GEAR TECHNOLOGY
THE JOURNAL OF GEAR MANUFACTURING
MAY / JUNE 1993

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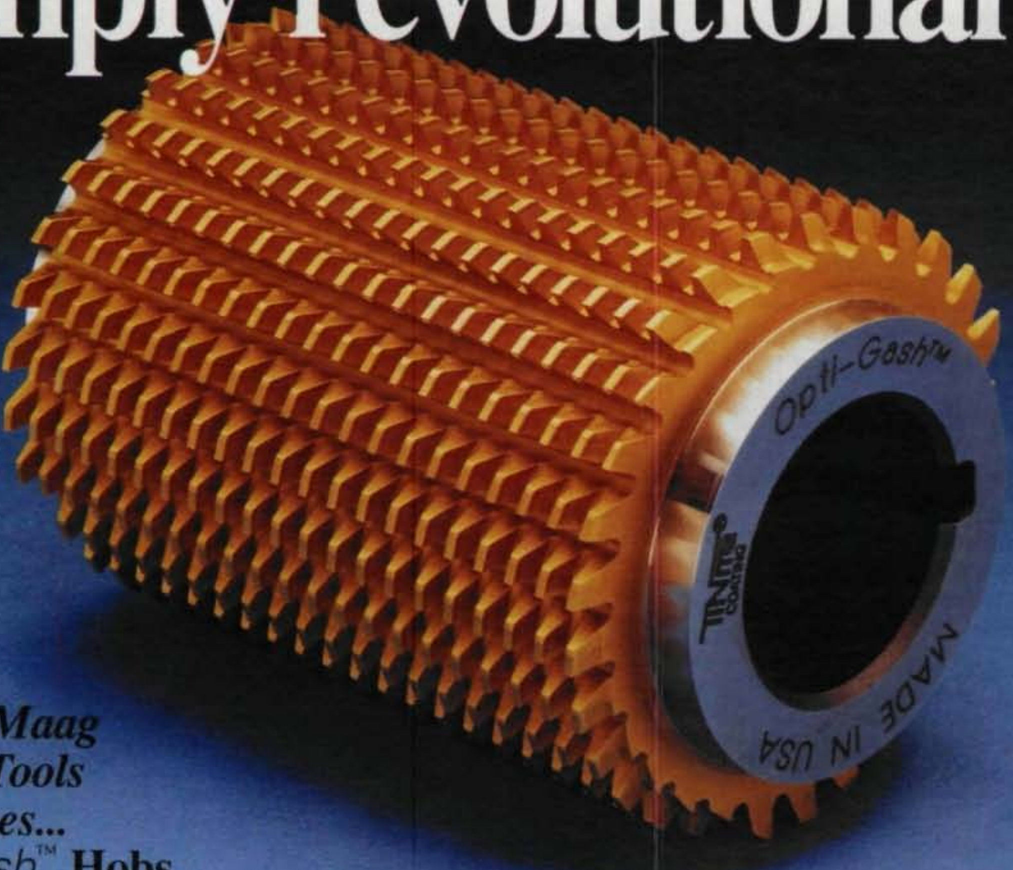

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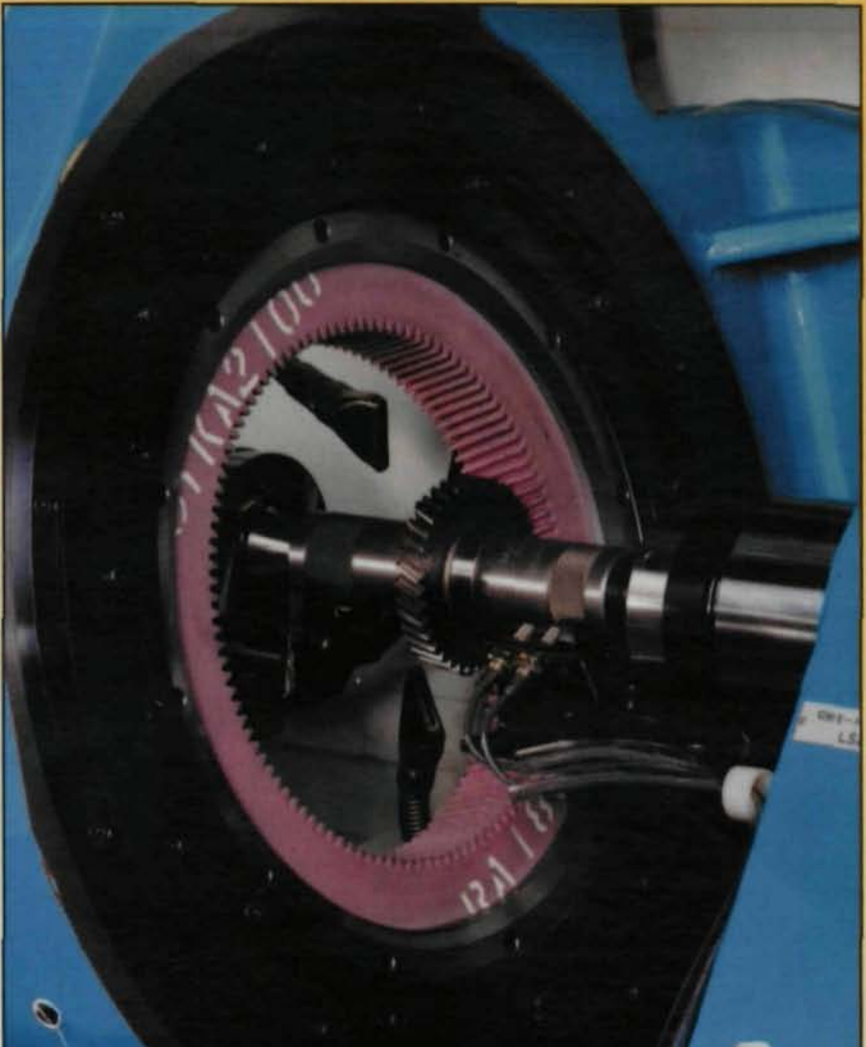


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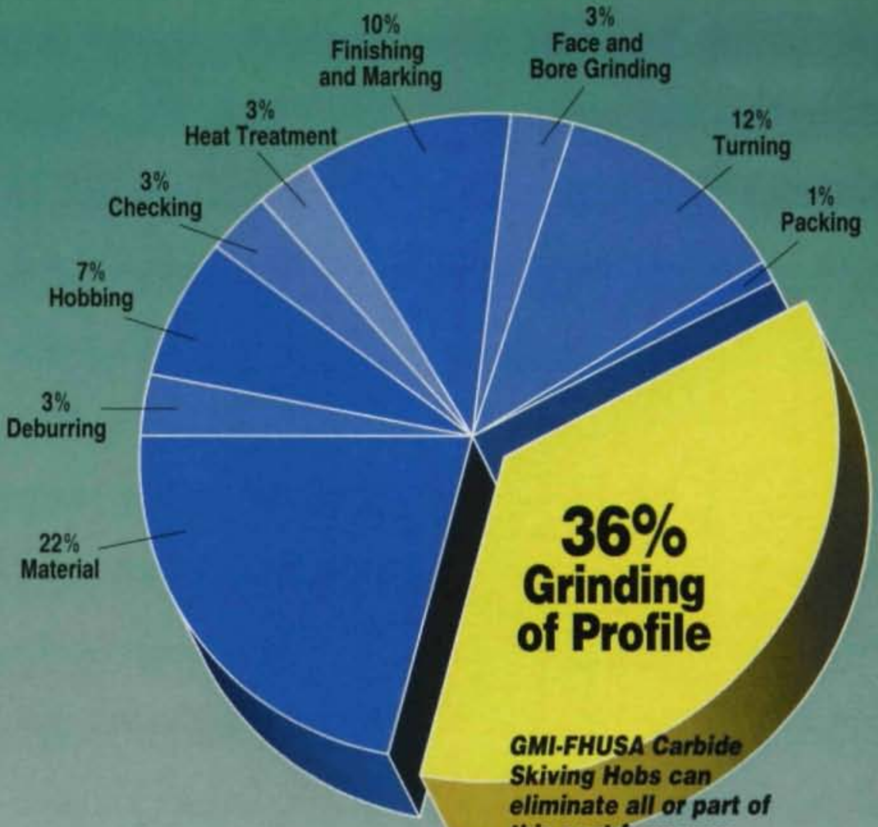

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GMI-FHUSA
At the Cutting Edge!

The Limits of the Computer Revolution

PUBLISHER'S PAGE

In this issue of *Gear Technology*, we are focusing on using computers to their greatest advantage in gear design and manufacturing. In a sense, that's old news. It's a cliché to suggest that computers make our work life easier and more productive. No company that wishes to remain competitive in today's global manufacturing environment can afford to be without computers in all their manifestations. We need them in the office; we need them next to our desks in place of drafting boards; we need them on the shop floor.

The challenge is no longer to integrate the computer into our work lives, but to keep up with the technical advances in computing that seem to come along faster than we can absorb them. Sometimes it seems as though we have to keep running faster and faster just to keep even. But in the end, the effort always seems worth it. The new technology makes possible operations that previously were impractical, too expensive, or simply not doable. It opens doors that once were firmly locked.

In this issue alone, we cover computer software that will help make design decisions, assess the possibility for reusing old tooling, and even train the computer to begin to "think" like an engineer. That's pretty exciting stuff.

While acknowledging the scope of this kind of progress and the justifiable excitement about it, I'd like to raise a small, cautionary note. In our eagerness to embrace the latest and greatest in computer technology, let's remember that the best computer hardware and software in the world is still no substitute for solid engineering training and experience. A computer is still only as good as the people who work with it, and it cannot pluck a gear design from air. Someone who knows what good gear design is has to tell that to the computer before it can begin its analysis.

An instructive analogy can be drawn from the world of publishing. In the last five years, computerized publishing has literally revolutionized the way that printed material is produced. Skills like typesetting and designing, that were the product of years of training, are suddenly available in a software package for less than $500. Programs are now available that will lay out the pages of a magazine in hours, a process that used to take days of tedious hand work by a person trained in art and design. If one believes the ads and the literature, for less than $10,000 you to can purchase "everything you need" to do your own magazine, advertisements, or newsletter.

Well, yes and no. The desktop publishing lesson that many companies have learned to their sorrow is that buying the latest hardware and software and

There is still no substitute for a solid engineering education and experience in the field.

PUBLISHER'S PAGE

investing in a training course about it does not make your secretary a designer or a writer. A software package may enable someone to lay out the pages of a newsletter on the computer, but it doesn't teach that someone anything about design, use of typefaces, balance, or any of the other things that go into making an attractive, readable printed piece. Page design software in the hands of the unskilled just lays out ugly pages very quickly and efficiently. Any editor can tell you that you trust the spellchecker on your word processor to catch all the errors at your peril, and that the program has yet to be written that grasps the subtleties of English grammar and syntax.

The lesson for gear engineers is clear. There is still no substitute for a solid engineering education and experience in the field. If we allow ourselves to fall into the habit of trusting the computer to provide all our design solutions, we overlook all the answers that fall outside the parameters for which the computer has been programmed. Until the computer is built and programmed that can take all of an engineer's training, experience, and intuition, and apply them to problems in unique ways that have never been tried before, engineers will still need to think beyond the limits of what a computer can analyze.

One of the great blessings of the computer is the freedom it gives: The freedom from tedious, repetitive work; the freedom to multiply the number of possible solutions to a problem; the freedom to ask, "what would happen if," and eliminate bad answers with the touch of a delete key. The other side of the coin is the danger of giving away our freedom by depending too heavily on the computer. If we allow ourselves to be awed by what the computer can do so much faster and more efficiently than we can, we forget the many more things the computer can't do at all. If we allow ourselves to become dependent on the computer for all our answers, we give away the very freedom the computer gives us.

A wise man once defined education as being able to differentiate between what you do know and what you don't... knowing where to go to find out what you need to know... and knowing how to use the information once you get it. These are still the responsibility of the engineer. These are the things the computer cannot do for us. This kind of knowledge is acquired only by experience and hard work; by cracking the books; working out the calculations (with or without a computer); watching the machinery work in the field — and sometimes watching it fail and then tearing it down to see why — by trusting your instincts informed by your past experience; by allowing a spark of inspiration to flare and see what it lights up.

The sum of all these parts is what makes a good engineer. A good computer system can help hone them, make them more efficient. What it cannot do is substitute for them.

None of us has the option of signing on for the computer revolution. We've been drafted. And none of us would want to give up our computers any more than we'd want to go back to the days prior to the industrial revolution. But let's not be deceived: Computers have freed us from the tedious and repetitive tasks only to make us available for the infinitely harder and more challenging work of being good, creative engineers.

Michael Goldstein

Michael Goldstein,
Publisher/Editor-in-Chief

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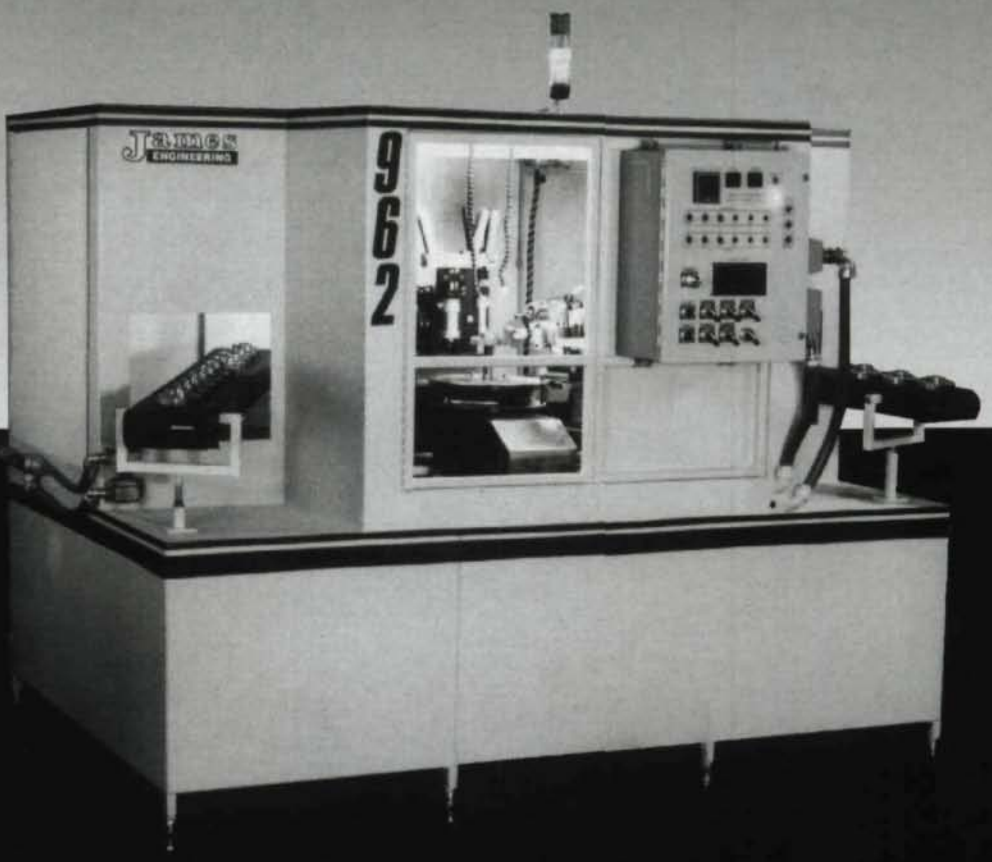

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Delivering The Goods

A good freight forwarder can help you with the important business of getting your goods from here to there, when "there" is overseas.

Nancy Bartels

One of the key questions to be answered when exporting is how you are going to get your product to your customer. All the time, effort, and money you've spent to make a sale in the first place can be wasted if the shipment is late, damaged, or lost, or if delivery becomes an expensive bureaucratic nightmare for either you or the buyer.

Efficient and affordable shipping is also an important marketing tool, all the more so when exporting. Being able to guarantee delivery under certain terms and conditions can make the difference between a sale and a "no thanks." And money saved or spent in shipping is bound to impact your bottom line.

It is, of course, possible to handle all the nuances of overseas shipping on your own, but the process is time-consuming and, to the untrained, full of pitfalls; and correcting mistakes in delivery overseas is twice as complicated as doing it here. Especially for the newcomer to exporting, leaving the important business of getting your product from here to there may best be left in the hands of an expert — a freight forwarder.

Call Early and Often

Because terms and conditions of delivery can be important negotiating points in an overseas deal and because knowing up front how much shipping will cost is important to pricing, get your freight forwarder involved early in your export plans. It's not a bad idea to go to a freight forwarder even before you've made your first overseas deal, just to learn the ground rules. And this initial research shouldn't cost you a cent.

> **Being able to provide your customer with efficient and affordable shipping is an important marketing tool. Being able to guarantee delivery under certain terms and conditions can make the difference between a sale and a "no thanks."**

Mr. Henry Gayheart, branch manager of Wilson UTC Chicago, a freight forwarding company with offices all over the country, says, "I've never heard of a freight forwarder who is not eager to give information out for free. They wouldn't even think of charging for giving advice to a new exporter. Call or visit their office and ask the questions you need to ask."

These questions should include the kind of docu-

MANAGEMENT MATTERS

Managing a business today is hard work. Let "Management Matters" lend a hand. Tell us what management matters interest you. Write to us at P.O. Box 1426, Elk Grove, IL 60009, or call our staff at (708) 437-6604.

Henry Gayheart
is branch manager of Wilson UTC Chicago, IL. Wilson UTC is a freight forwarding company with offices thoughout the United States.

mentation needed in various countries, special regulations that might apply, advice about packaging and means of transportation, kinds of insurance, comparative costs, required inspections, and anything else you might need to know about shipping overseas. Later, when you've chosen a forwarder, you will be charged on a per transaction basis. Costs will generally run between $75-$125 per transaction, depending on location.

Defining Your Terms

Another subject you may wish to discuss with your freight forwarder early in the export process is "incoterms." This is the special language of overseas shipping — one that it's important for you to know because it will impact on how successful your export operation will be and also because it will help you and your freight forwarder define your (and, therefore, his) responsibility for particular shipments.

