instantaneous axis of rotation O_gI and the shape (Figs. 2 and 3). The longitudinal shape (the spiral) can be right-handed or left-handed, similar to the right-handed and left-handed helical gears. Fig. 3 shows right-handed spirals.

Tooth Element Proportions

The axial section of the Palloid gearing and the Cyclo Palloid gearing is shown in Fig 4a. This gearing has a constant height of the teeth.

The axial section of the Gleason's gearing is shown in Fig.4b. Tooth height changes proportionally to the distance from the apex and the three cones – the pitch cone, dedendum cone, and addendum cones – have the same apex. In some cases, the gears are designed with different apices for the mentioned cones to provide a constant backlash between the dedendums and addendums of mating gears.

The transverse diametral pitch is given for the back cone. The pitch diameter for the gear is determined by

$$d_i = \frac{N_i}{P} \qquad (i = 1,2) \tag{6}$$

where P is the diametral pitch and N_i is the tooth number.

The outer cone distance A_o is determined by

$$A_O = \frac{d_i}{2 \sin \gamma_i} \tag{7}$$

The addendum and dedendum angles are represented by Fig. 4b.

$$\Delta_1 = \tan^{-1} \frac{a}{A_O} \tag{8}$$

$$\Delta_2 = \tan^{-1} \frac{b}{A_O} \tag{9}$$

Here a and b are the dimensions of the addendum and dedendum for the back cone expressed in terms of the diametral pitch.

Acknowledgement: *Reprinted from Theory of Gearing, Faydor L. Litvin. NASA R.P. 1212, AVSCOM T.R. 88-C-085. Available from the Superintendent of Documents, U.S. Govt. Printing Office, Washington, D.C.*

