GEAR TECHNOLOGY

The Journal of Gear Manufact

GEAR MANUFACTURING IN THE '90s

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January/February 1995

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CIM—Pipe Dream or Wave of the Future?

- **The Paperless Factory**
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JANUARY/FEBRUARY 1995

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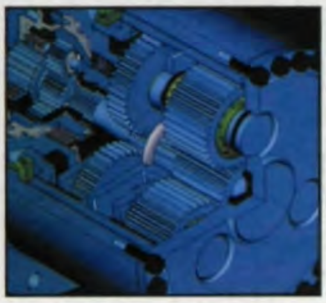
GEARING IN THE '90s



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CHANGES

Changes

Welcome to the new *Gear Technology*. With this issue we begin bringing you a new look—a new cover, new graphics, a new, broader and more inclusive editorial focus. Our goal is to be an even better resource for the entire gear industry.

To our loyal readers who have told us how much they value the "old" *Gear Technology*, please be reassured that we will continue to bring you high-quality research articles that cover the latest in gear design and manufacturing advances. At the same time, we will be expanding our coverage and making both our graphics and editorial more "reader-friendly."

As we have prepared this first issue of the "new" *Gear Tech*, our focus subject—computers and gear manufacturing—has been resonant of our situation here. Just as the changing times and needs of our readers have demanded that we change the way we do things, the changing times, technology and demands of the marketplace require that gear manufacturers and designers let go of some comfortable, even cherished, practices to keep up with the competition.

In our conversations with some of you over the last few weeks, we have heard the same refrain: The successful gear manufacturer today will produce gears faster, more efficiently, perhaps in smaller lot sizes, and at lower costs than ever before. And to meet these goals, these manufacturers will integrate the computer even more thoroughly into their total business environment.

While the computer revolution has come more slowly to the gear industry than to some other areas of manufacturing, it has indeed arrived. Ready or not, cybergearing is here. The question no longer is whether we should consider integrating computers into our manufacturing processes, but when, how and which ones. Even for those among us for whom the computer manufacturing revolution is old news, the rapid developments in both CNC hardware and software demand constant watching.

WAITING FOR THE RATE OF CHANGE TO SLOW

is to wait for a bus that will never arrive.

And that's the rub. Computer technology seems to change faster than a Pentium chip can process data, and in an industry where a machine upgrade can cost a hundred thousand dollars or more, nobody wants to be stuck in an obsolescence backwater six months down the road. On the other hand, waiting for the technological change to slow down before upgrading is to wait for a bus that's never going to arrive.

But there are solutions. They're not always simple, neat, tidy or risk-free, but they're there. In this issue, we hope to help you sort through the megabytes of information on computerized gear design and manufacturing so you can arrive at the solution that's best for your particular situation.

Change, even when it's for the better, is never comfortable. The learning curve is frequently deeper, more expensive and harder to navigate than we first thought. But it can be done. The companies featured in this issue have done it. With intelligent planning and care, you can do it too.

Michael Goldstein

Michael Goldstein
Publisher & Editor-in-Chief

Jim Gleason of The Gleason Works

What follows is the first of a series of interviews Gear Technology *is conducting with leaders in the gear industry. We will be asking them for their insights on where the industry is, where it's been and where they see it going in the future. Our first interview is with Jim Gleason, president and chairman of Gleason Corporation, Rochester, NY.*

GT: What do you see as the state of the American gear industry today? Is it better or worse off than it was 10 years ago?

JG: I think the American gear industry is in significantly better shape than it was 10 or even five years ago. There are a number of reasons for this. The U.S. economy has certainly buoyed up every one of the U.S. manufacturers. Secondly, there are a number of things that the manufacturers themselves have done to improve their situation. For example, many manufacturers have streamlined their organizational structures, and many have applied total quality principles to their operations.

GT: Where do you see the gear industry being 10 years from now? Will it grow or shrink?

JG: American companies are going to have to think about establishing a presence outside the U.S. It will become ever more important to be able to serve the customer in more

Jim Gleason

than one geographic region of the world. If American manufacturers are able to gain market share overseas, I think there will be some room for growth, but I don't think it will be dramatic. Increasing productivity will probably put some limits on staffing levels, but as equipment manufacturers, we hope that capital investment in new machines is also a part of increasing productivity.

GT: What do you see as the strengths and weaknesses of the American gear industry today?

JG: We're operating in an environment where our cost structures are very competitive. Many of the American firms have taken the issue of quality very seriously, and many have instituted programs to improve both quality and productivity. The current economy will probably provide a source of capital so that reinvestment and needed improvements will be affordable for many firms. We're at a point where the strength of U.S. industry is quite good. We're operating in an industry where the participants vary greatly in size from the very large to the very small. Some of the small firms are going to have to work very hard doing the things that will help make them competitive. That includes acquiring state-of-the-art equipment and working hard at establishing quality credentials and presence in markets outside the United States.

GT: Where do you see Gleason as a company being in 10 years?

JG: From a strategic point of view, we're committed to increasing the breadth of our product offerings in all phases of gear manufacturing and to fine-tuning our manufacturing operation to the point where we clearly have the broadest and most productive gear machinery product line in the industry. We have an opportunity to expand our product and market offerings to areas that are affiliated with gear manufacturing, but not specifically within that category, such as more comprehensive service and preventative maintenance contracts or equipment to manufacture other products with geometric shapes as complex as gears. First we have to get our own house totally in order to have state-of-the-art manufacturing. If we're going to convince anybody else that they ought to buy new machines, then we should be a shining example of that in our own plant.