Incoterms define whether you or the buyer will assume shipping costs and the conditions under which title to the goods will be transferred. They also define whether you or the buyer is responsible when goods are lost or damaged. Incoterms provide a common language for you, your customer, and your freight forwarder, so each of you knows precisely what has been agreed to, thus cutting down on possible disagreements among you about who is responsible for what.

Incoterms cover all the possible combinations of responsibility. You may sell your goods "ex-works" or "ex-factory." In that case, the buyer takes delivery off the edge of your loading dock. He is responsible for the cargo after that, paying for all shipping, insurance, customs charges, etc. The other extreme is "delivered duty paid." If you agree to this arrangement, you are the one responsible for the goods until the point when they are placed on the buyer's dock.

Most sales fall somewhere between these two extremes. You should be familiar with the possible choices because they will have an impact on your pricing and other marketing strategies. They can become important negotiation points in an overseas deal.

Your freight forwarder must know what terms you have agreed to because they will certainly affect the way he arranges for your goods to be delivered. Copies of *Incoterms 90*, the most recent revision, and *The Guide to Incoterms*, a companion volume, are available from the International Chamber of Commerce.

Choosing the Right Forwarder

Because the freight forwarder is such an important part of your export team, choose one carefully. Begin by getting some recommendations. Major steamship companies or international airlines will often give the names and numbers of several forwarders with whom they work regularly. Or ask others who ship regularly overseas whom they use.

Then look at the diversity of the company's operation. Gayheart phrases the question this way: "Does this company have the ability to handle the transport of my products from my door to my customer's door all the way through and control it at all points? Can he control the movement of the cargo so that it doesn't

MANAGEMENT MATTERS

Common Incoterms

Free Carrier (at a named port) — In this arrangement, the title to the cargo is transferred when it is loaded on a ship at the named port. As seller you must pay for getting the goods there and any inland freight, containerization, and loading charges, and you must provide the buyer with a clean bill of lading.

FOB Airport — You must deliver the shipment to the airline at the specified airport. At that point title transfers to the buyer.

Free Along Ship (FAS) — You are responsible for all costs to get the shipment alongside the carrier vessel. The buyer is responsible for clearing them for export and loading them.

Cost and Freight — You pay to get the shipment to the named port; the customer assumes the risk for loss when the goods are delivered to a named carrier at the port.

Cost, Insurance, and Freight — You are responsible for all C&F costs, plus insurance. Title belongs to the buyer once the shipment is delivered to the named port.

sit someplace, and can he be responsible for it at all times? It is rare that a shipment will require that kind of complete control, but it's a good test of a freight forwarder because it shows how deep they are, how much investment they have both here and abroad. It's an indicator of the forwarder's ability and experience.

"You want a forwarder who can say to a shipping company, 'I want you to handle these ten cartons the same way you handle the other 10,000 I send you every year. I want special handling, and I want to know where this shipment is at all times.'

"You also want one with the ability to change gears quickly. If you need to change your instructions from, say, shipping by ocean to air because a customer needs delivery in a hurry, you want the freight forwarder to be able to say, 'No problem.' "

Another important criterion in selecting a forwarder is financial strength. Freight forwarders must be licensed by the Federal Maritime Commission, but that license is not difficult to get, and it alone is no guarantee that a company is reliable. Says Gayheart, "When you ship with a freight forwarder, you want to ship with someone who has been around for a while and also is going to be around in the future. You're building a relationship that you want to last. As your export business increases, you want this forwarder to be there for you the whole time."

The third important thing to look for in a freight forwarder is personnel. Check employee turnover rate. Ideally, the forwarder will assign one person to your account, and you will work with him or her exclusively. "You don't want someone who's only going to be there long enough to learn your special needs and then be gone, leaving you to start over," says Gayheart.

He adds, "You don't want to work with a company that doesn't take care of its people, where people have a bad attitude toward management, and, therefore, a bad attitude toward their customers. You want people that are respected and held in high regard in the industry. [Freight forwarding] is a people to people transaction. Freight forwarders don't normally own trucks, aircraft, or vessels. They are people who are making telephone calls, going out and looking at cargo, giving advice, telling other people what to do. The most important thing about freight forwarding is really communication."

Communication Is Everything

If, "the economy," was the president's watchword during the campaign, yours should be "communication," when dealing with your freight forwarder. Says Gayheart, "The first thing a customer should have is a clear knowledge of what he wants the freight forwarder to do and what the freight forwarder's responsibility is. There has to be a clear understanding of what the trading terms are, at what point the importer's responsibilities begin, etc."

The medium for this communication is the transmittal letter. It should contain your detailed and precise instructions to the freight forwarder. It should tell your forwarder where the shipment is, when it is to be moved, how, where it's going, when it has to be there, who's picking it up from your dock, whether you want it sent air or ocean freight, and anything else that's pertinent. In short, this letter should explain in detail exactly what you want to happen to your shipment. The clearer and more detailed this letter is, the fewer hassles will occur along the way.

> **"Freight forwarding is a people-to-people transaction. Forwarders don't own trucks, aircraft, or ships. They are people making phone calls, going out and looking at cargo, giving advice... The most important thing about freight forwarding is really communication."**

Getting Your Papers in Order

The transmittal letter is only the first of a whole pile of documents that lie at the heart of any overseas transaction. Gayheart says, "These documents assure the buyer that he gets what he's contracted to get. They help assure the seller that he gets what he contracted for, which is the money. They also assure the seller that his cargo is handled properly, so that his customer is satisfied and perhaps re-orders."

He underlines their importance by adding, "The movement and flow of the documents is what makes the cargo move from point to point. The cargo does not move unless the documents move."

Among the documents that will be required to move your cargo are:

The commercial invoice. This is the basic document in any overseas transaction, and a copy of it needs to go to your freight forwarder. It contains the terms of the sale, who is paying for what part of the shipping, insurance, duties, and fees, and the basic details about the cargo, the number of packages, the weights, dimensions, etc.

The letter of credit. Many overseas transactions will involve a letter of credit. A letter of credit is important because it guarantees the one thing that you as the seller want to be sure of — that you're going to be paid for this merchandise. On the other side, the buyer will want certain guarantees as well, which will also appear in the letter of credit.

Gayheart explains, "A buyer may say, 'I'll guarantee payment, but I also want to guarantee the quality of the goods, the date of delivery, and their condition.' The letter of credit may dictate the mode of transportation, the type of packaging, certain inspections."

If your transaction involves a letter of credit, be sure your forwarder gets a copy of it well before the shipping date. Says Gayheart, "Your forwarder will go through the letter and advise you as to whether or not you can live up to your side of this bargain. For example, it's common to have language in the letter of credit that says, 'no transshipments.' But it may very well be that you can't get this product to its destination without transshipping it, so your forwarder can advise you to have this language taken out.

"He or she can also advise you about packaging, inspections, or other stipulations in the letter of credit. The forwarder needs to know all these things, so arrangements can be made to provide for them."

The bill of lading. This is a crucial document because it is a receipt for the cargo as well as a contract for transportation between you, the shipper, and the carrier. It may also be a negotiable instrument which transfers title to the goods. In that case, whoever owns the original bill of lading owns the goods.

Miscellaneous documents. Numerous other documents need to accompany or precede your shipment to its destination. These papers include various export licenses, packing lists, dock receipts, insurance certificates, and clearances. Your freight forwarder will help you gather these together and see to it that they are in the right place at the right time for your shipment to proceed smoothly.

Getting your goods from Point A to Point B on time, in good condition, and at an affordable price is the name of the game in successful exporting. Choosing a good freight forwarder, communicating your needs to him clearly, and listening to his or her advice are key steps in a winning strategy that will put your company among the winners in this global game of the '90s. ■

CALENDAR

MAY 11-12

SME Broaching Technology Clinic. Hyatt Regency Woodfield, Schaumburg (Chicago), IL. For more information or registration, call Mike Traicoff at SME Headquarters, (313) 271-1500, x596.

MAY 20-22

AGMA 77th Annual Meeting. The Grove Park Inn, Asheville, NC. Theme of the meeting is "Competitiveness." For more information, call AGMA Headquarters, (703) 684-0211.

JUNE 8-9

SME Fundamentals of Gear Design & Manufacturing Clinic. Embassy Suites-Livonia, Livonia (Detroit), MI. Call SME Headquarters, 271-1500, x596 for more information.

JUNE 14-18

AGMA GEAR TRAINING SCHOOL, IIT Research Institute, Chicago, IL. Covering basics of hobbers, shapers, and inspection. Call AGMA Headquarters, (703) 684-0211.

JUNE 21-22

"Micro Computer Application." University of Wisconsin-Milwaukee. Two-day seminar to provide a framework within which the student may develop a computer-aided gear design system suited to individual needs. For more information, contact Richard G. Albers, Center for Continuing Engineering Education, UWM, (414) 227-3125.

Practical Optimization of Helical Gears Using Computer Software

Rodrigo López Sansalvador & Juan Carlos Jáuregui C.
Centro de Investigación y Asistencia
Técnica del Estado de Querétaro A.C.

Summary

The aim of this article is to show a practical procedure for designing optimum helical gears. The optimization procedure is adapted to technical limitations, and it is focused on real-world cases. To emphasize the applicability of the procedure presented here, the most common optimization techniques are described. Afterwards, a description of some of the functions to be optimized is given, limiting parameters and restrictions are defined, and, finally, a graphic method is described.

Introduction

Before defining optimization techniques and optimum gear design, it is necessary to introduce certain concepts. Any mechanical system, in this case a gear set, can be represented by a model where all the physical properties are approximately reproduced. And in most cases, the system model can be expressed as a mathematical model.

A mathematical model is a model that represents a system by mathematical relationships, and it can be divided into system variables, system parameters, system constraints, and mathematical relations.

A mechanical system can be modelled for two reasons. The first is to evaluate or analyze its behavior. The second reason is to obtain a design. A design is defined by its geometric configuration, the materials used, and the task it performs.

In most cases, there is more than one solution when designing a mechanical system. Therefore, a criterion for selecting the "best solution" must be established.

A design can be modified to generate different alternatives, and the purpose of the study is to define a criterion for evaluating alternatives and choosing the best one. Cost has to be related to another quantity easier to evaluate. An evaluation model that includes an evaluation criterion is a decision-making model, called an optimization model.

The design procedure has four steps:

1. Recognition of a need,
2. Statement of the problem,
3. Creation of alternative solutions,
4. Selection of alternatives.

Searching for the optimum solution is a technique that can become very cumbersome, but basically it can be described as follows:

1. The selection of a set of variables to describe the design alternatives;

2. The selection of an objective expressed in terms of the design variables, which should be minimized or maximized;

3. The determination of a set of constraints, expressed in terms of the design variables, which must be satisfied by any design.

A summary of the formal mathematical treatment of the optimization procedure is related next.

Mathematical Definition of Optimization

Assume that the design variables are named $x_1, x_2, x_3, \ldots x_n$, and that they can be arranged into a vector **x**. It is also assumed that the design variables are real numbers. The objective of the optimization has to be expressed as a function $f(\mathbf{x})$ of the design variables. The constraints are classified as equality and inequality constraints. They also have to be functions of $\mathbf{x}$. Therefore, the constraints of the design must be expressed as:

$h(\mathbf{x}) = 0$ for equality constraints

$g(\mathbf{x}) < 0$ for inequality constraints

Resuming the optimization problem, it can be stated as:

Min $f(\mathbf{x})$ over $\mathbf{x}$

subject to

$\boldsymbol{h}(\mathbf{x}) = 0$, and $\boldsymbol{g}(\mathbf{x}) < 0$

where **h** and **g** are vectors representing several constraint functions.

There are some cases where the designer wants to satisfy more than one optimization function. One alternative is to combine the individual optimization function into a global function if possible. The other alternative is to formulate the optimization problem as

$$\min F(\mathbf{x}) = w_1 f_1(\mathbf{x}) + w_2 f_2(\mathbf{x}) + \dots + w_n f_n(\mathbf{x})$$

with

$$w_1 + w_2 + \dots + w_n = 1$$

But this alternative may lead to an erroneous solution, since the weighting values are selected in a subjective manner.

Depending on each particular optimization problem, there will be a mathematical solution for the proposed model. To prove that the model has a mathematical solution, several aspects can be formulated. These concepts will be extended when explaining the graphical optimization method.

1. *Solution Domain*. It is the isolated region within the space solution defined by the $\mathbf{x}$ variables. The boundaries of the solution domain are the inequality constraints. Any point inside the isolated region represents a solution for the design problem, but only one must be selected as the optimum.

2. *Boundaries*. They are represented by the equality values of the inequality constraints $g(\mathbf{x})$. The absence of proper bounds may cause a serious problem. In many cases, the solution is found at the boundaries of the solution domain.

3. *Monotony*. This is a property of certain functions that for an increment of the independent variables, $\mathbf{x}$ produces an increment or decrement of the function. This property can be exploited because it can be proved that in a monotonic function bounded by a constraint, the optimum is always at the boundaries.

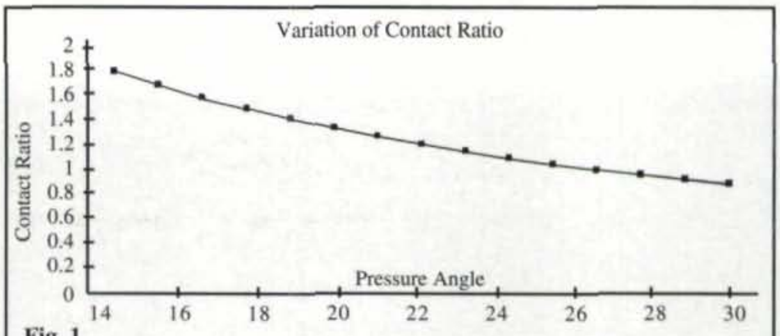

Fig. 1

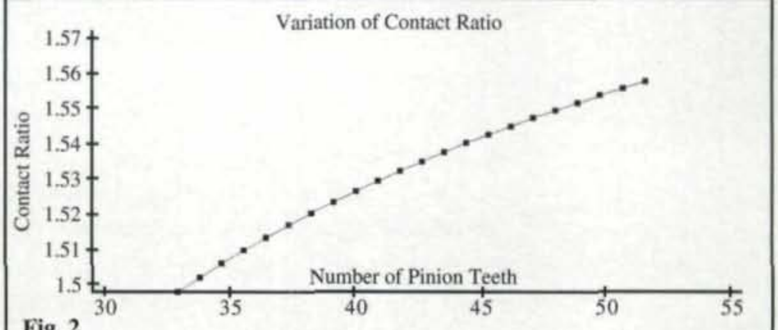

Fig. 2

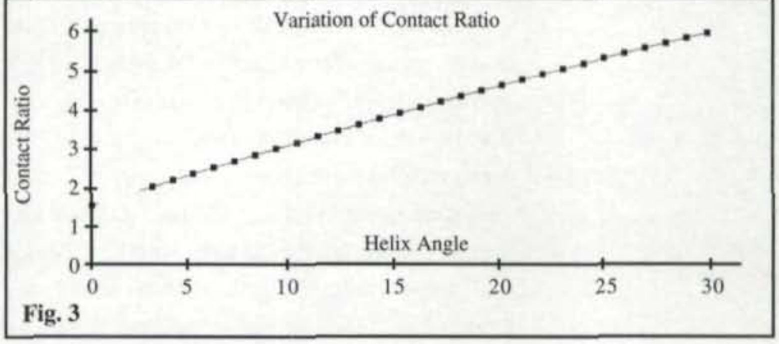

Fig. 3

It is very important to point out that the design functions of gear sets behave monotonically. Examples of this behavior are shown in Figs. 1-3 where the contact ratio is plotted against pressure angle, pinion teeth number, and helix angle. If the objective function is the contact ratio, and the independent variable is the helix angle, from Fig. 3 it can be said that the optimum is at the upper value of the helix angle.

Graphical Optimization Technique for Helical Gears

In previous sections, the optimum design of mechanical systems has been briefly defined, but little has been said regarding optimum gear design. Optimum gear design is a subject that has awakened the interest of engineers around the world, and many papers and articles have been published regarding this subject. Optimum gear design has the particularity that each problem has different objective functions, constraints, and parameters; thus, it is not possible to define a unique procedure for designing optimum gears.

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A more general way of searching for the optimum was studied, and a simpler optimization technique was developed. The algorithms specially developed for optimum design, such as the Reduced Gradient Method, the Gradient Projection Method, Box's Method, Johnson's Method,(1-2) etc., can be very difficult to apply because of the complexity of the mathematical model for gear design. The technique presented here is based on

1. Definition of the objective function based on real needs,

2. Definition of the gear design variables and parameters,

3. Identification of the design constraints,

4. Construction of the solution domain with gear design software instead of by constructing the mathematical model with an optimization program.

5. Graphical representation of the solution design region and conduct of a search for the optimum point. Once the graphical representation of the solution domain is obtained, the location of the optimum is very simple.

The idea of a graphical solution is simple and easy to handle. First of all, the solution domain is all known, and the selection of the boundaries (constraints) and objective functions can be reordinated using a general purpose graphics program. The optimization can be conducted with one or two independent variables (optimization with more independent variables can be obtained by grouping the variables in pairs, leaving the rest of them as parameters).

Objective Function. In optimum gear design, the objective function can be a single function or several functions, depending on each application and each particular case. For instance, the objective function that seems to be most logical is cost. But cost is affected by different parameters, and the engineering definition of cost can be expressed in different ways. For example, an objective function will be to reduce the manufacturing cost. This can be achieved by designing a gear set modifying only the helix angle: therefore, the manufacturing cost will depend only on the settings of the cutting machine. Or the solution will depend not only on the helix angle, but on the teeth number, speed ratio, materials, heat treatment, etc., and the optimization will be more complex.

The definition of the objective function is the starting point of the optimization, and it has to be identified as precisely as possible, in order to reduce time-consuming calculations and problem statements. In the automobile industry, for example, objective functions might be described as noise and perhaps cost. Therefore, the mathematical model for the optimization problem will be more complex.