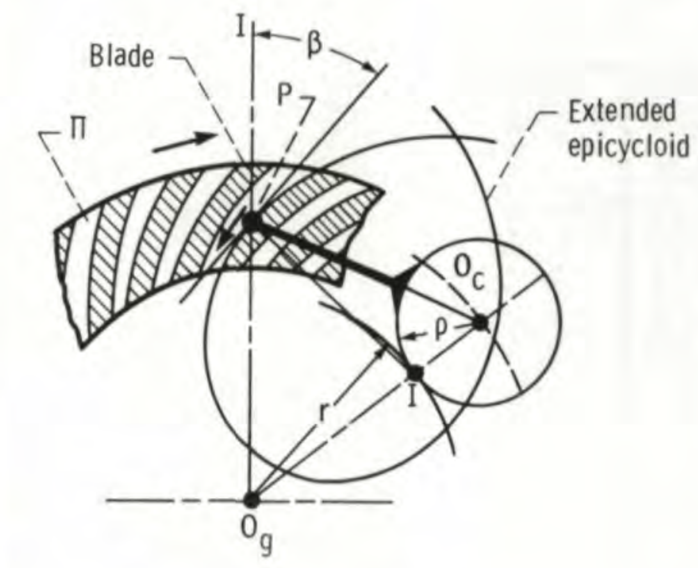


Fig. 3

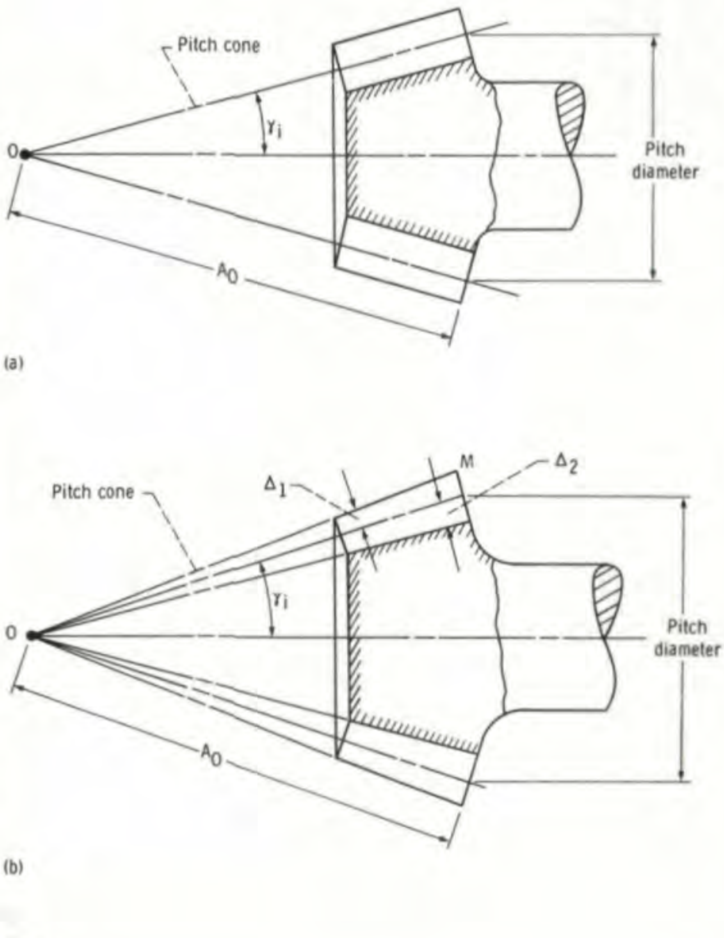


Fig. 4

GEAR FUNDAMENTALS

Hard Finishing By Conventional Generating and Form Grinding

Rex Newman,
Teledyne Continental Motors, Mobile, AL

Introduction

The quality of a gear and its performance is determined by the following five parameters, which should be specified for each gear: Pitch diameter, involute form, lead accuracy, spacing accuracy, and true axis of rotation. The first four parameters can be measured or charted and have to be within tolerance with respect to the fifth. Pitch diameter, involute, lead, and spacing of a gear can have master gear quality when measured or charted on a testing machine, but the gear might perform badly if the true axis of rotation after installation is no longer the same one used when testing the gear.

This fact leads to the first requirement which should be met when finishing gears: The surfaces used to position the gear in its final assembly should also be used to position the gear for either soft or hard finishing. A second requirement, which is increasingly accepted, is that the equipment used for soft or hard finishing gears should provide controlled motion to accurately produce involute, lead, and spacing.

Other methods used to hard finish gear teeth include skiving (using carbide cutters), lapping (using abrasive grit suspended in oil), and honing (using an abrasive grit stone in the form of a mating gear).

These four methods each have limitations, and one must decide which will best meet the requirements of the gear application. An understanding of each process will serve as a guide to using the best and most economical method.

High-temperature, high-alloy gear materials used today are being ground out of the solid in less time than cutting in some cases. With the new grinding and abrasive technology used today, grinding out of the solid is becoming an economical alternative to other approaches.

High-performance and heavy loaded gears are generally carburized and hardened. To increase their life and durability, the teeth must be ground to achieve a controlled tooth geometry. In many cases modified involutes and crowning are required to reduce end loading. Grinding gear teeth is the method to use to achieve these modifications.

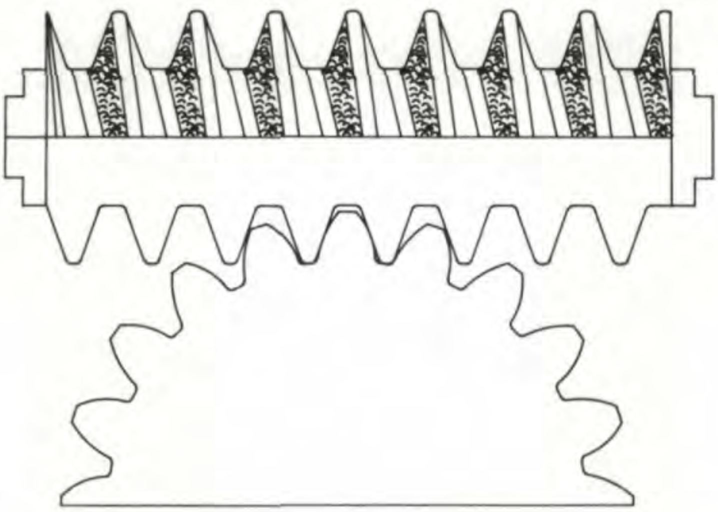
Purpose of Grinding Gear Teeth

Gear teeth are ground to assure accuracy and consistency of tooth geometry. Grinding may also be the most economical method of finishing gear teeth. Generally ground gears are carburized and hardened. The heat treating process has the tendency to distort the gear blank, thus affecting the tooth accuracy, requiring hard finishing of the teeth. Grinding gear teeth provides a reliable method of finishing gear teeth.

Case-Hardened Gear Teeth

Stock removal of the teeth of carburized and hardened gears must be controlled. It is recommended that no more than 20% of the effective case depth be removed. For example, the stock removal should not exceed .007 for case depths of .025 to .035.