The relation between the objective function and the mathematical model is determined based on the designer's judgment and experience. Some of these relationships are:

Cost > Teeth Number, Face Width, Cutting Machine Settings, Surface Finishing, etc.

Noise > Contact Ratio, Teeth Number, etc.

Independent Variables and Parameters. The list of variables for designing a gear set is very large. In the examples presented in this article, the independent variables are pinion teeth number, helix angle, and pressure angle. The dependent variables are pinion and gear pitting and bending stresses, contact ratio, length of action, tangential velocity, critical scoring number, and/or speed ratio and center distance. The parameters are material properties, transmitted power, design factors (stress multipliers) AGMA quality level, and/or speed ratio and center distance.

Constraints. Constraints are variables that define the boundaries of the solution domain, and almost any solution of an optimum gear design lies in a boundary. Typical constraints are the minimum life due to bending or pitting stresses, the maximum allowable scoring number, the minimum contact ratio, the AGMA quality level, etc.

Solution Domain. Once the independent and dependent variables and the parameters are determined, and the constraints are defined, the solution domain can be constructed by storing all the calculations performed with a design software into a database. The data can be arranged for producing plots of the solution domain. Fig. 4 shows an example of a solution domain. Then a 3D plot of the behavior of the objective function can be obtained, as shown in Fig. 5. In this example, the objective function is the maximization of the pinion bending life, and the optimum is located at the intersection of the maximum pressure angle and the minimum contact ratio limit. Fig. 6 shows another example where the independent variables are the pinion teeth number and the pressure angle, and the objective function is the contact ratio.

Searching the Optimum. After the solution domain is defined and the database is filled in, the identification of the optimum is a quite simple task. First, define the objective function within the dependent variables. Second, select up to two independent variables for generating the plots. Plot the optimization function with respect to the independent variables. The optimum can be located directly from the plot. If the database is large, the data can be analyzed by blocks of information; in other words, by isolating small regions of the solution domain.

If the gear design problem was defined with more than two independent variables, the former procedure can be used by isolating two of the independent variables, keeping the rest of them as parameters, and locating the optimum for the reduced solution domain. Then with the two independent variables that define the optimum as parameters, repeat the search using another two variables, and so on This procedure may seem quite complicated, but with a general purpose database program, it is simplified.

Example 1. The definition of the problem is as follows:

Objective function — Maximize the contact ratio for a minimum cost.

In this case, cost is related to those parameters that can be modified without affecting the production cost. The helix angle, for instance, has to be set up on the cutting machine, therefore, a modification on its value affects the characteristics of the design without modifying the cost of the gear. Therefore, only two independent variables are selected: helix and pressure angles.

According to the designer's criterion and application of the design, the parameters must be established. For this example, the parameters are

Speed ratio	2
Normal Diametral Pitch	10
Pinion Teeth Number	40
Face Width	2.6
Addendum Proportions	Normal
AGMA Quality Level	10
Material Properties	BHN = 180 Sat = 25,000 psi Sac = 85,000 psi E = 30 X 10^6

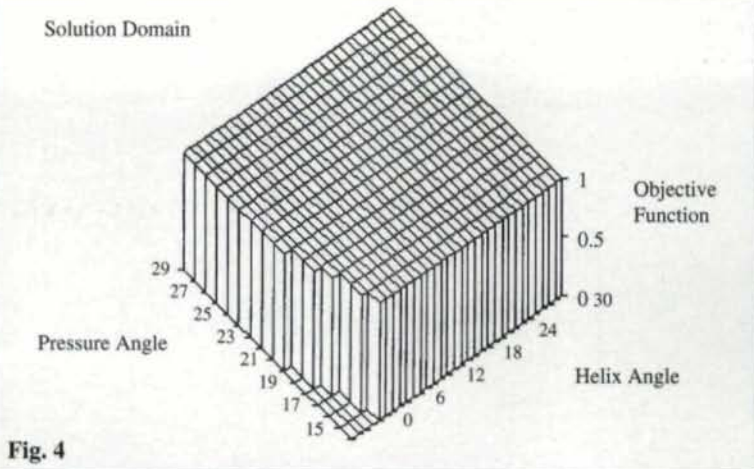

Fig. 4

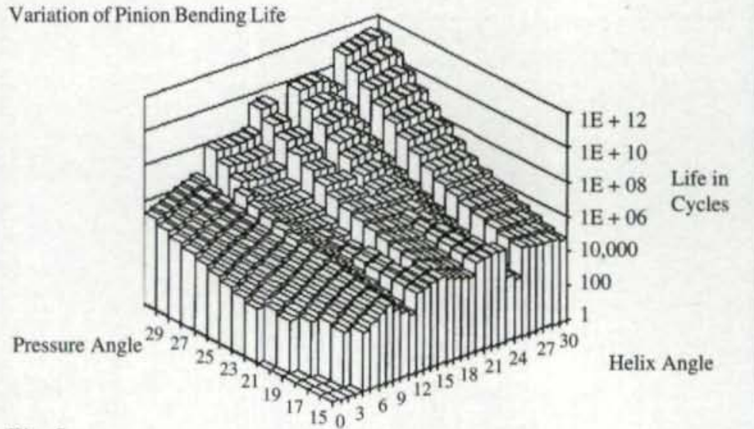

Fig. 5

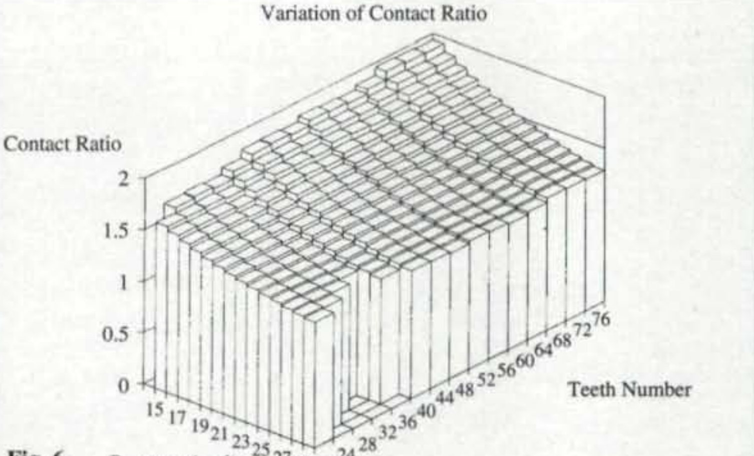

Fig. 6

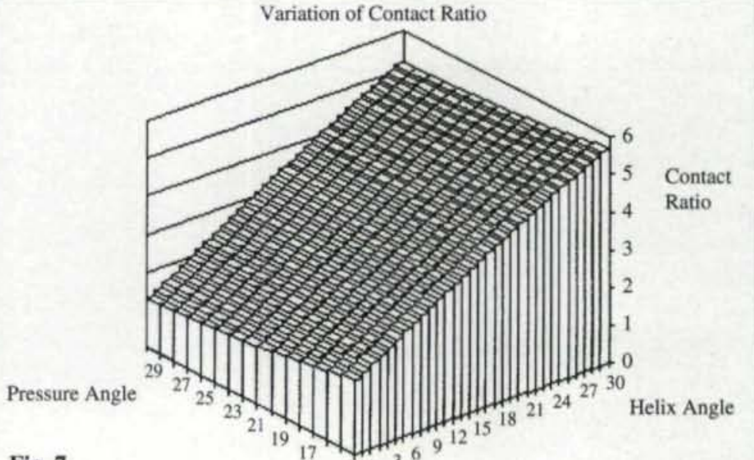

Fig. 7

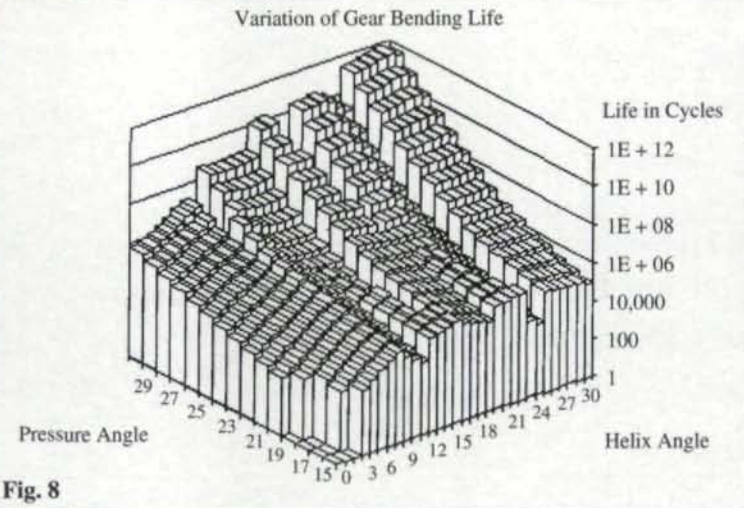

Fig. 8

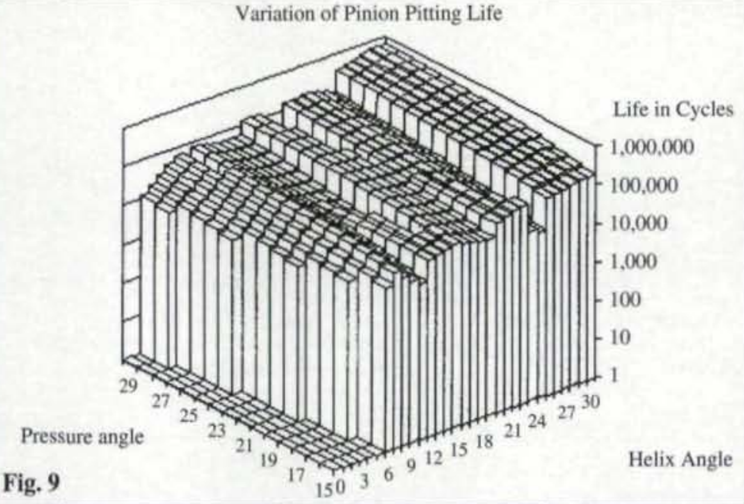

Fig. 9

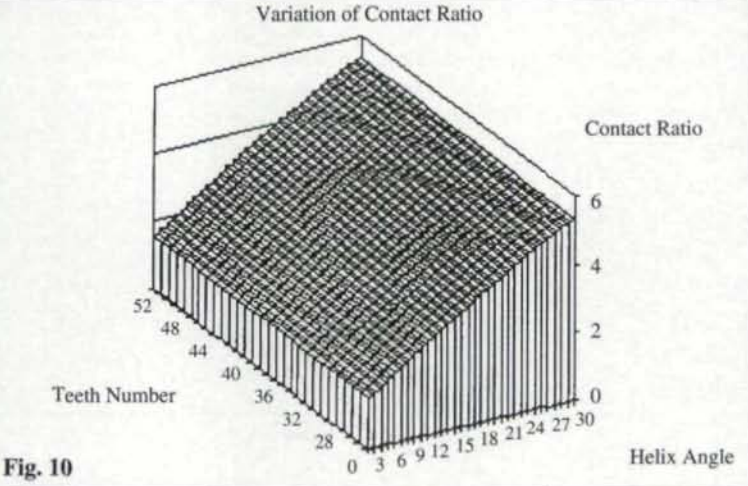

Fig. 10

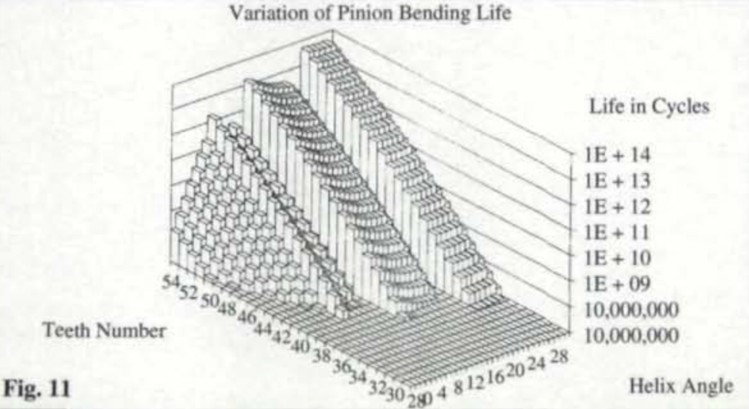

Fig. 11

Eliminating the parameters from the design functions, the dependent variables are obtained: Center distance, gear teeth number, pitting stress, bending stress, scoring number, pitting life, bending life.

The constraints are defined by the designer, and the limiting values are imposed from each particular application. In this case, the inequality constraints are

Critical Scoring Number < 20,000
Contact Ratio 1.2
Bending Life > 1 X 10^7
Pitting Life > 1 X 10^7
Helix Angle 45°
14.5° < Pressure Angle < 28°

The equality constraints are all the application factors for calculating pitting and bending stresses. It is important to point out that the stress is not limited to the allowable material stresses. Instead, the life is limited to a minimum value.

All the possible solutions were calculated with gear design software, and they were stored into a general purpose graphics program. The program generates plots of the calculated variables. The results were plotted as shown in Figs. 7, 8, and 9. Fig. 7 shows the variation of the contact ratio as a function of the independent variables. This can be seen the solution domain and the location of the optimum. From this figure, it can be stated that the optimum is found at the point where the helix angle equals 45° and the pressure angle equals 15°.

Figs. 8 and 9 show the behavior of gear bending life and pinion pitting life. At this point, the designer must take into consideration the particular application of the gear set. If the failure criterion is pitting, then the optimum will be the point with maximum contact ratio. If the failure criterion is bending, then the optimum will be at the point the helix angle equals 30°, and the pressure angle equals 28°. If the design must satisfy both criteria, the designer should select the most restrictive solution.

Example 2. The definition of the problem is as follows:

Objective function — Maximize the contact ratio and bending life. In this case, instead of the pressure angle, the influence of the pinion teeth number is studied.

Independent Variables — helix angle and teeth number. The design definition is about the same as in Example 1.

The parameters are:

Speed ratio	2
Normal Diametral Pitch	10
Pressure Angle	20°
Face Width	2.6
Addendum Proportions	Normal
AGMA Quality Level	10
Material Properties	BHN = 180 Sat = 25,000 psi Sac = 85,000 psi $E = 30 \times 10^6$

Eliminating the parameters from the design functions, the dependent variables are obtained:

Dependent Variables

Center Distance
Gear Teeth Number
Pitting Stress
Bending Stress
Scoring Number
Pitting Life
Bending Life

The constraints are defined by the designer, and the limiting values are imposed from each particular application. In this case, the inequality constraints are:

Constraints

Critical Scoring Number < 20,000
Contact Ratio > 1.2
Bending Life > 1×10^7
Pitting Life 1×10^7
Helix Angle < 30°
Pinion Teeth Number > 6

The equality constraints are the same as in Example 1.

The solution domain was calculated with a gear design software program, and all the data were stored into a general purpose graphics program. The results were plotted as shown in Figs. 10-12. Fig. 10 shows the variation of the contact ratio as a function of the independent variables. The solution domain is seen, and the optimum is located along the line for the value of helix angle equal to 30° The objective function was the contact ratio and the bending life. Therefore, the behavior of bending life is plotted in Fig. 11, and the optimum value is located at the point the helix angle equals 30° and 34 teeth. To verify that this solution is in agreement with the pitting life, Fig. 12 shows the behavior of pitting life. From this figure, it is verified that the optimum lies at an allowable solution.

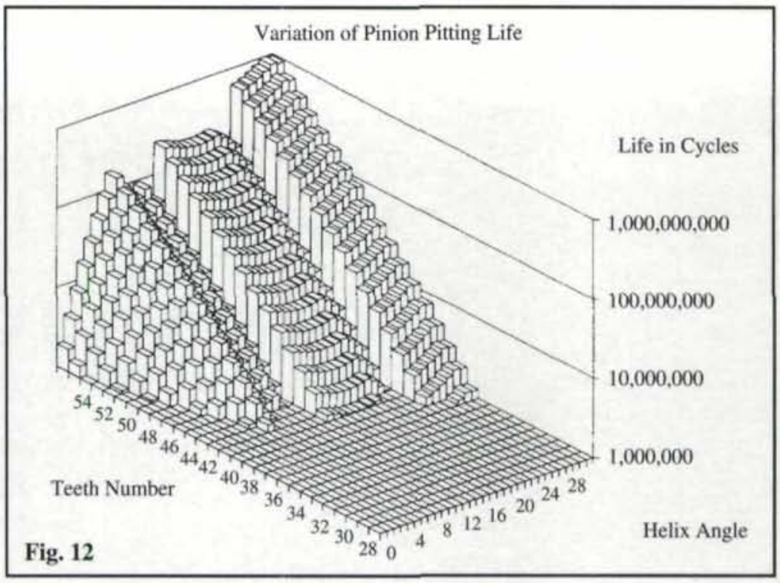

Fig. 12

Conclusions

A simple procedure for optimum gear design was presented. The procedure is adjustable for the optimization of any combination of objective functions, and it allows the designer to impose actual restrictions. Besides, it is not necessary to have a deep understanding of complicted optimization techniques. Also, this procedure does not require special optimization programs. Any gear design optimization problem can be solved by generating with a gear design software plots of the solution domain. The location of the optimum is simple, and it can be determined visually from the plot or reviewing the data.

Graphical optimization gives an overview of the entire problem and allows the designer to identify the optimum solution without complicated interpretation of the results. ■

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Computerized Recycling of Used Gear Shaver Cutters

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Most gear cutting shops have shelves full of expensive tooling used in the past for cutting gears which are no longer in production. It is anticipated that these cutters will be used again in the future. While this may take place if the cutters are "standard," and the gears to be cut are "standard," most of the design work done today involves high pressure angle gears for strength, or designs for high contact ratio to reduce noise. The re-use of a cutter under these conditions requires a tedious mathematical analysis, which is no problem if a computer with the right software is available. This article describes a computerized graphical display which provides a quick analysis of the potential for the re-use of shaving cutters stored in a computer file.

Shaving cutters are very expensive and their re-use offers considerable savings. Other benefits are the reduced inventory of cutters and minimum delay in gear processing if some way can be found to evaluate these cutters' potential for re-use. Computer software is available to facilitate the search of existing cutters to learn if any are useable as is, or if they can be modified to be used. Every cutter is a candidate for being selected. An obsolete cutter may be useable or possibly modified to become useable. An existing active cutter may be modified, and after meeting an immediate need, be returned to its assigned activity by being resharpened to its original curve. This will sacrifice some of the life of the cutter, but may be justified to minimize the delay of producing parts or the cost of purchasing a new shaver.

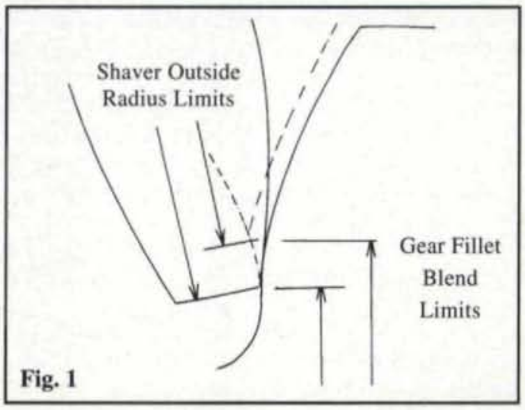

Fig. 1

For a shaving cutter to be useable, it must have the right base pitch, hand, and the proper helix angle to provide good shaving action. It is not obvious if the tooth length will permit shaving to the proper point in the fillet of the gear. If the tooth is too long, it will interfere in the root of the gear. If it is too short, it may not shave in the area where the mating gear tooth tip will make contact.

There are two approaches to assessing a shaving cutter's potential use in gear finishing. The first approach is to explore the fillet of the gear when a protuberance hob is used as a pre-shave cutter. The purpose of this study is to select a shaving cutter which will blend smoothly in the fillet of the gear. The second approach is to study the path of a candidate shaving cutter when a nonprotuberance cutter has been used as a pre-shave cutter. In this case the purpose is to select a shaving cutter which will penetrate to shave the flank of the tooth deeply enough to provide a shaved surface for the contact of the mating gear and may or may not reach the fillet. This second approach requires the "pairing" of gears, and caution must be used in designing a gear to match one which has been shaved in this manner.

The initial step in the first approach is to study the action of the pre-shave cutter to determine two unique radii of the gear. The first radius is the point of maximum relief in the fillet formed by the protuberance of the pre-shave cutter. The second is the radius where the cutter protuberance has left the involute profile with adequate finishing stock for "cleanup." This does not need to be the full amount of finishing stock on the gear flank. If less than full stock is specified, it allows a greater outside diameter on the mating gear and a possible higher contact ratio. Ideally the outside diameter of the shaving cutter will finish the tooth to between these two unique radii with a nearly perfect blend in the fillet (Fig. 1).

To find the desired shaver cutter outside diameter it is necessary to compute the tight mesh center distance of the shaver and gear using an iterative procedure. Then calculate the working line of action, the radius that the tip of the cutter will have to be to reach the maximum relief in the fillet, and the radius to the point of required shaving stock for cleanup. The candidate shaving cutter must have an outside radius between these two values to be useful. The closer it is to the maximum relief value, the better. If the outside radius of the shaver is too large, it may be reduced to make it useable.

Shaving cutters may be sharpened a number of times. In so doing, the tooth thickness is reduced, which results in the shaver penetrating deeper into the gear. Therefore, the outside diameter must be reduced as well. The amount of outside reduction depends upon the involute angle when tight meshed with the gear being shaved. The suppliers of shaving cutters provide blueprint dimensions of the shaver outside diameter and tooth thickness when "new" and at "life." These dimensions are unique for a certain gear and are used for establishing a "sharpening curve" for the shaving cutter. These data can be plotted to show a curve of tooth thickness versus outside diameter throughout the life of the cutter.

While tooth thickness and outside diameter are the basic criteria, it is a common practice to use the terms "HOP" and "HOD." These terms stand for "height of pins" and "height of (outside) diameter," with measurements made from the circumference of the precision bore of the shaving cutter (Fig. 2). The HOP dimension is the distance from the closest circumference of the bore to the top of the pin placed between the teeth of the shaver, a process similar to measuring tooth thickness of gear teeth with "dimension over pins." The HOD dimension is the distance from the closest circumference of the bore to the top of the shaver tooth.

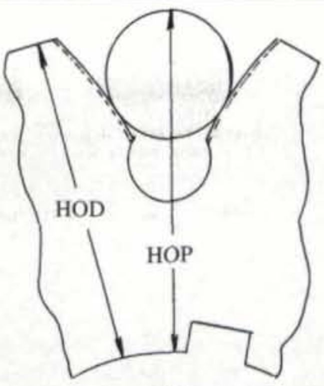

Fig. 2

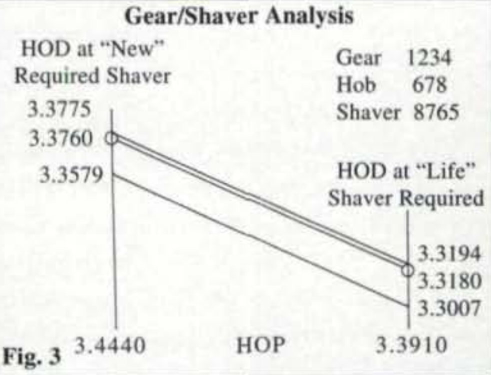

Fig. 3

A computer graphic display (Fig. 3) uses the HOP and HOD dimensions. The two vertical lines represent the tooth thickness (HOP) of the shaving cutter when new and at life. The circles on each of these lines represent the outside diameter (HOD) of a shaving cutter with tooth thickness (HOP) given at the bottom of the vertical lines. The line connecting the circles may be called the sharpening line. A shaver on the shelf may have a HOP and a HOD anywhere along this line, depending upon how many times it has been sharpened.

The two other sloping parallel lines on the computer screen are unique to the gear to be shaved. Taking the shaver's new tooth thickness (HOP) dimension, two shaver radii are calculated as described before, to meet the maximum relief and the desired shaving stock radii of the gear. The same is done for the "life" tooth thickness. These dimensions are placed on the two vertical lines and with the interconnecting lines form a parallelogram. If the shaver sharpening curve falls within this parallelogram, the shaver may be used to shave the gear.

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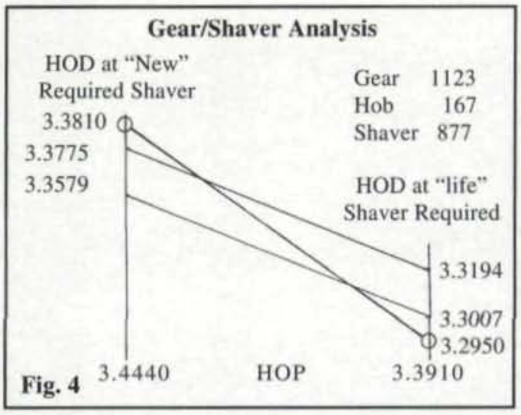

Fig. 4

If the shaver curve is outside the parallelogram, and the shaver has no prospect for other future use, it may be possible to modify it to get it into the parallelogram. If the sharpening curve is above the parallelogram, then by grinding the outside diameter, the sharpening curve will be moved downward and become useable. If the sharpening curve given is below the parallelogram, it may have only the tooth profile sharpened, and this will move the sharpening curve to the right and possibly enter the acceptable area.

The graphic display is a quick reference to the compatibility of a shaver/gear combination. The actual selection will require judgment of the urgency of getting the job done, number of gears to be shaved, and whether to modify obsolete cutters on the shelf. If the shaver is to be used for an application with long slender teeth, when it was originally designed for low contact ratio gears, there may be a problem with shaving the ends of the teeth. Shaver suppliers do not specify the depth of the tooth or root end of the shaving profile where it meets the drilled hole.

A shaver search computer program should have an option input so that if a particular shaver looks promising, an up-to-date measurement of the HOP and HOD can be input, and as a result the present capability known.

For the second approach, selecting a shaving cutter associated with a non-protuberance pre-shave cutter, the minimum radius on the workpiece gear where the mating gear tooth tip will touch is used instead of the previous two fillet radii discussed. This will occur at minimum gear center distance and maximum mating gear outside diameter. These values will establish a line with end points for new and life conditions. Since the shaving cutter now must have an outside diameter large enough to reach below the mating gear contact point, the same diagram requires that the sharpening curve of the shaver be above the line. A small margin of safety should be available to prevent any interference with the shaving stock remaining following the "rolling out" of the shaving cutter. This is especially true if the mating gear has more teeth than the shaving cutter. A calculation of the shaver tip/gear root clearance should be included in the display.

Two examples are shown on a computer screen. The first example is a "perfect" selection when using a protuberance cutter (Fig. 3). The shaving cutter sharpening curve, as indicated by the circles on each end, lies slightly below the top line of the parallelogram. This line represents the outside diameter of a shaving cutter which will reach the maximum relief of the gear fillet.

The second example (Fig. 4) shows a shaving cutter with the outside diameter (HOD) too large when new, but during its life it is reduced by the sharpening process, so that it enters the parallelogram of acceptance. However, near its life point of the sharpening curve, it again leaves the parallelogram of acceptance and cannot be used. Since it is very possible that a shaver on the shelf is in a "half-life" condition, it can be selected for use in this example.

Fig. 4 can also be used to show the situation corresponding to the second approach described above. If the top line of the parallelogram represents the outside diameter (HOD) of the shaving cutter required to reach the point where the mating gear tooth tip will make contact, then this shaving cutter will be useable when new to shave the gear. However, as the shaver is sharpened on the existing sharpening curve, it will go below the top line and will not shave deep enough to provide a good surface for the mating gear. If this shaving cutter is to be dedicated to this gear, than a new sharpening curve should be developed. As the shaver is sharpened, the amount removed from the outside diameter should be reduced so that the sharpening curve remains above the top line of this parallelogram.

The graphic display permits nearly instantaneous evaluation of the feasibility of using an existing shaving cutter to shave a new gear. If the computer has a file of shaving cutters, it is possible to evaluate a large inventory of cutters in a matter of minutes to learn whether any of the existing cutters are useable. A simple change of the pre-shave hob or shaper from a computer file will make possible a new search. ■

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IMT Div. of Carl Zeiss, Inc.	8	9
ITW Heartland	22	46
James Engineering	3	10
M & M Precision	10	2
Manufactured Gear & Gage, Inc.	26	47
National Broach & Machine Co.	25	BC
Niagara Gear Corp.	7	8
Normac, Inc.	15	48
Pfauter-Maag Cutting Tools, L.P.	2	1
Profile Engineering, Inc.	23	46
Pro-Gear Co., Inc.	24	46
Software Engineering Service	20	46
Starcut Sales, Inc.	4	4
Van Gerpen-Reece Engineering	21	46

Initial Design of Gears Using an Artificial Neural Net

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Introduction

Many CAD (Computer Aided Design) systems have been developed and implemented to produce a superior quality design and to increase the design productivity in the gear industry. In general, it is true that a major portion of design tasks can be performed by CAD systems currently available. However, they can only address the computational aspects of gear design that typically require decision-making as well. In most industrial gear design practices, the initial design is the critical task that significantly effects the final results. However, the decisions about estimating or changing gear size parameters must be made by a gear design expert.

To move one step forward, two new system developing techniques have been investigated. One is the artificial neural net, and the other is the expert system known as artificial intelligence. The former is well-suited to estimating initial gear size, while the latter is the choice for changing parameters. This article demonstrates the adaptability of an artificial neural net for the initial gear design which is a part of the Intelligence GearCAD system under development, that emulates the entire gear design procedure, including the decision-making tasks.

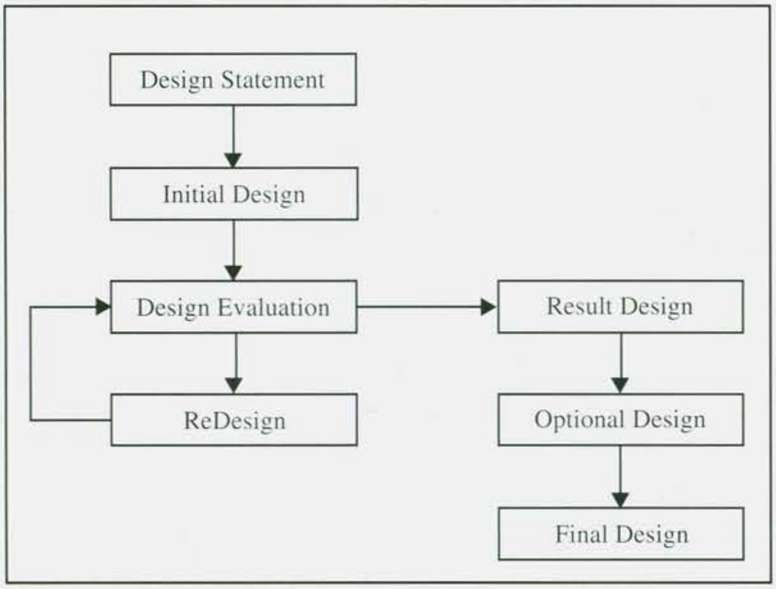

Fig. 1 - Simplified mechanical design stages.

Initial Gear Design

In Fig. 1, a model of the mechanical design procedure is illustrated. Similar models have been used to develop mechanical engineering CAD and expert systems.[10-11] This simplified design model is adaptable to most mechanical element designs including gear design. A specific model representative of gear design which corresponds to Fig. 1 is shown in Fig. 2.

The first stage of designing a gear set is estimating the necessary gear size parameters based on user-specified requirements. Once these parameters are selected, gear and tool geometries will be calculated and evaluated by the AGMA (American Gear Manufacturers Association) power rating standard.[8] If the power rating result is unsatisfactory, the result will be analyzed and the necessary parameters will be changed. The second and the third stages will be repeated in an iterative manner until the AGMA power rating is satisfied. The final stage is designing a gear blank, which is customarily done after a successful power rating is achieved.

In practice, engineers go through the initial design stage only once during the entire design procedure. The number of iterations carried out to complete the gear design depends upon how well the gear size parameters are estimated in the initial design stage. Consequently, an efficient gear design can only be achieved by properly estimating the initial gear size parameters.

The estimated parameters required for the initial design stage consist of the center distance, diametral pitch, pinion teeth number, and gear teeth number, or alternately, the total number of teeth. These four are the essential parameters necessary to carry out the AGMA power rating procedures. Equation 1 illustrates how these four parameters are related to each other while assuming the helix angle is zero.

$$DP = \frac{N_T}{2\,CD} \qquad (1a)$$

$$N_T = N_P + N_G \qquad (1b)$$

where, *DP* Diametral Pitch
CD Center Distance
N_G Gear Teeth Number
N_P Pinion Teeth Number
N_T Total Teeth Number

The determination of one parameter in Expression 1a is dependent on the two other parameters. Therefore, at least two parameters must be estimated by the engineer. There may be many combinations of solutions which satisfy Equation 1 for a single example. Finding a superior solution among a myriad of possibilities depends upon the ability of an engineer. Proper initial parameter estimations usually require years of experience, as well as an organized knowledge of the field. In most cases, the accumulated design data through the history of a company is also an essential factor. This type of design task is known as decision making. Fig. 3 shows the factors involved in a gear engineer's decision making.

Two Steps of Initial Gear Design

The initial gear design stage consists of two steps. First, an engineer refers to a standard product catalog to identify the proper model. The selection is based on the user's specifications, which include horsepower, speed ratio, and input RPM. At this step, the center distance is obtained with the proper selection of model size. Next, the number of pinion and gear teeth will be estimated by a trial and error method. The ratio of estimated number of pinion and gear teeth must not exceed the predetermined percentage of error over the required speed ratio. The diametral pitch can then be calculated using these estimated values. This procedure is only one example of a number of initial gear design methods used in the industry. The method shown here was obtained from an engineer with many years of experience in both designing and manufacturing, actively working in the gear industry.

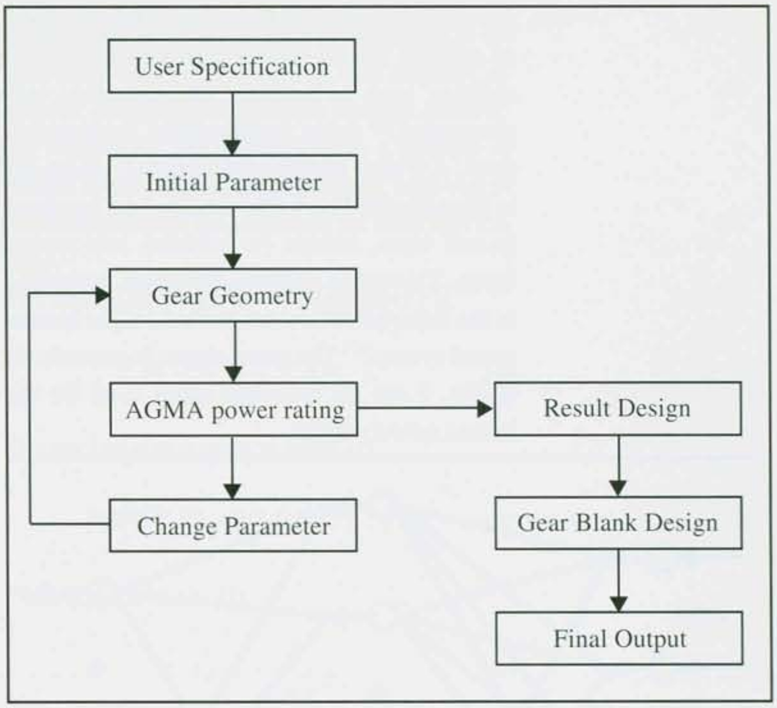

Fig. 2 - Modeled gear design stages.