Abusive grinding of gear teeth must be avoided. Generally abusive grinding will temper the gear tooth surface and reduce the surface hardness.



THREADED WHEEL GEAR GRINDING METHOD

Tempering of the tooth surface may not be seen by the naked eye, but can be determined by the Nital etch process. Severe tempering often causes local rehardening, which, in turn, can cause surface cracks, and can be determined by magnafluxing the gear.

Gear Grinding Methods

Gear teeth are ground by one of two basic methods – either form or generate grinding. Generate gear grinding machines all use the fundamental rack principal. There are three approaches to this principal, each using a different wheel geometry. They are dish-shaped wheels, threaded wheels, and conical wheels.

Form gear grinding is capable of grinding both external and internal spur and helical gear teeth. There is a wide range of sizes and diametral pitches in grinding machines. Form grinding machines use disk wheels, which are formed by dressing with a diamond to include the complete envelope of the involute tooth space.

Types of Generating Grinders

Threaded Wheel Gear Grinders. (Reishauer) (Okomoto). These gear grinders are fast, high-precision machines employing a 13¾" diameter threaded grinding wheel. A section of the threaded wheel is an involute rack. The machine was designed for external spur or helical gears up to 30" in diameter with helix angles up to 45°. The face width capacity ranges up to 11 inches. Pitch and helix angle determine the maximum face width of helical gears. The two screws provided pitch ranges from 6 to 48 DP or from 20 to 120 DP. The principle of the threaded wheel generating grinder is the same as the gear hobbing machine. The gear is mounted vertically and moves axially in both directions during the grinding cycle. The grinding wheel is fed into the work at the end of each pass and is automatically changed from rough to finish grinding speed. A hydraulic, actuated collet type clamping device can be disengaged to

GEAR GRINDING MACHINES

- **GENERATE GRIND**

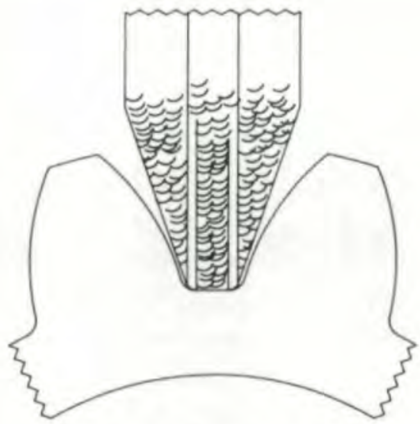
— DISH-SHAPED WHEEL	**MAAG — SWITZERLAND**
— THREADED WHEEL	**REISHAUER — SWITZERLAND** **OKAMOTO — JAPAN**
— CONICAL WHEEL	**REISHAUER — SWITZERLAND** **HOFLER — GERMANY** **LIEBHERR — GERMANY** **PFAUTER-KAPP — GERMANY**

Rex Newman

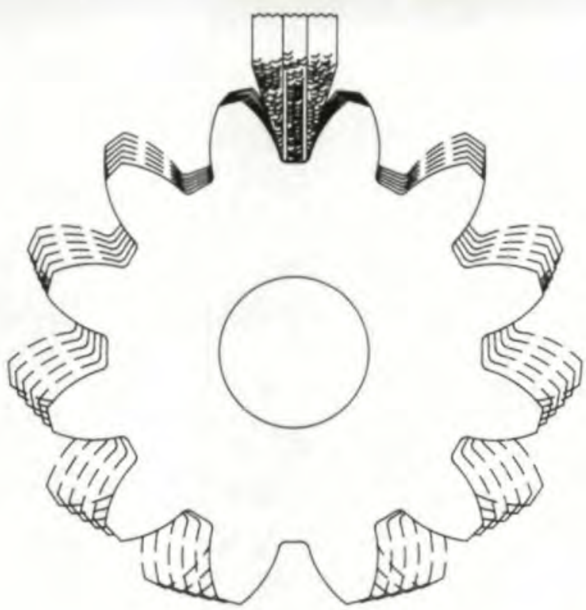
is a senior gear manufacturing engineer with over 35 years' experience in various phases of aerospace precision gear manufacturing. He attended Arizona State University and is a member of the AGMA Manufacturing Committee.

allow the work to free the wheel for exceptionally fine finishes.