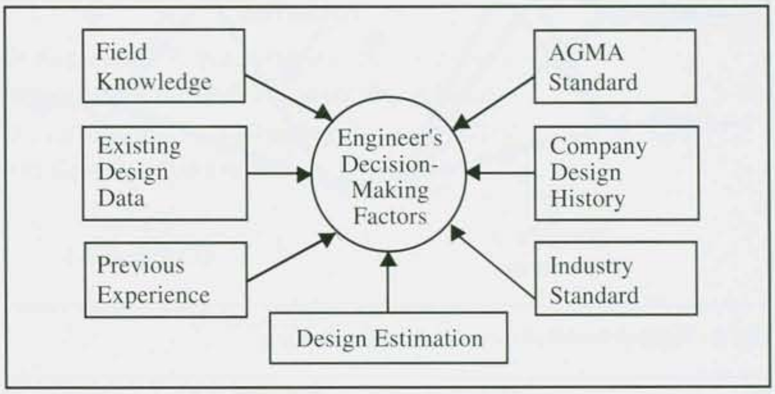

Fig. 3 - Engineer's decision-making factors.

Artificial Neural Net

The artificial neural net is composed of highly interconnected layers which attempt to achieve

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human neuron-like performance.(3) It is designed to emulate human neural activities, exhibiting abilities, such as learning, generalization, and abstraction,(4) using mathematical implementations. A typical model of the artificial neural net is illustrated in Fig. 4 The modeled net has three layers: input, hidden (or middle), and output layers. This model is extremely simple, compared to the hundred trillion connections of the human neural system.(2) The terms shown in parenthesis in Fig. 4 are the anatomic terms used for the human neural system.

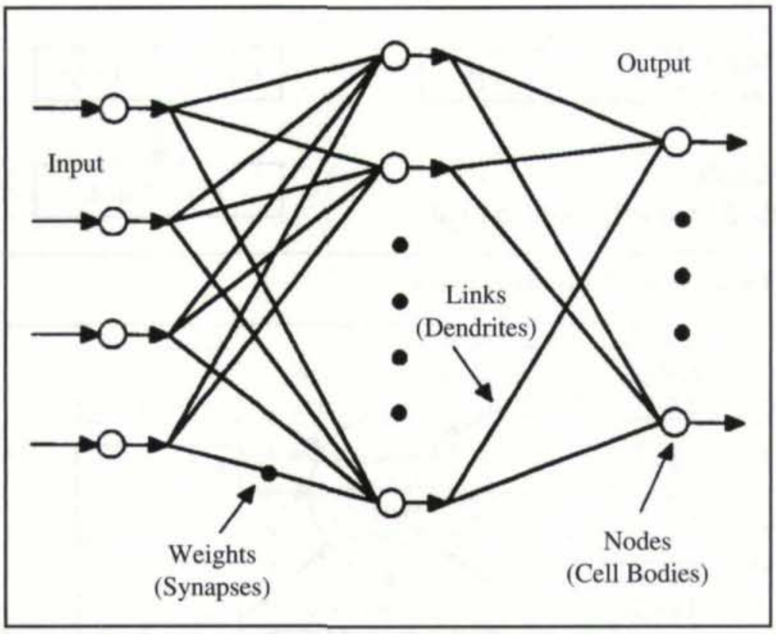

Fig. 4 - Typical model of an artificial neural net.

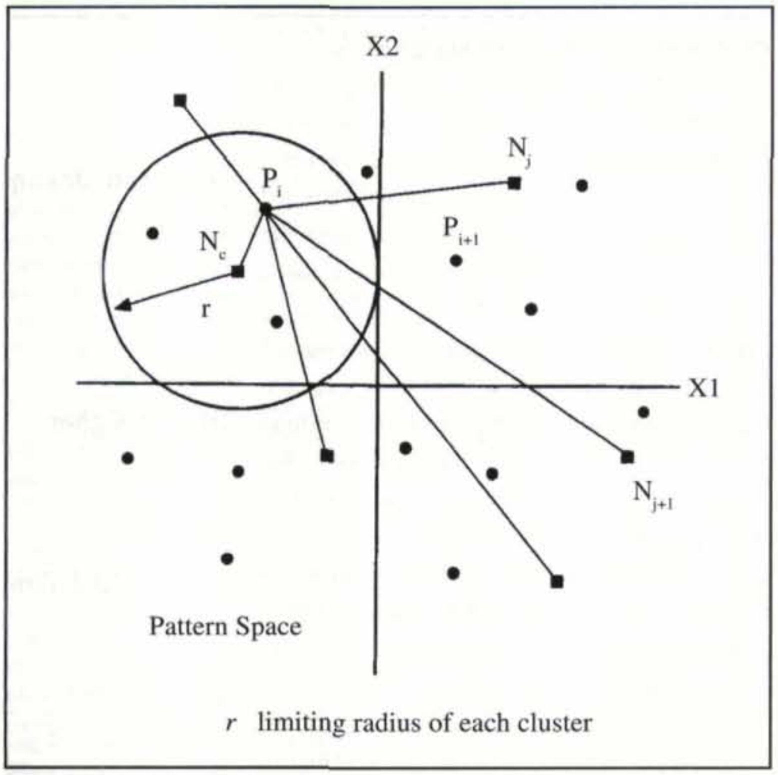

Fig. 5 - Single step of LVQ algorithm.

In Fig. 4, each node in one layer receives multiple signals from the nodes in the previous layer. The strength of each signal is determined by the value of the connecting weight between paired nodes. The signals conveyed to the node are summed and averaged (or mathematically evaluated) to decide whether this node will activate or not. If the node activates, the signal generated will be transmitted to the nodes in the next layer.

The artificial neural net is not functional without existing knowledge, just as a human engineer cannot perform a task without pre-existing knowledge of the field. The net must be trained with known knowledge patterns that consist of input and the corresponding target output. The knowledge patterns are fed through the net so that the connecting weights can be learned and memorized. Once all the connecting weights are established, the net will produce the proper output when the same or similar input pattern is seen. Accordingly, the quality of the knowledge patterns used for training influences the quality of the estimated outputs. The net is said to be successfully trained if the estimated outputs match the target outputs within a certain level of error. Because the training knowledge patterns may not be perfect, there is always the chance that an errant estimation may appear, just as the performance of the human engineer will be inaccurate if incorrect knowledge was used in training.

Artificial Neural Net Algorithms

Many artificial neural net algorithms have been developed and implemented. Although there are some structural variations, the basic idea is equivalent in terms of implementing a human neural system. Each algorithm has its own characteristics and applicable regime. After the nature of initial gear design was investigated, two algorithms, namely LVQ (Learning Vector Quantization) and GDR (Generalized Delta Rule), were selected to emulate two steps of initial gear design.

LVQ is also known as the pattern recognition or classification method, which classifies available knowledge patterns in a pattern space.(5) Each pattern must have its own class label (or class I.D.). LVQ forms clusters, which include identically labeled patterns, while remembering their weight centers. When a new input pattern without a class label, not encountered previously, is seen, LVQ locates the cluster weight center which is closest to the new input pattern and sends the class label of the selected cluster as the output. In other words, LVQ simply tells where the new input pattern belongs.

In Fig. 5, a single step of the LVQ is illustrated. At any k^{th} step, the distances between one of training patterns $P_i \in R^n$, $i = 1,2,\ldots, l$, and the neurons (or reference vectors(3)) $N_j \in R^n, j = 1, 2,\ldots, m$, are measured using Euclidean distance (*ED*) metric to find the nearest neuron N_c.

$$ED_j = \sum_{q=1}^{n} (p_q - n_q)^2 \qquad (2)$$

where, P_q Elements of P_i
n_q Elements of N_j

The neurons, N_j's, are initially located randomly in the pattern space, and the closest neuron, N_c, becomes a candidate for one of the many cluster centers that will appear after all steps are performed. If the closest neuron has the identical class label as the pattern, this neuron is moved toward the pattern as the reward for a correct classification. Otherwise the neuron is moved away from the pattern as the punishment for an incorrect classification.(3) Equation 3a is used to represent the move toward the pattern, and Equation 3b is used for the move away. For all other neurons, Equation 3c is applied.

$$N_c^{k+1} = N_c^k + \alpha(P_j - N_c^k) \qquad (3.a)$$

$$N_c^{k+1} = N_c^k - \alpha(P_j - N_c^k) \qquad (3.b)$$

$$N_j^{k+1} = N_j^k, \text{ for } j \neq c \qquad (3.c)$$

where, α is a monotonically decreasing momentum rate and preferably less than 1.0.(3) In practice, the determination of α in non-trivial. When the neuron N_c is moving toward the pattern, it is known that the pattern belongs to this neuron at the k^{th} iteration. The same method will be applied to all available patterns, and the step will be repeated iteratively until all the clusters are formed.

GDR also requires knowledge patterns which have inputs and corresponding target outputs for training. The knowledge patterns are supplied to the net in a feed-forward manner to find a connecting weight matrix, and then those weights are adjusted by the back-propagation of error to reduce the total net error. The GDR net shown in Fig. 6 uses the typical artificial neural net construction introduced in Fig. 4. The outputs of the nodes in one layer are transmitted to nodes in the next layer through connections that amplify, attenuate, or inhibit such outputs through connecting weights.(1) The net may have a number of hidden layers. However, in practice, only one or two hidden layers are sufficient for most applications.(5)

The output of a node in the input layer *i* is

$$O_i = I_i, \ i = 1, 2,\ldots,n \qquad (4)$$

The net input to a node in layer *j* is

$$net_j = \sum_i W_{ji} O_i, \ j = 1, 2,\ldots, m \qquad (5)$$

The output of node *j* is

$$O_j = \frac{1}{1 + e^{-f}} \qquad (6)$$

$$f = net_j + \theta_j \qquad (7)$$

In Expression 7, the parameter θ_j serves as a threshold or bias. Similarly, input net_k and output O_k can be found by substituting the subscript *j* to *k* in Equations 5 through 7.

$$net_k = \sum_j W_{kj} O_j, \ k = 1, 2,\ldots, l \qquad (8)$$

$$O_k = \frac{1}{1 + e^{-f}} \qquad (9)$$

$$f = net_k + \theta_k \qquad (10)$$

All knowledge patterns will be fed through the net by the feed-forward procedures, Equations 4

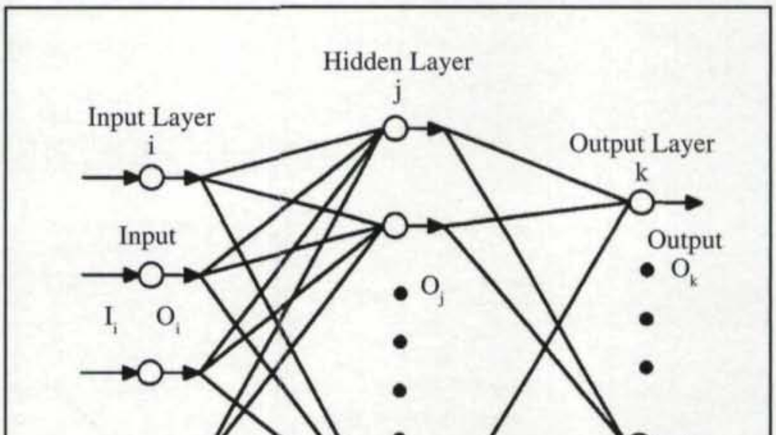

Fig. 6 - Net construction of GDR algorithm.

through 10. Usually, outputs $\{O_{pk}\}$ generated by the net will not be the same as the target or desired outputs $\{T_{pk}\}$. The square of the difference (or pattern error) between these two values is

$$E_P = \frac{1}{2}\Sigma\,(T_{pk} - O_{pk})^2 \qquad (11)$$

and the average net error is

$$E_{net} = \frac{1}{2p}\sum_P \sum_k (T_{pk} - O_{pk})^2 \qquad (12)$$

$$p = 1, 2, \ldots, P$$

where, *P* Number of Patterns

If E_{net} falls into the acceptable error range, the net is successfully trained. Otherwise, the following procedures are necessary to minimize the error. The convergence toward improved values for the connecting weights and thresholds can be achieved by taking incremental changes ΔW_{kj} proportional to $\partial E/\partial W_{kj}$.(1)

$$\Delta W_{kj} = -\eta\,\frac{\partial E}{\partial W_{kj}} \qquad (13)$$

$$= -\eta\,\frac{\partial E}{\partial\, net_k}\,\frac{\partial\, net_k}{\partial W_{kj}}$$

where, η Learning Rate
Therefore,

$$\Delta W_{kj} = -\eta\,\delta_k\,O_j \qquad (14)$$

$$\text{where, } \delta_k = -\frac{\partial E}{\partial\, net_k},\quad O_j = \frac{\partial\, net_k}{\partial W_{kj}}$$

The term δ_k, which is the error to be propagated backward for the k^{th} node in the layer, can be rewritten as

$$\delta_k = -\frac{\partial E}{\partial O_k}\,\frac{\partial O_k}{\partial\, net_k} \qquad (15)$$

$$= (T_k - O_k)\, f'_k\,(net_k)$$

$$= (T_k - O_k)\, O_k\,(1 - O_k)$$

By similar mathematical procedures (details can be found in Ref. 1),

$$\Delta W_{ji} = -\eta\,\delta_j\,O_i \qquad (16)$$

$$\delta_j = O_j\,(1 - O_j)\sum_k \delta_k\,W_{kj} \qquad (17)$$

The δ's at an internal node can be evaluated in terms of the δ's at an upper layer. Thus, starting at the highest layer (or output layer), δ_k can be evaluated using Expression 15, and the errors can be propagated backward to the lower layers. The connecting weights now will be updated as follows,

$$W_{ji}^{n+1} = W_{ji}^{n} + \Delta W_{ji}^{n} \qquad (18)$$

$$\text{where, } \quad \Delta W_{ji}^{n} = \eta\,(\delta_j O_i) + \alpha\Delta\, W_{ji}^{n}$$

The momentum rate α has been added to Expressions 14 and 16 to reduce the risk of oscillations while training the net in the iterative approach.(1) The α also allows a larger value of η, thereby speeding convergency.(4) Both η and α influence the training results and should be carefully selected by trial and error. The improved connecting weight matrix will be used at the next iteration, and the procedure is repeated until the system error reaches the desired level.

Applications

As mentioned earlier, two steps of the initial gear design are emulated using the artificial neural nets. Although it is possible to apply a single neural net to perform the desired task, two different algorithms, LVQ and GDR, are used intentionally in order to emulate human performance more accurately. It will also prevent from training a single neural net with the entire patterns which may be thousands.

The product catalog(12) obtained from the local gear manufacturing company served as the training knowledge patterns. The catalog contains three input values, horsepower, input RMP, and speed ratio. In addition, the catalog also includes the model number which implies proper center distance. The patterns are neatly tabulated to the ones which may use the same center distance. The model numbers in the catalog were used as the class labels, as well as the desired outputs of each pattern.

The patterns of four selected models are plotted in Fig. 7. From this figure, it can be seen that the patterns belonging to one model are scattered along the axes of speed ratio and input RPM. The patterns in each model tend to form a distribution surface which may be the portion of a sphere. However, it is almost impossible to form any clusters with this kind of pattern. Thus, the original three dimensional patterns are transformed and mapped onto a two dimensional pattern space using Equations 19 through 22. Fig. 8 shows the transformed patterns mapped onto the new space.

$$A = 100\ \frac{I_1\ I_2}{I_3} \qquad (19)$$

$$B = 10\ \frac{e^{I_1}\ I_2^3}{I_3^2\ \overline{I_3}} \qquad (20)$$

$$X_1 = 5\ \overline{A}\ \ \overline{B} \qquad (21)$$

$$X_2 = 3A \qquad (22)$$

where, I_1 Speed Ratio
I_2 Horsepower
I_3 Input RPM
X_1, X_2 Transformed Pattern

Fig. 9 illustrates the multiple GDR net construction connected to a single LVQ net for the initial gear design application. The number of GDR nets required is determined by the number of models available in the product catalog. Accordingly, each GDR net is to be trained with the patterns that belong to the same model. A single hidden layer with three nodes is used for each GDR net. For a triple-reduction case, three such multiple nets should be combined.

The number of clusters formed using the LVQ net depends upon the size of the limiting radius *r* in Fig. 5, which controls the size of the clusters. If the limiting radius is overly large, some clusters having different model numbers (or different class labels) will overlap. If the limiting radius is too small, too many clusters will be formed. Therefore, an optimized value is required.

After the each net is successfully trained, the LVQ net can produce the model number and center distance when a new input pattern (horsepower, speed ratio, and input RMP) is provided. The output, a model number, will serve to determine the matching GDR net which will estimate the diametral pitch. The GDR net also uses the same input as the LVQ net. In real-world design, the number of pinion and gear teeth are estimated, and the diametral pitch is calculated using this estimation. However, the number of pinion and gear teeth relative to the speed ratio are not functionally distributed. Therefore, the diametral pitch is selected as the target output in this application. Afterwards, the other parameters can be calculated sing the estimated param-

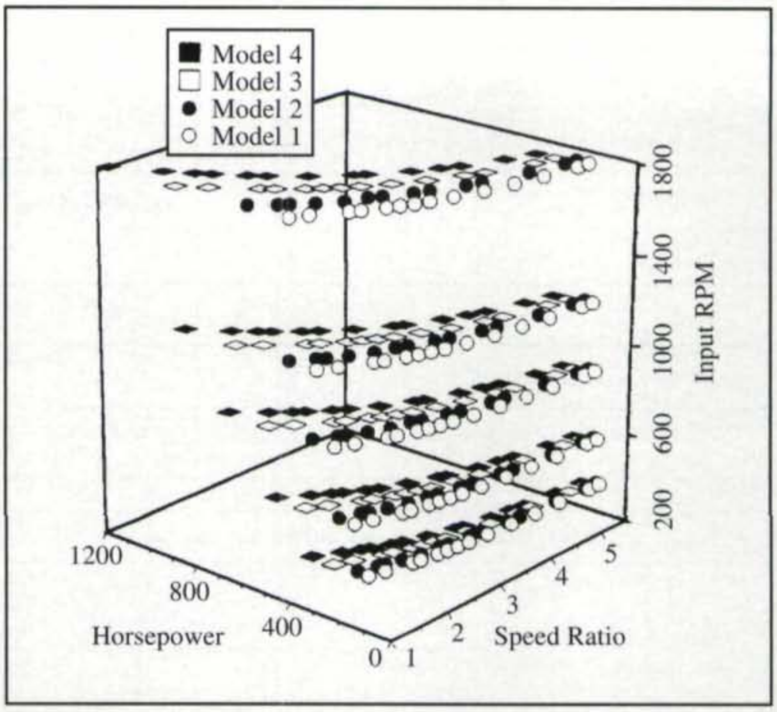

Fig. 7 - Original catalog training patterns.