Crush-forming a new grinding wheel thread requires approximately four hours. For this reason most users stock pre-formed wheels. Dressing a pre-crushed wheel requires only about 20 minutes. Where profile modifications are required, it takes somewhat longer. The universal truing attachment can dress the wheel to produce involute profiles or modified tips and flanks. There are two types of diamond-plated rolls mounted on motorized spindles available for dressing these wheels also. The single roll requires a very precise roll and dresses both sides of the wheel at one time. The two-roll method has two diamond rolls mounted on independent spindles and makes it easier to adjust for diamond roll wear.



CONICAL WHEEL
GEAR GRINDING METHOD



INVOLUTE TOOTH PROFILE
GENERATION WITH CONICAL WHEEL

As the work passes axially through the grinding wheel, the gear rocks axially to produce crowning. The magnitude and location of the axial profile modification is controlled by cams mounted on the work slide.

The threaded wheel gear grinder is capable of producing tooth profile, spacing, and lead within 200 millionths of an inch. The surface finish produced is excellent.

Generally best results are obtained with a good grinding oil and a vitrified, aluminum oxide grinding wheel specification of 38A (120/180) (H/J) 9V.

Conical Wheel Gear Grinder. (Pratt & Whitney Div., Colt Industries). These machines have not been manufactured since World War II; however, a large number of them are still in use in the U.S. The machines are capable of grinding spur and helical external gears only, with capacities for gears up to 18" in diameter.

The cross section of the conical grinding wheel is a straight profile rack tooth. The overhead grinding wheel head ram reciprocates rapidly as the work table feeds slowly back and forth at right angles to the gear axis. As the work table reciprocates slowly, the master gear rolls in mesh with the stationary rack, causing the work gear to roll in timed relation to the rapidly reciprocating grinding wheel. This results in a generating action. Indexing occurs at the end of the table stroke where the master rack is raised, and the master gear indexed one tooth.

The wheel dresser is a simple diamond tool mechanism, set to dress the straight sides of the grinding wheel to the normal pressure angle of the gear.

The recommended grinding wheels and grinding coolants are similar to those recommended for form gear grinders.

Saucer-shaped wheel gear grinder (MAAG). The generating gear grinding machine employs two saucer-shaped grinding wheels. The grinders are suitable for grinding external spur and helical gears with the various models having capacities up to 142" in diameter. The diametral pitch range varies from 6 to 25 DP on the smallest machine to 1 to 9 DP on the largest machine.

The planes established by the rim of the saucer-shaped grinding wheels represent the straight profile rack tooth on which the work gear rolls during the grinding cycle. The gear generating motion is effected by a pitch or base circle block and steel tapes. The work gear oscillates under the grinding wheels as the upper work table reciprocates rapidly at right angles to the axis of the gear.

Helical gears require that an additional rotation be superimposed on the generating motion, the magnitude and direction of which is dependent upon the helix angle. This is effected by a sliding block and guide which impart transverse motion to the tape support stand in proportion to the axial feed motion. The lateral movement of the tape stand is converted by the pitch block and tapes into the additional rotary motion required.

Axial modification of the gear teeth is also effected by the axial feed motion which independently shifts the grinding wheels laterally in timed relation to the feed stroke by means of a cam-operated, hydromechanical reducing feed system.

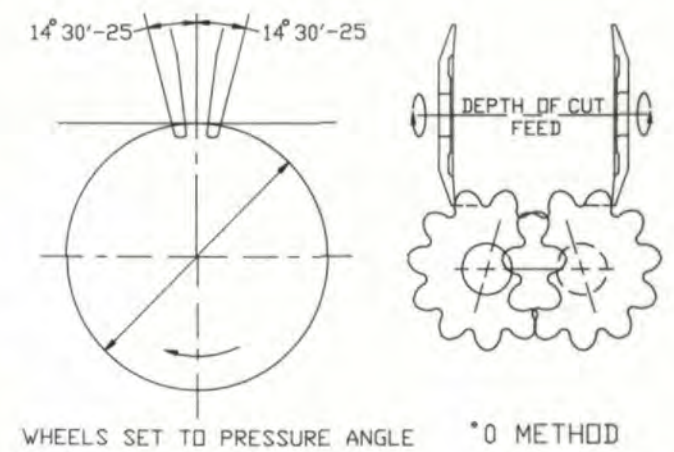
The grinders employ a 15/20° method and a 0° method. In the 15/20° method, the grinding wheels are inclined at the pressure angle of the gear to be ground, and the pitch block coincides with the pitch circle of the gear. This method produces the familiar criss-cross grinding pattern and is the easiest to set up. The 15/20° method has the advantage that the rim of the saucer-shaped grinding wheel produces a generated fillet curve. The 15/20° method is not suitable for grinding profile or axial tooth modifications.

The 0° method is an extension of the 15/20° method. The parallel grinding wheels are set at 0° pressure angle, and a pitch block, which coincides with the base circle of the gear to be ground, is used. Theoretically only one point on the rim of the saucer-shaped grinding wheels contact the work. This method has the advantage of being two to three times as fast as the 15/20° method, and it also makes profile and axial tooth grinding modifications possible. Since the contact point on rim of the grinding wheel generates a cusp, it is necessary to protuberance-cut gears to be ground with the 0° method in order to avoid undesirable ridges in the root fillets.

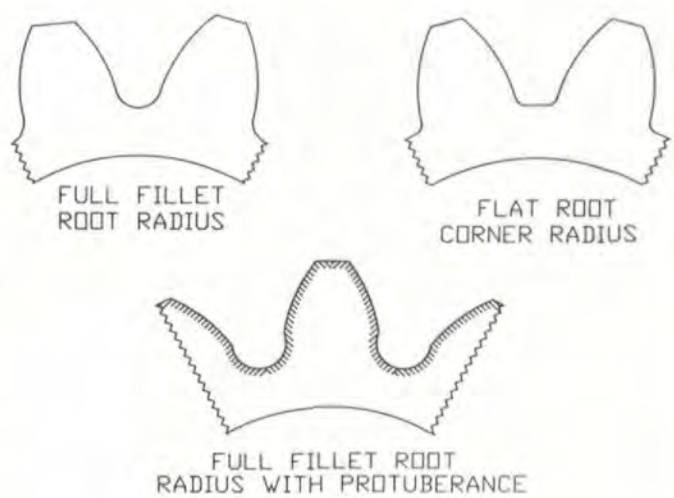
The following ranges of specifications for grinding wheels are recommended for use with dry, saucer-shaped generating wheels: (32A/38A) (46/80) (H/L) (5/9) V.

Theoretically the rim of the saucer-shaped grinding wheel contacts the tooth flank at one or two points, depending upon the angle setting of the wheels. The point generation method removes metal at a relatively slower rate than form grinding, but generates less heat and thereby obviates the need for grinding coolants or oils. The grinding dust is removed by a dust collector provided with the machine.

The vertical column, which can be swivelled to



DISH-SHAPED WHEEL GEAR GRINDING METHOD



the desired helix angle, supports the two separately powered grinding wheelheads. The grinding head slide can be adjusted vertically to accommodate different gear sizes. The individual grinding heads can be swivelled to the angle corresponding to the gear pressure angle or to vertical for zero-angle grinding. The grinding heads are also displaced laterally for various pitches.

In order to compensate for tooth beam deflections under varying loads, it is desirable to relieve the tooth profile at the tip and the flank. Profile modifications are achieved by a hydromechanical, cam-operated system, which moves the grinding spindles laterally in timed relation with the generating stroke.

Grinding Wheels

Grinding wheels have five wheel specifications to control them. They are abrasive, grit size, grade (hardness), structure, and bond.

Abrasive: Aluminum oxide is the most common abrasive used to grind gear teeth. Cubic Boron Nitride (CBN), referred to as Borazon,™ is being introduced as an alternative abrasive.

Grit size: Generally 50 to 80 grit size is used to grind carburized and hardened gear teeth. Micro-finish is a prime factor in judging what grit size is required.

Grade: Soft to medium grade (H, I, or J) is a good start for hard gears.

Structure: Structure should be medium, between 6 and 7.

Bond: Generally a vitrified bond is used. Vitrified wheels perform best on precision grinding where form is required to be held.

Wheel surface feed is important, and in most cases, 4,000 to 5,000 surface feet per minute is a desirable speed.

Basic Grinding Rules

The harder the part, the softer the grade.
The finer the grit, the better the finish.
Decreasing the surface speed will result in a softer effect of the grade.
Decreasing the surface speed will reduce tempering, but will effect wheel form.