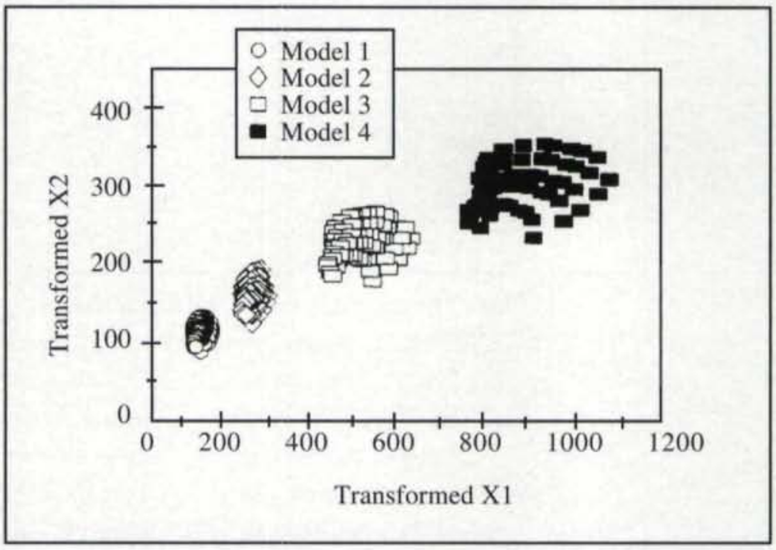

Fig. 8 - Transformed training patterns.

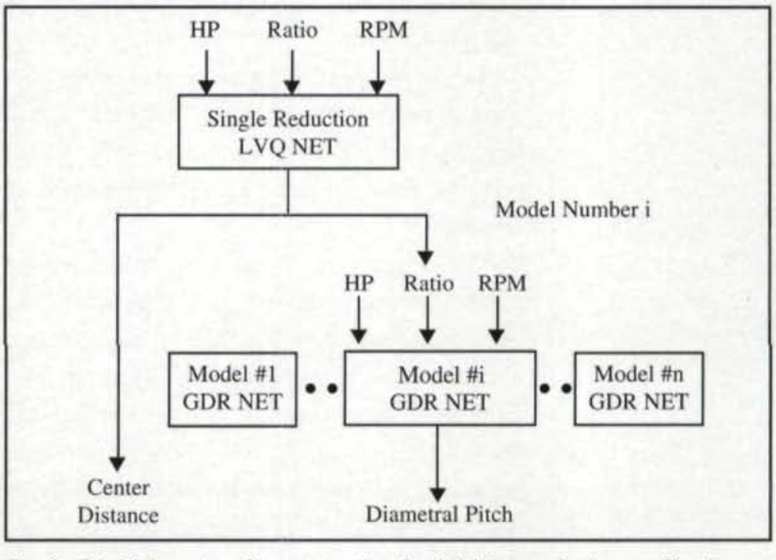

Fig. 9 - Multiple network construction for initial gear design application.

Table I - Error of Estimated Outputs

70 patterns in each model	Error % before adjusted	Error % after adjuster	Total Net error
Model 1	20	7	0.000041
Model 2	14	7	0.000043
Model 3	5	5	0.000018
Model 4	9	9	0.000023
Average	14	7	0.000031

Table II Error Factors for different η and α

		Error Factors			
η	α	Model 1	Model 2	Model 3	Model 4
0.70	0.50	1.03	1.05	1.01	1.01
0.90	0.70	1.00	1.00	1.00	1.00
0.95	0.90	0.92	0.94	0.93	0.97
0.99	0.95	0.93	0.97	0.90	0.90

eters, the center distance, and diametral pitch.

In Table I, the percentages of the net errors after 20,000 iterations are tabulated. The percentages indicate the number of incorrect estimations made by the GDR nets over the number of the training patterns. While investigating those incorrectly estimated diametral pitches, it was found that some of the values were not commonly used in the gear industry. Thus, those uncommon diametral pitches must be adjusted to the recommended values.(6) The error percentages were decreased after adjustment, which are shown in the third column in Table I. The average error for the four selected models is practically acceptable.

There are several considerations in using the GDR algorithm for initial gear design task. The first consideration is how to find the adequate learning rate, η, and momentum rate, α. The typical values of η and α for most applications are 0.9 and 0.7, respectively.(3) Suggestions can be found in Table II, which shows the error factors relative to the typical values. The η can be selected between 0.95 and 0.99, while the α can be selected between 0.9 and 0.95. When the α was increased higher than 0.95, the training seemed to become trapped in a local error minimum, and the error was not improved. It was also found that the number of iterations higher than 20,000 did not improve the results.

How the available training patterns were organized was also important. The test was performed with three different sorting methods of training patterns; sorted by input RMP, by horsepower, and by speed ratio. As a result, it was learned that the training patterns sorted by input RMP order produced the best results. When the number of nodes in the hidden layer was increased to six, no improvement was observed at the same number of iterations. When the number of decimal places was increased from two to four, the number of iterations was decreased by 25% at the same error level.

Numerous test designs were completed with the entirely trained artificial neural net. Each test design was evaluated by a commercially available AGMA power rating software.(13) About 60% of the test designs passed the power rating without changing any initial gear size parameters, while the balance required several changes to pass within a few iterations.

Conclusions

Once the net is trained with the available design knowledge, it can provide the estimated output in a single iteration, usually in seconds. If the outputs generated by the net have been approved as good estimations, these input and output patterns can be added to the existing design knowledge in order to achieve better performance in the future. The company's design knowledge will grow automatically by adding new patterns to the knowledge data base. It will ensure that all available design knowledge of engineers is collected and organized without special effort. By using the artificial neural net, the design time for inexperienced engineers can be reduced, and a design consistent with past designs achived.

Another advantage is that the artificial neural net can be trained to deal with incomplete and uncertain evidence. It understands the relationship between inputs and outputs, and does not burden the engineer with specific analyses. If conventional techniques are used, the engineer must find their mathematical relationship before developing any system, which may require many years of field experience and an extensive mathematical background.

Although the artificial neural net successfully emulates the performance of the human engineer for the initial gear design task, there are still some disadvantages to overcome. The most critical disadvantage is the slow training time. It took hours to train a neural net with 70 knowledge patterns in one model, which consisted of only three inputs and one output, on a fairly capable personal computer, such as a 80386-based PC. In the case of single reductions, 22 such models are to be found in the catalog used. Furthermore, when new knowledge patterns are to be added to the existing patterns, the entire neural net must be retrained.

Human neurons transmit signals at a very slow speed, considering the immense velocity of signal transmission in a modern digital computer. However, the brain's huge computational rate is achieved by a tremendous number of parallel computational units.(2) The most advanced modern computer systems are packed with only a few parallel processing units, implying that the ability of the artificial neural net is limited by current computer hardware technology.

As previously mentioned, another important fact is that inaccurate training knowledge patterns will lead to inaccurate estimated outputs. Thus, knowledge patterns must be prepared carefully before any artificial neural net is applied in real practice.

Nevertheless, the results of this work provide the applicability of the artificial neural net to the initial gear design to emulate the decision-making tasks of the human engineer using the identical design steps. In general, similar methods can be adapted to many mechanical engineering design problems. More detailed implementation must be carried out to enhance the quality of estimations of the artificial neural net. ■

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GEAR FUNDAMENTALS

Coarse Pitch Gears

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This article discusses briefly some common manufacturing problems relating to coarse pitch gears and their suggested solutions. Most of the discussion will be limited to a low-quantity production environment using universal machine tools.

Material Selection and Heat Treatment

Table I shows common heat treatment methods and some standard grades of material associated with them.

Selection of gear material shape. Once the heat treatment and material have been selected, the starting shape or form of the material is chosen. The shape and size of the finished gear blank will dictate the form of the material to be used, such as hot rolled bar, forged bar, step forging, rolled ring forging, casting, etc. See Figs. 1-5 for some typical coarse gear blanks. The choice is also based on many other factors, such as design requirements, cost, and availability. The material and related details should always be reviewed from a manufacturing point of view. A certain percentage of material must be removed from a hot rolled bar, particularly in the gear tooth area. Excessive material removal from any shape should be followed by stress relieving before finish machining.

Table 1

Heat Treatment Method	***Material***	***Comments***
Through-Hardening	**1040, 4140 4150, 4340**	**Practically any medium-carbon steel can be used.**
Nitriding	**4140, 4340, Nitralloys**	**Any number of other alloys can be nitrided.**
Induction Hardening	**4140, 4150, 4340**	**Any medium-carbon steel can be used.**
Flame Hardening	**4140, 4150, 4340, 4640**	**Any medium-carbon steel can be used.**
Case Carburizing & Hardening	**4620, 8620, 4320, 4820, 3310, 9310**	**Any low-carbon steel can be carburized.**

Correction for distortion in heat treatment. It is normal practice to make some kind of correction of distortions caused by heat treatment. Possible corrections include, a) changing the lead or helix angle in threaded worms and helical gears before heat treatment to compensate for the change after heat treatment; b) altering tooth contact in bevel gears to minimize the effect of change in a hardening process; c) tooth size correction to compensate for changes in heat treatment.

In case of high production, samples are normally checked before and after heat treatment. The changes are recorded and analyzed. The production pieces are then modified to compensate for the predicted heat treatment distortions.

In case of low-quantity production or in a jobbing atmosphere, testing of actual pieces is not feasible. Thus, manufacturing engineering should make a study and provide guidelines for corrections during production to compensate for heat treatment distortions.

"No carb" paint. In many cases carbon removal operations can be effectively reduced or eliminated by the use of no carb paint.

Masking paint for nitrided parts. Masking paint can be used to keep certain areas soft as required by design or for post-machining.

Use of quench press to control distortions. Fig. 6. shows a quench press set up to quench a

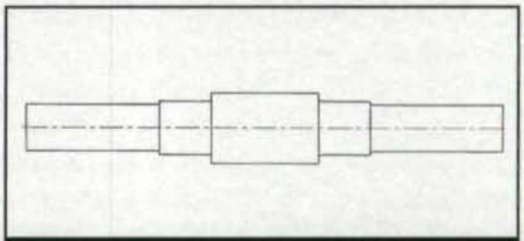

Fig. 1 - Step forging outline.

webbed cylindrical gear. Normally an expanding die is used to keep the part round, and a clamping die to keep it flat. The arrows in Fig. 6 show the suggested path for quenching oil.

Scale removal after hardening. This becomes quite important in certain cases, as scale can have many detrimental effects, including loading up the grinding wheel.

Tool Selection

Customized tools and test pieces offer many ways to enhance gear quality and productivity. For example, they can help to optimize protuberance and grinding allowances for ground gears and correct the amount of radius of teeth tips. But many times, universal tooling is the only choice for various reasons, including economic and time constraints. Below are some suggested strategies to control tooling problems.

Root fillet. Standardize root fillets for all new designs and use them whenever possible. Fig. 7 shows a comparison of standard fillet and full fillet. In most cases, switching from standard to full fillet improves the gear rating. However, there are some special situations where this conversion can cause negative effects, such as insufficient wall thickness between the root of the teeth and the bore.

Topping hobs. Topping hobs should be considered as special hobs, and their use in coarse pitch gears is very limited. Sometimes they can be useful in finishing the outside diameter on the teeth cutting machine along with the rest of the tooth. But this process has not been found to be practical for various reasons, such as time, tool life, and surface finish.

Semi-topping hobs. Semi-topping hobs can be very useful in coarse pitch gears to cut down the deburring time and control the amount of tip radius/chamfer on the tips of teeth. Great care must be taken in the design of semi-topping hobs, since serious damage can be caused by removing an excessive percentage of the active tooth profile.

Multi-thread hobs. Proper use of multi-thread hobs can increase production and reduce both time and tool cost. Concerns to be taken into account while using multi-thread hobs are: number of teeth in the gear vs. number of threads in the hob; total number of teeth in the gear, because a low number of teeth in the gear may not be suitable for multi-thread hobs; quality of the hob; hob resharpening; quality and surface finish limitations obtained with the use of multi-thread hobs.

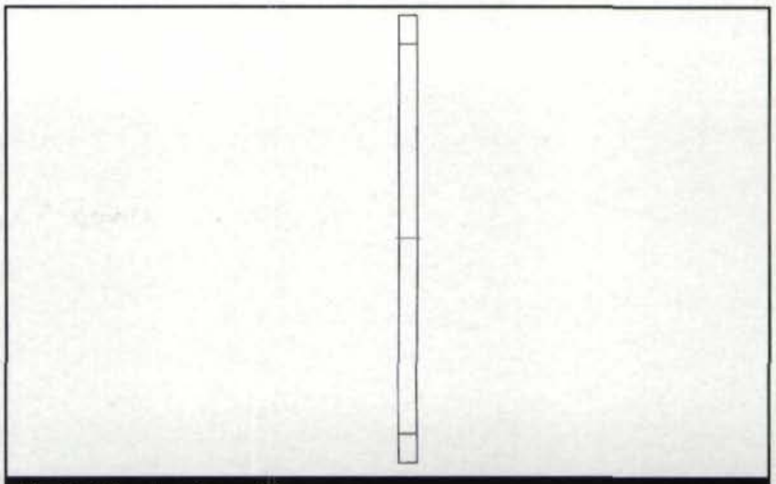

Fig. 2 - Ring forging outline.

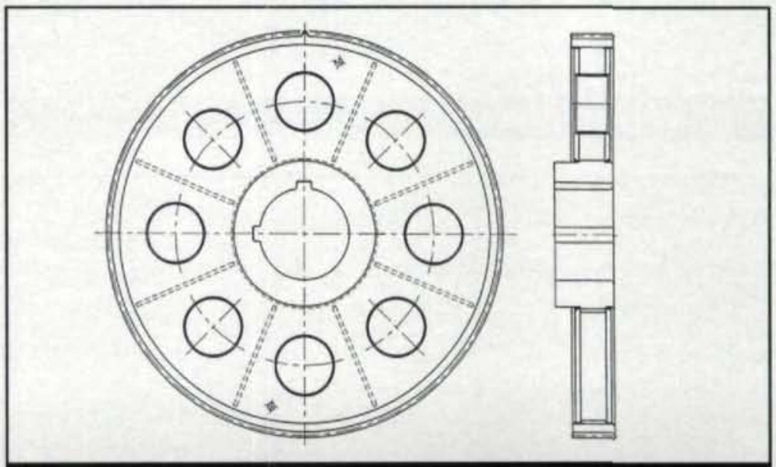

Fig. 3 - Gear weldment.

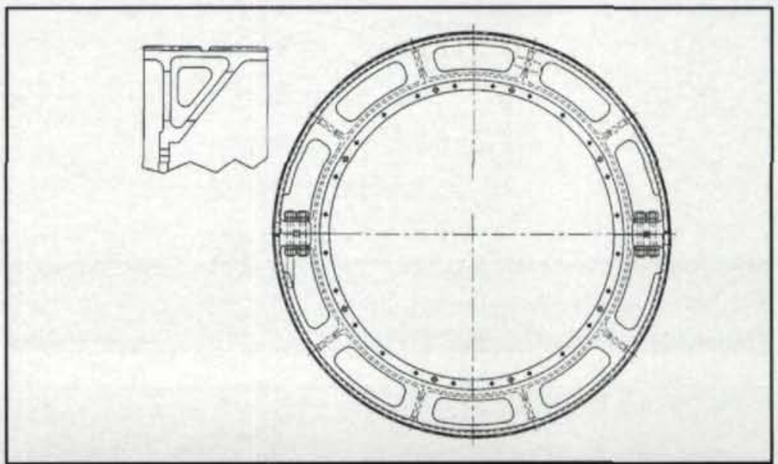

Fig. 4 - Casting (2-piece design).

Grinding allowance. The amount of grinding allowance required for various pitches and sizes should be standardized based on past data and experience and the heat treatment method used. This is a must for ordering the tools, as the amount of grinding allowance effects the tool design.

Protuberance. The correct amount of protu-

Yogi Sharma

works in gear manufacturing and design at Philadelphia Gear Corp. He holds advanced degrees in mechanical and industrial engineering and is a licensed mechanical engineer in the State of Pennsylvania. He is also a Senior Member of SME.

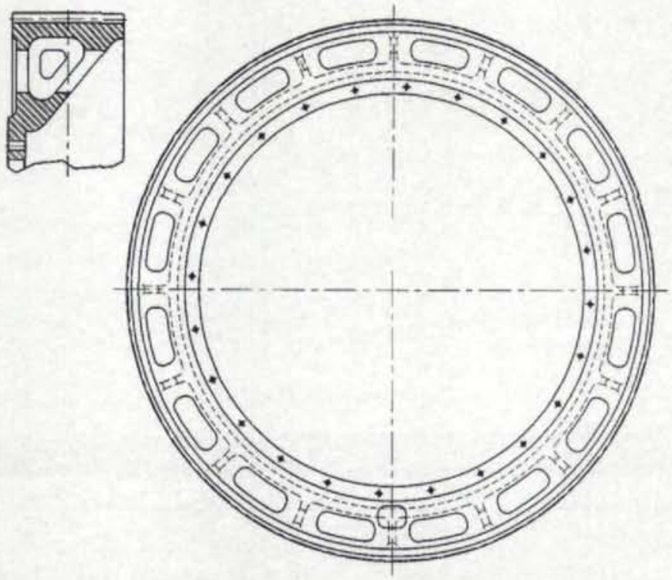

Fig. 5 - Casting (1-piece design).