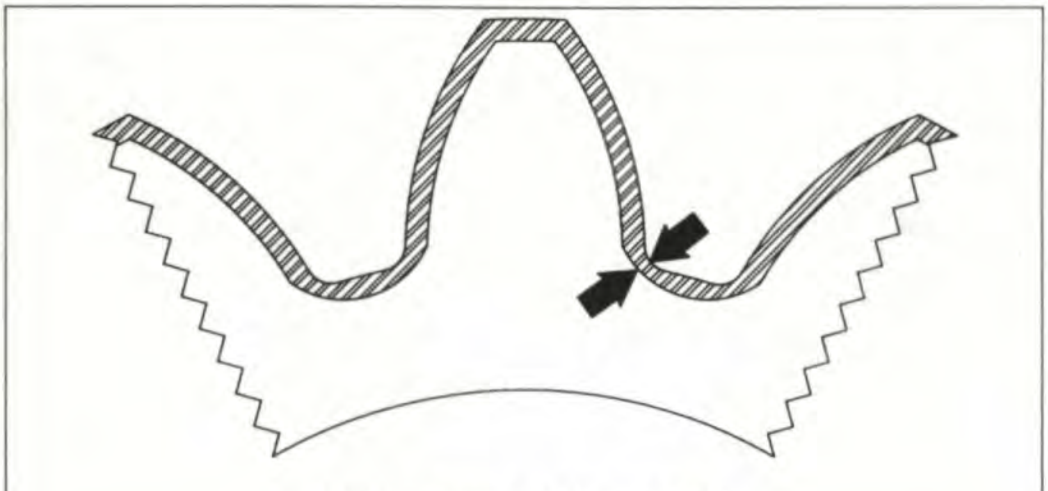
Form Gear Grinders

The form gear grinder is capable of grinding both external and internal spur and helical gears up to 36" in diameter. The machines have capacity for diametral pitches from 64 to 2. An automatic grinding cycle is provided which reduces the necessary reliance on operator skill, and, at the same time, increases the accuracy of the gears ground on a production basis by insuring exact repeatability of the selected optimum grinding cycle.

The gear to be ground is carried between centers in the index head and the tailstock. The index head, tailstock, and the dresser are mounted on the work table, which reciprocates under the grinding wheel. The grinding wheel head is mounted on column ways and supported by a grinding feed mechanism, which raises the grinding wheel after automatic dressing at finish size.

On the older machine models, the two diamond tools which dress the grinding wheel are actuated by templates through reduction cams or pantographs. The grinding wheel is dressed with sufficient accuracy to produce tooth profiles ground within a tolerance band of 200 millionths (0.000200) of an inch. Since the dresser is cam-actuated, non-involute tooth forms, such as cycloidal teeth, Wildhaber-Novikov gears, straight-sided splines, and parallel-sided splines, as well as half-round bearing grooves, can be produced with equal ease and accuracy.

Current dressing technology uses numerical



SHALLOW CASE DEPTH IN ROOT FILLETS

controlled dressers, which have ball screw feeds. They are more accurate and much easier to set up. The dressing of the wheel provides an exact duplication of the tooth space of the part being ground. This includes the profile, root, and root radius, and determines the tooth thickness.

The gear is indexed by accurately ground, hardened index plates with the number of gashes corresponding to the number of teeth in the gear to be ground. Gears are normally ground with a maximum tooth spacing variation between adjacent teeth of 200 millionths (0.000200) of an inch. The lead produced is within 100 millionths of an inch per inch of face width.

GEAR GRINDING MACHINES

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The grinders also equipped with crowning or axial modification devices. The vertical motion of the grinding wheel is superimposed on the grinding feed and produces a fully crowned tooth or end ease-off designed to prevent end loading of the teeth due to mounting support deflections under varying operating loads.

The automatic grinding cycle reduces the hazard of surface tempering. However, additional insurance can be had and better finishes obtained by using a high grade, well-filtered, sulphurized or chlorinated grinding oil.

Recommended grinding wheels are vitrified aluminum oxide wheels with 29A semi-friable or hard brittle universal 38A abrasive. The grain sizes vary from 46 to 80 for combined rough and finish grind. The hardness varies from H to J, and the structure from a medium 5 to 9. The grinding wheel range is (29A/38A) (46/80) (H/J) 5/9/ V.

Conclusion

Production time estimates must be used with caution. Appreciable deviations from the estimated grinding time will be effected by variations in the accuracy required, gear blank quality, grinding stock, grinding cycle, grinding wheel used, coolant efficiency, tooling loading fixtures, etc.

A direct comparison of the gear grinding cycle time with the cycle time of other gear tooth finishing methods, such as finish cutting, shaving, and honing, does not reflect the true relative cost of producing ground gears with the cost of producing quality unground gears. Gear grinding can effect substantial cost savings in cutting, perishable tools, and inspection. Studies have shown that hardened and ground precision gears may cost less to product than comparable unground gears.

Acknowledgement: *This article was presented at the AGMA Gear Manufacturing Symposiom, April 1-3, 1990, Cincinnati, OH. Printed with permission of the copyright holder, the American Gear Manufacturers Association, 1500 King Street, Suite 201, Alexandria, VA, 22314. The opinions, statements, and conclusions presented in the paper are those of the Author and in no way represent the position or opinion of the AMERICAN GEAR MANUFACTURERS ASSOCIATION.*

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Our Experts Discuss...

William L. Janninck

Question: ***I have just become involved*** **with the inspection of gears in a production operation and wonder why the procedure specifies that four involute checks must be made on each side of the tooth of the gear being produced, where one tooth is checked and charted in each quadrant of the gear. Why is this done? These particular gears are checked in the pre-shaved, finish-shaved, and after-heat-treat condition, so a lot of profile checking must be done.**

Answer: The involute or profile check is one of the elemental checks made during the process of inspecting gears. The others include lead or parallelism, tooth spacing, and runout. In this case, reference is made only to the element of profile, which is usually based on a modified involute curve, where the modifications may include tip relief or both tip and root flank relief, called involute crowning. Routinely, the results of this check are recorded as a trace on a chart, and the results are verified by reference to a profile diagram or "K" chart, usually supported by some additional written dimensional limits, such as profile inclination, form inclination averaging, form reversals, holes, or steps.

Ordinarily, the profile check is made in the center plane of the gear tooth face, and this only shows the conditions in a very narrow band traced by the sensing stylus. In other words, the check only examines a very narrow slice of the entire tooth flank. Consider that usually many teeth in the gear are tested. Then checking only one trace on one tooth is a poor way of judging the profile merits of the entire gear. Checking four teeth approximately 90° apart yields a better sampling of what might exist on the gear, but is still not a good sample size if the gear comes from an unknown source. But in this case at least, different teeth are examined in four separately removed regions on the gear circumference.

One does not freely accept the use of such a small sampling on the profile until there is some evidence that the process is consistent and is under control. At least a few gears must be checked for profile in a number of positions across the face, as well as many teeth around the gear perimeter, to assure this. The shaving process, for example, does have a consistency in its process, and the four profile checks are reasonably sufficient once some historical data is developed, and the gear is in production.

On gears with smaller numbers of teeth, the runout error can cause a scattering of the involute traces for the four quadrants checked. Frequently the overall profile error from tip to root, taken from the four checks, is averaged, cancelling the runout effect.

Then, of course, the same inspection procedure must be done for the opposite tooth flank, usually working to the same tolerances. Planet gears and idler gears must work on both flanks, while other gears may be identified as to driving or following flanks and might be toleranced separately.

The quality demands made on gears specifically for involute or profile control are usually related primarily to the final quality level required and secondarily to the manufacturing methods employed. When the gear shaving process

SHOP FLOOR

is used to finish-machine a gear, then considerations of certain interim quality levels between the pre-shave cutting of the gear and the shaving process are essential, because in the shaving process, no external rotational control is present, and the gear being shaved is its own steering or guiding element, and its pre-shaved accuracy will affect the final shaved accuracy level. In other words, pre-shaved accuracy can control the results after shaving. The better the gear before shaving, the better the gear after shaving.

If a gear is subjected to a heat treating process after the shaving operation, then the gear must be again inspected to assure the final quality level is met. Obviously this means some adjustments and

William L. Janninck

is a consultant for ITW-Illinois Tools, a division of Illinois Tool Works, Inc. He has nearly 40 years' experience in engineering and manufacturing. He is a member of AGMA and ASME and is the author of many articles on tool applications, gaging, gear designs, and gear inspection. To contact Mr. Janninck, circle Reader Service No. 45.

allowances must be prescribed in the dimensioning of the shaved profile in anticipation of changes during the thermal processing.

Today some of the monotony associated with manual profile inspection, recording, and analysis can be reduced with the use of programmable computer controlled gear inspection equipment. It can also be highly useful when extensive checking must be done when doing developmental work or doing troubleshooting work.