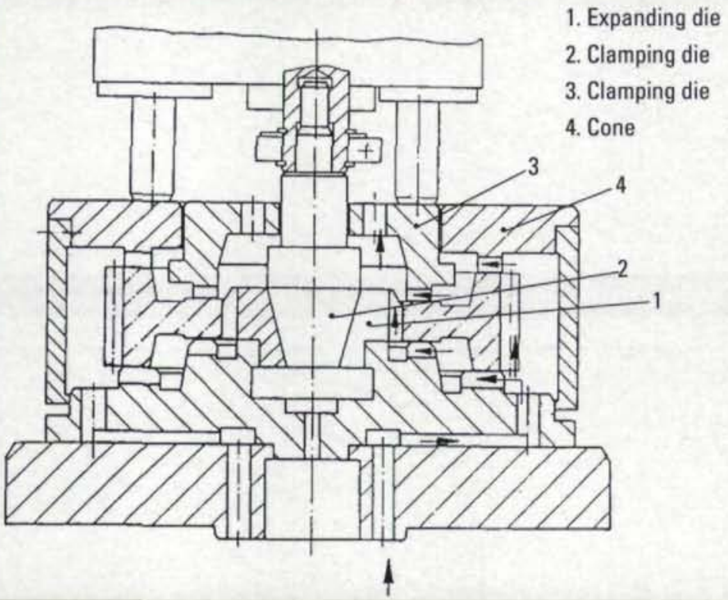

Fig. 6 - Quenching a cylindrical gear with special configuration. (Ref. Klingelnberg quench press.)

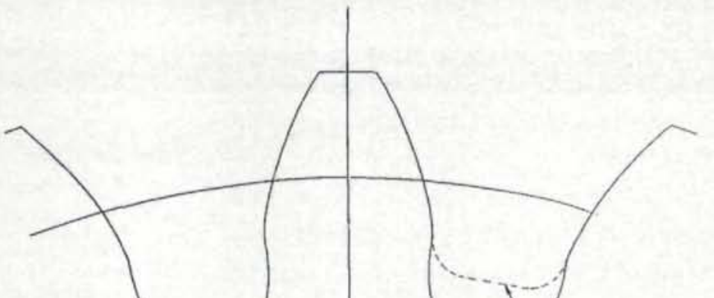

Fig. 7 - Standard vs. full fillet.

berance is very critical for ground and shaved gears. Excessive protuberance can cause an uncleaned profile along the tooth, while insufficient protuberance can cause a grinding step problem. Fig. 8 shows a protuberance tool.

Tool material. Tool material should be chosen very carefully. Fig. 9 shows a comparison of some of the material commonly used for high speed tools.

Tool coating. The use of special cutting tool coatings, such as TiN and TiCN, can help in many ways. For instance, they can reduce tool cost by prolonging tool life and producing better surface finish and lower cutting times by the use of higher feeds and speeds.

Tool resharpening. Tool resharpening is one of the most neglected subjects in gear manufacturing. Poor tool sharpening causes many problems, such as poor profile, premature tool failure, unsatisfactory surface finish, etc. A good tool sharpening program includes updating and maintaining tool sharpening equipment; proper grinding wheels, good sharpening fixtures, and inspection of tools before and after tool sharpening.

Proper care and attention to tool sharpening is very critical in coarse pitch gear manufacturing. It will make an important difference in the performance of the hob and hobbing machine.

Proper storage and record keeping. Careful practice here can eliminate many unnecessary delays and cut down on tool costs.

Teeth Cutting

Gear Blank Hardness. The hardness range of the gear blank at gear cutting primarily depends upon the selected material and the hardening method. Case-carburizing steels rarely cause tool problems at soft cutting because of lower hardness. On the other hand, through-hardened, induction-hardened, and nitrided parts may cause problems, depending on the material and blank hardness. The following are some suggested methods for handling through-hardened gears with hardness values higher than a normal range.

Rotary roughing cutters (with carbide inserts). A rotary roughing cutter with carbide inserts can rough gear teeth with higher hardness in much shorter time than high speed steel tools (hob, rack, or Fellows type). As a matter of fact, roughing with a rotary cutter is very useful for large, coarse pitch gears in any condition. It saves time and lowers the tool cost. The factors to be kept in mind for roughing are using the proper tool for certain DPN and pressure angles; using a machine with a single indexing arrangement; and using proper surface speed and feed for carbide cutters.

Some new, large hobbing machines are being manufactured with the capability of roughing with rotary carbide cutters. Some old hobbing machines can be modified to use this method of roughing.

Roughing annealed blanks. Some higher hardness gears can be roughed in an annealed condition, heat treated to the required hardness, and then finish-machined, including teeth cutting. This method provides uniform hardness throughout the tooth, including the root area. Some very coarse pitch gears are produced this way to achieve proper hardness on the entire tooth. When using this approach, the following factors should be kept in mind: extra operations will be needed for teeth cutting, heat treatment, and finish-machining; and certain gear configurations may cause some additional problems at heat treatment after rough machining and teeth roughing.

Controlling Higher Range of Hardness Values. Usually the hardness of a gear blank is specified as a range. The rating is calculated based on the lower value, while the higher value depends on the normal heat treating standards. Any closing of this range requires an additional tempering cycle, which can possibly cause the hardness to drop below the lower value. But for higher hardness coarse pitch gears, any control on the higher limit will definitely help at teeth cutting, while offsetting any additional cost of heat treatment. Control of the higher hardness limit will also benefit tooth cutting, since high speed steel tools become very inefficient above certain hardness values.

Use of specially designed hobs. Many specially designed hobs, such as rough hobs with positive rake, shear-cut hobs, multi-section hobs, multi-thread hobs, etc. can reduce tool cost and cutting time.

Teeth cutting times. Teeth cutting times can be improved by controlling such items as proper work holding fixture, correct and sufficient cutting tools, properly machined gear blanks, properly sharpened tools, maintained machine tools, regularly trained personnel, well kept coolant system, correct feed and speed, right among of cuts, and resharpening of tool at correct time.

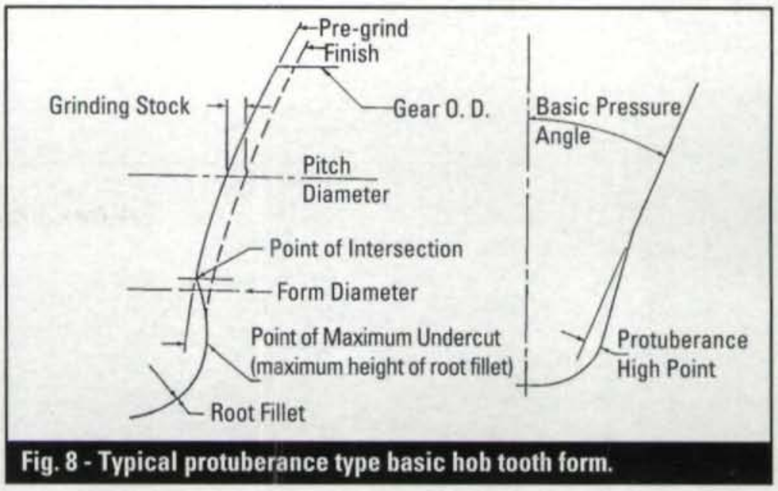

Fig. 8 - Typical protuberance type basic hob tooth form.

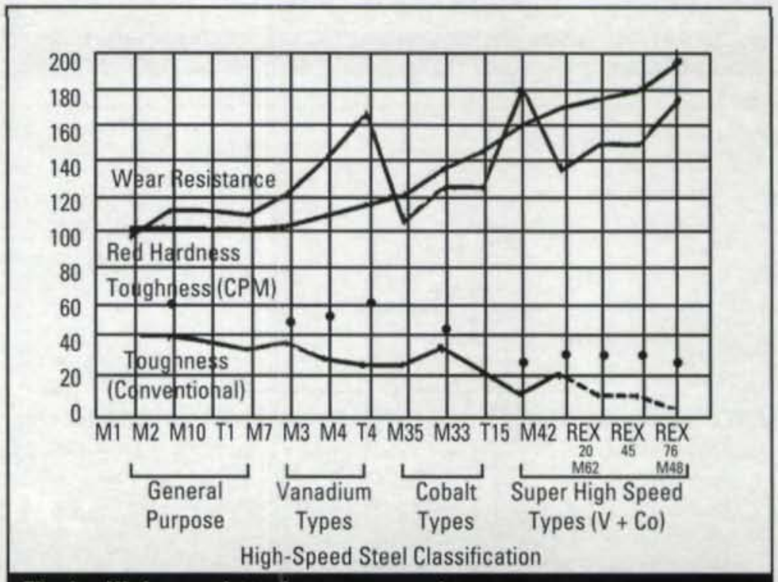

Fig. 9 - High-speed steel comparagraph.

Surface finish. The surface finish of coarse pitch gear teeth depends on many factors, including the method used for teeth cutting, such as hobbing, shaping (Maag or Fellows), or form milling. The following are some important concerns that directly or indirectly effect surface finish:

- Feed and speed at final cut.
- Material for final cut. The correct amount of stock removed in final cut must not be overlooked. Too much or too little stock are both detrimental to surface finish at final cut.
- Sharpened tool before final cut.
- Material hardness and machinability.
- Minimum material removal. Whenever possible it is desirable to remove a minimum amount or no material at all from the roots of teeth during the final cut. One approach is to rough cut teeth with a modified tool that allows little or no material to be removed at final cut. The cutting tool holds a better cutting edge and provides a better surface finish when the tip of the tool does little or no work.

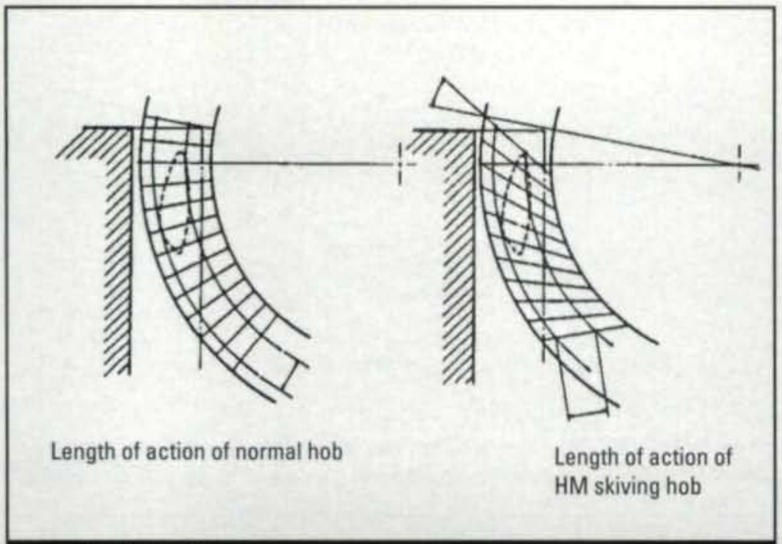

Fig. 10 - Hob skiving.

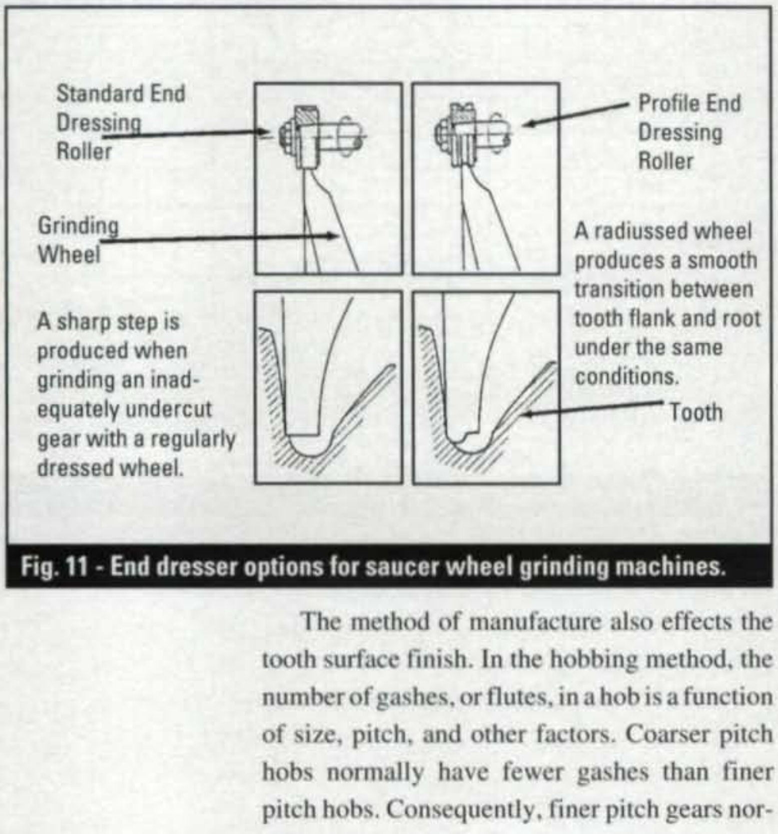

Fig. 11 - End dresser options for saucer wheel grinding machines.

The method of manufacture also effects the tooth surface finish. In the hobbing method, the number of gashes, or flutes, in a hob is a function of size, pitch, and other factors. Coarser pitch hobs normally have fewer gashes than finer pitch hobs. Consequently, finer pitch gears normally have a better tooth finish surface than coarser pitch gears.

Skiving or Hard Cutting

Skiving or hard cutting in hobbing or shaping is a term used to describe the operation in which hardened teeth are roughed or finished using a carbide tipped hob or CBN insert tools. Skiving in hobbing has limitations on quality based on many factors including machine, quality and sharpening of the tool, setup, gear geometry, etc. (See Figs. 10-11.)

Skiving hob sharpening. The carbide skiving hob is normally sharpened using a diamond wheel. Special setups are required at every sharpening to keep the pressure angle constant. A properly sharpened skiving hob is very critical for successful skiving. Improper sharpening can even produce hairline cracks in carbide inserts.

Protuberance and root clearance. Skiving hobs, as well as CBN tools, have been found inefficient in removing metal from roots because of premature chipping of tools. Therefore, proper protuberance and root clearance must be produced at soft teeth cutting prior to heat treatment.

Feeds and speeds. Feed and speed in skiving and hard cutting is important, not only for quality and time, but also for the successful execution of the process itself. Improper feed and speed can cause poor tool life, long machine time, poor quality, and many other problems. These problems can cancel all the advantages of the skiving or hard cutting. Tool suppliers should be contacted for recommended feed and speed values, which later can be optimized for each individual situation.

Skiving as a pregrind operation. Skive hobbing as a pregrind operation can be very helpful in many ways, as discussed in the section on Gear Tooth Grinding. Skiving can reduce the run time on critically loaded tooth grinding machines. In setups with limited grinding capability, skive hobbing can also be advantageous as rough finishing operations for CBN hard cutting.

CBN hard finishing of gears. CBN hard finishing is being used more and more on spiral bevel gears using rotary cutters, as well as on parallel axis gears using shaper type machines (rack type). This method provides gear teeth with the quality and surface finish of grinding without the possibility of metallurgical damage. This method also provides a means to finish larger gears which will not fit on a grinding machine. For example, gears which were originally designed as through-hardened, since no grinding capacity was available for finishing, can be case-hardened and hard-finished. Thus, the gear set rating is increased considerably without increasing the size of the set.

Gear Tooth Grinding

Gear grinding steps. Grinding steps in tooth fillets are very detrimental and have various causes. They act as stress risers and also reduce the critical case depth in tooth fillets. Any subsequent work performed to remove the steps raises the cost and can cause other problems. Here are some suggested approaches to eliminate or reduce the steps in tooth fillet.

- Always use a hob with proper protuberance, thickness, blend angle, fillet radius, etc.
- Use the correct amount of grinding allowance on tooth thickness at cutting.
- Grind the tooth flank to proper depth. Define and use the point of maximum undercut during grinding setup.
- Continuously train and educate personnel.
- Monitor and resolve problems by immediate attention.

Sometimes it will be quite difficult to avoid steps completely, because of excessive distortion at heat treatment, use of improper tools, excessive grinding allowance, etc. In such cases, use of a grinding wheel with tip radius can avoid sharp corners in grinding steps. The amount of radius can be selected on the basis of DPN, grinding machine, and all other factors. The same approach can be used in conical wheel grinding machines.

Gear grinding cracks. Gear grinding cracks usually indicate that there is a process control problem, either in heat treatment or gear grinding, or both. The correct amount of case carbon content is very critical, because an insufficient amount can cause low hardness problems; whereas, an excessive case carbon content can cause the presence of retained austenite. The grinding process generates pressure and heat, which causes transformation. Retained austenite transformation at grinding is considered a source of surface tempering or cracks or both.

Free carbides or carbide networks in case structure are another side effect of excessive case carbon content. Excessive hardness of the material (free carbides) can cause localized overheating. Overheating during the grinding results in surface tempering or cracks or both.

Heat treatment operations usually result in some film on the surface of heat treated parts. This scale must be removed before grinding, as it tends to load the grinding wheel. Surface oxidation in heat treatment produces a thin layer of decarburized and soft material on teeth flanks. This material loads up the grinding wheel, causing overheating, leading to surface tempering or cracks or both.

Excessive tooth distortions in an irregular pattern make it difficult for machine operators to locate the highest point on the gear tooth surface. If the grinding cut is not started at this point, excessive amounts of material will be removed during the cut from high points. Excessive cuts will generate overheating and can lead to cracking or surface tempering or both. This problem can be handled easily by the machine operator on a machine with threaded wheels and continuous indexing.

Gear grinding variables. The variables in gear grinding operations are the gear grinding machine, the grinding wheel, the coolant, in the case of wet grinding, and the grinding machine setup. Any problem with one or more variables can lead to various problems, including cracks on teeth. As discussed before, excessive heating at any point in the grinding operation can lead to surface tempering or grinding cracks or both. This overheating can be caused by a combination of factors, such as malfunction of the gear grinding machine, use of an improper grinding wheel, unsuitable coolant, improper positioning of coolant nozzle, or an excessive amount of cut or material removal.

Gear grinding cost. In a jobbing or low-batch production atmosphere, gear grinding time and, consequently, cost is an important matter. The time estimation is normally based on many factors in grinding, such as the number of teeth, DPB, helix angle, face, material, grinding allowance, quality, method, and machine. The final time estimate is then modified on the basis of past experience. Somehow the estimated time usually falls short of actual time. In the current competitive world, the gear grinding cost has to be maintained at a reasonable level. Below are some suggested approaches;

- Setup preparation cannot be overemphasized in a low-production atmosphere. It is good practice to have more than one item ready for the grinding machine. In case something goes wrong at the last minute with the first item in the line, the next in line can be started without excessive idle time.
- Heat treatment distortions and inadequate manufacturing process control will deliver gears with high inaccuracies to gear grinding. This will increase grinding time. Therefore, good control during the heat treatment and manufacturing processes will cut grinding times, reduce the number of scrapped parts, and enhance quality.
- Good preventive maintenance of gear grinding machines will keep downtime to a minimum.
- Training and education of personnel is quite critical and must not be overlooked.

- Use of skiving hobs can be very helpful in many ways. For instance, skiving can remove most of the distortions caused by heat treatment and present a gear for tooth grinding with limited grind allowance. This will reduce grinding time, remove any heat treatment scale or decarburized and soft layers of material from teeth flanks, and reduce the possibility of the surface tempering or grinding cracks or both.

Stress relieving after tooth grinding. A stress relieving operation after tooth grinding is highly desirable in all critical applications. The stress relieving minimizes the possibility of latent grinding cracks. Latent grinding cracks are the cracks that develop in the storage or early period of use. The typical stress relieving for case-carburized and hardened parts is around 320° F for four hours, which can be further refined for every application. The stress relieving must be carried out as soon as possible after tooth grinding, as any excessively delayed stress relieving may be too late.

Grinding allowance at tooth cutting. Excessive grinding allowance causes many problems. To avoid excessive material left at teeth cutting, all cutting personnel should be trained, parts must be checked, and sized recorded after teeth cutting.

Handling of gears with grinding cracks. Any part with severe grinding cracks or surface tempering cannot be salvaged. The suggested approach for parts with minor problems include stress relieving, regrinding to remove cracks, checking final tooth sizes and remaining case depth, and reporting all findings to the engineering department for final disposition.

Gears with close tooth thickness tolerances. Many applications need close tooth tolerances. A practical approach is to keep an approved master gear in the same environment as the gears being ground and compare sizes. For the most part, the first piece of a batch can be used as a master after complete inspection.

Miscellaneous

Shaving, honing, and lapping of coarse pitch gears. Theoretically, any gear can be shaved or honed as long as a tool is available. In practice, usually shaving and honing is associated with parallel axes gears. Whereas lapping can be used for any kind of gear where either a mate or lap is available.

Increase in gear rating due to high material hardness vs. manufacturing problems. Allowable bending and contact stresses depend upon the hardness, the quality, and grade of material. higher hardness allows higher allowable stresses, providing a higher rating or smaller gear set for any condition. In manufacturing, high hardness above a certain range becomes a problem. The design and engineering group must work very closely with manufacturing to keep this situation under control. At a certain point, it is better to have a larger gear than a hard one because the manufacturing cost at impractical hardness values will outweigh the cost due to an increase in size. Also manufacturing must be reasonable and innovative in handling the harder gears, since lowering the hardness too much will make the design uneconomical due to the increase in size.

Machining of gears after heat treatment. Finish machining of gears after heat treatment is very critical and must not be overlooked or neglected. Gear teeth can be checked for runout in the plane of rotation on a turning or grinding machine with a roller in teeth, but there is no easy way to check in an axial plane. Quite often, overcorrections are made in one place, causing extra problems in the other place. One effective approach is to indicate proof surfaces (in both planes), which were created in machining before teeth cutting and used in teeth cutting.

Another very effective method is to turn or grind proof surfaces after hardening and check gear teeth for runout and lead. Then finish machine the gear bore and faces of shaft journals after making corrections based on runout and lead charts. The above method is effective, but needs two extra operations and longer manufacturing cycle. Also, it is ineffective when a gear has irregular distortions, such as a tapered length or oval-shaped diameter. ■

References:

Loy, William E. "Hard Gear Processing with Azumi Skiving Hobs." AGMA Technical Meeting, October, 1982.

Sharma, Yogi. "Gear Grinding Fundamentals." S.M.E. Gear Clinic, November, 1988.

Acknowledgement: *Presented at the SME Advanced Gear Clinic, October 20-22, 1992, Dearborn, MI. Reprinted with permission.*

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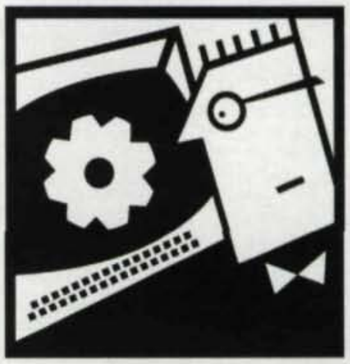
Using Hobs for Skiving; A Pre-Finish and Finishing Solution

William E. McElroy



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Our company manufactures a range of hardened and ground gears. We are looking into using skiving as part of our finishing process on gears in the 4-12 module range made from 17CrNiMO6 material and hardened to between 58 and 62 Rc. Can you tell us more about this process?

Bill McElroy replies: Skiving is basically a process which allows one to cut hardened materials with a thin, curled chip and produce a smooth finish. It is a method of finishing or pre-finishing hardened gears which may be more cost-effective than grinding. It can be used on spur or helical gears heat treated to between 50 and 62 Rc. Skiving improves gear quality by reducing errors from distortion. Moreover, compared to grinding, skiving (as a continuous generating process) can eliminate most cumulative spacing and concentricity errors. Quality levels of up to AGMA 11 can be achieved with skiving. In addition, for large DP gears (coarser than five), taking into account distortion, etc., skiving can reduce grind times by 50-70%.

Skiving can be done on conventional hobbing machines, however, the quality is totally dependent on machine rigidity, both static and dynamic. Newer machines which offer better machine rigidity, CNC controls to regulate feeds, speeds, and shifting, better chip removal, and better quality cutting tools are a better prospect for use in skiving.

Types of Skiving Hobs

Depending on circumstances, one of four types of hobs can be used for skiving. Solid carbide hobs are used for small modules (fine DPs) or for gears with a specified outside diameter. Inserted blade hobs with brazed tips are very economical, reducing hob costs while providing excellent quality. Solid hobs with brazed tips are also economical and should be used for applications with big modules (large DPs). Inserted carbide blade hobs have the advantage of increased tool life, based on their usable length. They can also improve the quality of the surface of the tooth flank.

Negative Rake Angle

When skiving it is important to use the hob to cut only on the involute profile of a gear, not into the root fillet area.

The negative rake angle of a skiving hob reduces the cutting force and shock resistance, as well as the vibration in the hobbing operation. Because of this angle, the cutting becomes easier, since the tool gradually penetrates into the gear.

Generally speaking, the rake angles vary between -15° and -30°, depending

William E. McElroy

is President of GMI, Independence, OH. He has nearly 25 years' experience in manufacturing and ten years in the technical sales and application of gear manufacturing equipment.

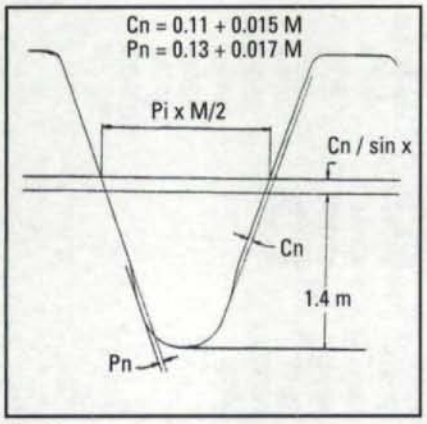


Fig. 1

on the tool geometry and module (DP).

The sharpening of the tool should be done with a diamond dressing wheel and coolant. The position of the dressing wheel will be determined by the value of the rake angle and skiving hob outside diameter. Table 1 shows the dressing wheel positions for resharpening all through the tool life.

Tool Reference Profile

The skiving process requires that some prior hobbing conditions be met.

Table I - Hob Sharpening Data

Part No.: HM.V22/12 Hob S/N: 2950

Tip
dk 48.300
DESPX -8.550
hr 2.000

h : 2.950
EPS : -20° 44'04"
ST : 4.70

Number of Resharpenings	Outside Diameter dk mm	S	DESP X mm	Angle EPS
1	48.300	0.000	-8.5500	-20.734 (-20° 44' 04")
2	48.100	0.551	-8.5024	-20.703 (-20° 42' 12")
3	47.900	0.548	-8.4572	-20.678 (-20° 40' 12")
4	47.700	0.544	-8.4146	-20.659 (-20° 39' 34")
5	47.500	0.541	-8.3744	-20.647 (-20° 38' 48")
6	47.300	0.538	-8.3366	-20.640 (-20° 38' 25")
7	47.100	0.534	-8.3012	-20.640 (-20° 38' 24")
8	46.900	0.531	-8.2683	-20.646 (-20° 38' 46")
9	46.700	0.527	-8.2379	-20.659 (-20° 39' 31")
10	46.500	0.524	-8.2099	-20.678 (-20° 40' 41")

Table II - Carbide Composition

ISO	Rockwell Hardness	Deflection Resistence	W	Co	Ti	Ta	C
P20	90	90	60 83	5 10	5 15	0 15	6 9
M10	91.5	100	70 86	4 9	3 11	0 11	6 8
M15	89.5 93	120 220	75 95	5 9	0 10	0 12	5 7
K05	89 93	150 230	85 97	3 8	0 3	0 7	5 7
K10	90.5	120	84 90	4 7	0 1	0 2	5 6

Table III

Feed Module (DP)	Rough mm (in)	Finish mm (in)
> 12 [< 2]	3 - 4mm/rev (.120 - .160"/rev)	2 - 3 mm/rev (.080 - .120"/rev)
> 12 [< 2]	2 - 3.5mm/rev (.008 - .140"/rev)	1.5 - 2.5mm/rev (.060 - .100"rev)

Table IV

Hardness HCR	Speed mm/min (in/min)
50-55	70 + 90 (220 - 290)
55-60	60 + 70 (190 - 220)
60-65	50 + 60 (160 - 190)

Table V

Module DP	Speed mm/min (in/min)
1 + 5 (5 - 25)	60 + 90 (190 - 290)
6 + 12 (2 - 4)	50 + 70 (160 - 220)
> 12 (< 2)	30 + 50 (96 - 160)

The pre-skiving operation, before heat treatment, should be done with a hob which has a protuberance on the tip of the tooth and with an addendum of 1.3 to 1.4 times the module, in such a way that an under-cutting at the bottom of the gear tooth is produced, avoiding any work on the tip of the skiving tool that would cause it to chip or break. (See Fig. 1.)

The skiving hob only removes the excess stock on the tooth flanks, thus reducing the cutting forces and guaranteeing a better finishing quality.

The cutting force generated during the skiving operation is 15-20% of that generated from normal gear hobbing operations.

Carbide Grade Quality

The selection of suitable carbide grade depends on the application of the skiving operation. The most useful grades are the cementation steels with hardness of 90-92 HRc. (See Table 2.) In our experience, the most used grades are K10 and M10. The K10 grade is the most universal one, due to its great tensile strength. The M10 has less tensile strength, but more wear resistance.

For a cutting oil, it is best to use one of low viscosity, 10-20 cst for 40° as coolant, if possible with a molybdenum additive. Dry (no coolant) cutting is also possible.

Speeds and Feeds

Tables 3-5 allow you to calculate the speeds and feeds needed to skive a variety of gears. The data is based on test results from hobs actually in use. They provide basic parameters, which will have to be altered to suit the particular conditions at the time of skiving.

A number of points should be kept in mind when skiving.

- The higher the feed rate, the less the wear.
- It is absolutely necessary to remove the same amount of material from

both flanks. The hob *must* be centered to the workpiece.

- The cutting speed will depend on the machine running condition, workpiece hardness (HRc) and module (DP).
- The cutting speed range should be between 30-90m/min (90-290 ft/min).
- Flank wear can be reduced by decreasing the cutting speed.
- The number of passes (1 or 2) will depend on workpiece heat-treat distortion and the quality required.
- Climb hobbing is the recommended method for less wear.
- Use plenty of coolant (cutting oil), even though the work can be done without coolant (dry), since the generated temperature is low.
- TiN coating offers higher wear resistance.
- The stock material to be removed by the skiving hob should be 0.11-0.15mm (.0044-.0060") per flank. It could be as much as 1mm (.040") in case of major heat-treat distortions. In those circumstances multiple cuts will be required.

Hob RPM Calculations

The hob rpm calculations are performed as follows:

Given that 1m = 3.281 feet and that the recommended speed is between 30-90m/min,

30M x 3.281 = 98 feet/minute

90M x 3.281 = 295 feet/minute

The relationship between hob diameter (if in inches, convert to feet) and circumferential distance is calculated as follows:

12" OD x (3.14) = 37.68"

12" = 3.14'

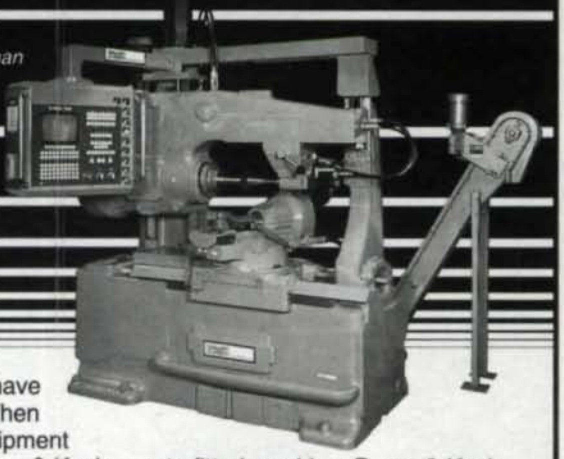
(If in feet, multiply by 3.14 ONLY)

To calculate the RPM:

$$\text{RPM} = \frac{\underline{98 \text{ ft/min.}}}{3.14 \text{ ft}} = 31 \text{ low end}$$

$$\text{RPM} = \frac{\underline{295 \text{ ft./min.}}}{3.14 \text{ ft.}} = 94 \text{ high end}$$

Feed rate/revolution = 1.5mm to 3mm = .060" to .120" ■



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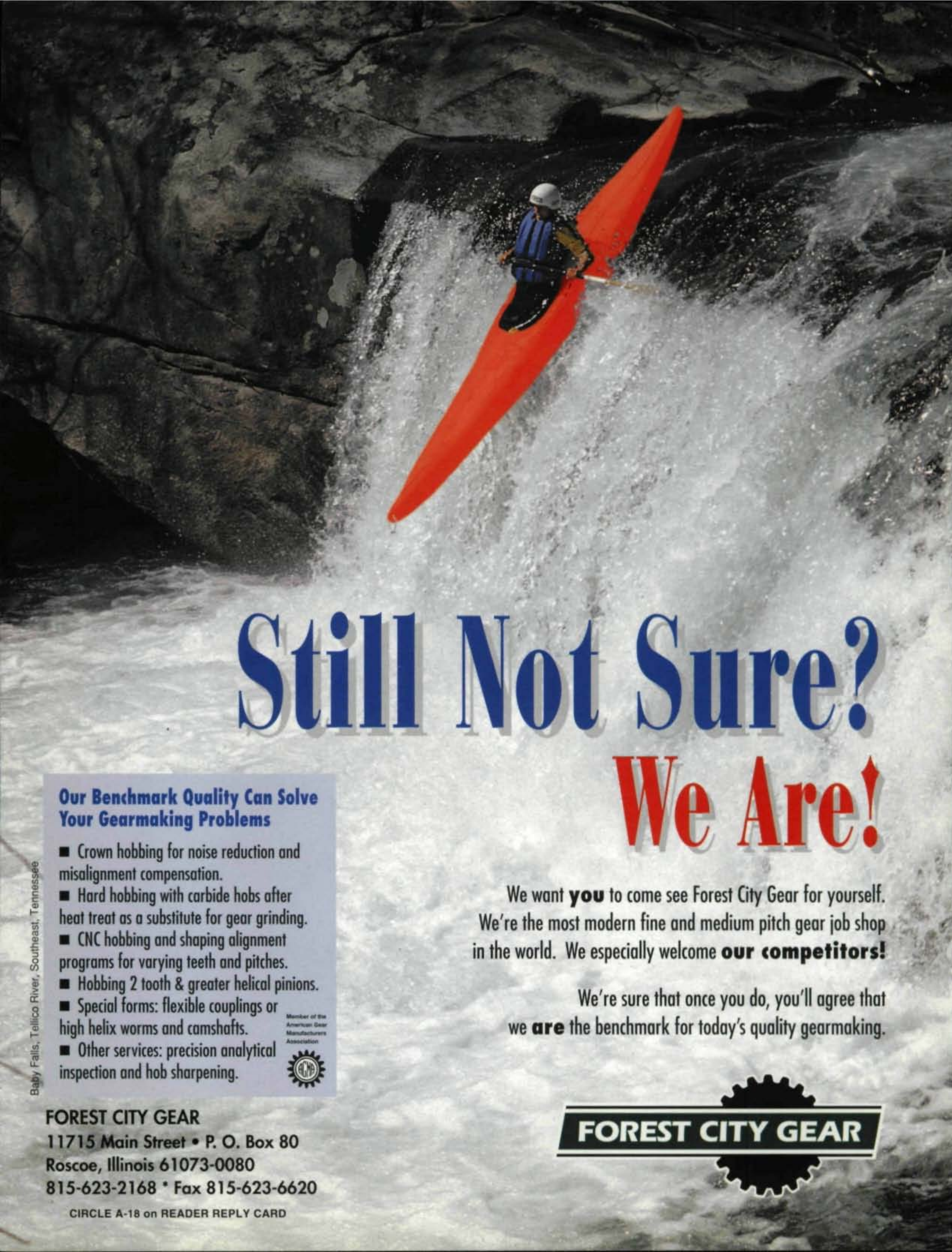
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