Question: As we monitor the wear occurring on hobs in our gear cutting operation, we notice that some different wear patterns develop. Most of the time they appear as edge wear where a definite wear land on the hob tooth side flank develops. At other times, the edge wear seems less, but a definite wear gouge occurs on the hob tooth cutting face. What causes the differences?

Answer: Factors involved in the development of wear patterns on rotary cutting tools, such as gear hobs, include the work material, hardness and microstructure, tool material, hardness, surface finish, surface treatment and special coatings, machine-tool-work rigidity and guidance, hob shifting methods, cutting speeds, feed rates, and coolants. Even things, such as climb or conventional cutting, and gear part geometry, such as helix angle or pressure angle, can have an influence.

In spite of all these variables, we can make some observations of average results seen on the cutting of typical carburizing gear steels being cut in the 180 BHN hardness range using uncoated hobs made of M-2 or M-3 high-speed steels. Usually the wear patterns observed can be divided into four categories. First, edge wear; second, face gouging or cratering; third, edge chipping; and last, peel back.

Edge wear alone is frequently found on single start or single thread hobs, where feeding the hob fast enough to utilize available machine power is possible. Because of the many available hob flutes and a limited feed rate, the tool cutting edge flank is abraded. This is due to a light chip load per tooth and is caused by skating or rubbing. This condition can be seen on any hob being applied with a light chip load per tooth.

Cratering is usually the result of substantial feed rates coupled with the use of high production, multiple-start hobs. The available power of the hobbing machine can be utilized, and substantially heavy chip loads are imposed on the hob tooth face, abrading away a pocket or crater area near the cutting edge where the chip impinges. Edge or flank wear, although also present, usually appears less severe when compared with the amount of cratering. If the crater wear approaches the cutting edge, it is probable that edge chipping will ultimately occur.

Chipping can also be caused by brittleness at the cutting edge from higher hardness, higher alloyed, high-speed steels, or from a surface treatment, such as nitriding. If a chip does occur, and the tool continues running, further edge damage can be seen as a washed out area nucleating at the chip. This is called peel back, and usually the evidence of the originating problem, such as a microchip, is gone. Peel back can progress very quickly when a tool is operating at high production speeds and feeds.

The use of titanium nitride as a tool coating has proven successful at deterring tool wear on hobs used in cutting steel materials. A single coating which remains on the side flanks of the hob, even after the face sharpening operation, is helpful when flank wear is predominant. If cratering occurs, then the recoating of the tools may be necessary after each sharpening to protect the tooth face. ■

Address your gearing questions to Gear Technology, P.O. Box 1426, Elk Grove, IL, 60009, or call (708) 437-6604.

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Early European Gear Applications

Nancy Bartels

a double-stage reduction gear system powered this hand-driven mangle from about the mid-1700s. The padded rollers were heated and pieces of linen, such as sheets and tablecloths, were forced between them for ironing. In an era when families were large and castles often numbered bedrooms in the dozens, this device was a lifesaver in the laundry room.

a hand-powered machine from the mid-1700s used to form band iron into wagon wheel rims. A double-stage reduction gear system is employed to move a set of adjustable rollers. To bend the rim to shape, the strip of heated metal was forced between the sets of rollers, which are on different levels. The rollers are connected by a screw, which can be adjusted to change the diameter of the rim. After forming, the ends of the metal rim were welded together around the wooden wheel by heating and hammering.

The gear is one of the oldest and most versatile mechanical devices used by humans. Examples of gearing have been found in our most ancient cultures, like China and Greece, and, because of their usefulness in such a wide variety of applications, they appear nearly everywhere. Here we show photos of gear-driven machinery from the mid-1700s and early 1800s. The photos were taken by our technical editor, Bill Janninck, at the Roscheider Hof Folk Art and Outdoor Museum in Konz and in Saarburg, Germany.

two views of a right angle drive, also from the late 1700s, used for powering a water wheel for a mill. These gears are of interest because the teeth are wooden. The metal rim was formed with slots (see top picture) for the teeth, which were shaved to fit and fixed into the slots later. When single teeth broke or wore out, they were easily replaced.

this worm gear mechanism, dating from the early 1800s, still raises and lowers sluice gates in the River Saar. The horizontal shaft at the top drives the two worms. They mesh with their worm gears, which, in turn, drive a special pinion in mesh with the plate-and-pin racks. These racks raise and lower the sluice gates as needed.