GT: Has the downsizing of the defense industry had a significant impact on Gleason's markets?
JG: Our total sales to the defense industry have been fairly sporadic, and, while there have been some marginal reductions, increases in the general commercial vehicle and other markets have much more than offset a drop in defense.

GT: How can gear machinery manufacturers compete in foreign markets?
JG: Let me turn that question around, because I think the foreign competitors better think about what they're going to do to compete with us. At present the total manufacturing costs in the U.S. are lower than in any other fully industrialized country. In the down economy of recent years, U.S. companies have become leaner and lowered costs. They have applied quality programs and offer quality as good as or better than foreign competitors. In addition, the currency exchange rates have lowered the cost of U.S.-made products for export.

GT: What role do you see for AGMA in the future of the gear industry?
JG: Because so many companies in this industry are small, an organization like AGMA can play a tremendously constructive role in keeping people informed about directions of technology, quality programs, how to approach foreign markets. . . a whole array of questions that small companies have a hard time answering. Of course, the traditional roles of setting standards that benefit the entire industry and communicating effectively internationally with respect to standards are also of vital importance.

GT: As an exporting manufacturer, what's your reaction to ISO 9000? Is it good or bad for your business?
JG: On balance I think it's positive. Any set of guidelines that can assist a company in improving its whole system of quality is good. Sometimes the application of those guidelines and standards can be a little too bureaucratic, and I think sometimes the application of these guidelines is for reasons other than to assure quality, such as limiting access to markets. But we don't view it as a hindrance. In fact, our tooling division is ISO 9000-certified, and we're looking forward to meeting European Community standards with regards to safety issues. The problem with ISO 9000 is that, in and of itself, it does not ensure that the products you deliver to your customers are quality products.

Any company that is truly interested in quality needs to go beyond ISO 9000 and put in place a total quality management system to assure that its customers are getting what they expect and want.

GT: Would you share some successes or failures in doing business with mainland China?

JG: Some of our machines in China actually predate the Chinese revolution. After the embargo was lifted, we were one of the first companies to go back in and actually ship machines. We now have nearly 700 machines in China. They have been a somewhat erratic, but very good market for us. Their economic cycles and political disturbances over the last 20 years have made it difficult to predict what's going to happen, but even that seems to have steadied itself. As their economic sophistication grows, they're going to be a major, growing market. On balance, our experience has been very positive. We've actually had as much trouble with U.S. export controls as we have ever had with the Chinese. While we view China as a terribly important market, I think it would be a mistake to sit back in the U.S. and assume all you have to do is put things in boxes and ship them over to China, and they're going to buy them. They have a huge requirement for building up their own capabilities, both in a broad sense and in respect to gear manufacturing, and I doubt they're willing to supply all of that by simply buying it offshore. Exporters need to be aggressive in establishing alliances within China. We've announced a joint venture for technical training and service in China and expect to have it consummated very shortly.

GT: What other "hot" markets should we be exploring in the coming years?

JG: Another very interesting international market is India. The technical capability and knowledge of their trained people is pretty impressive. We're also starting to see some interesting things coming out of South America, especially Brazil, and, of course, Mexico. There are a number of these interesting potential international markets with significant population bases that represent some very exciting prospects over the next 10 years.

GT: What role do you see the electronics revolution playing in gear manufacturing in the future? Will we continue to rely on dedicated CNC software/hardware, or will PC-based machines with networking and multi-tasking be the way of the future?

JG: I think the direction is clearly going to be toward PC for all kinds of reasons. The flexibility of what you can do in terms of user interfaces is far more dramatic. The cost of production is also going to be a major factor in the selection, and too many big things are driving us in that direction for it not to be important. I don't think the majority of machines produced in the U.S. by the year 2000 will be PC-based, but it won't be too many years after that.

GT: Are there any closing comments you'd like to make?

JG: I'd just like to re-emphasize that American gear manufacturers as a whole are in pretty good condition and have a very interesting solid base on which to build our future success. As someone who has a lot of concern for this industry, I think it's a nice prospect. It's been a while since we've been in this position. I'm very enthusiastic about our future.

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CNC Gear Manufacturing — Where Are We Now?

A report from the cutting edge and elsewhere.

Nancy Bartels

These days it's hard to get through breakfast without reading or hearing another story about how the computer is changing the way we live, sleep, eat, breathe, make things and do business. The message is that *everything* is computerized now, or, if it isn't, it will be by next Tuesday at the latest. Well, maybe.

No doubt it's hard to find a gear manufacturing facility in the country that doesn't have a computer at work doing something, even if it's only keeping the accounts. But beyond that, the truth is that the computer has come to the gear business a lot slower than to other areas of manufacturing. A lot of people are still out there cutting gears the old fashioned way—electromechanically.

Brian Cluff
American Pfauter

Gary Kimmet
The Gleason Works

But for how long? How accurate is the message, "Upgrade or die"? Is the vision of "the paperless factory" and CIM an achievable goal or Star Wars hype? Has the small size of the market and the complicated kinematics of the process doomed gear manufacturing to perennially playing catch-up ball in terms of the cyber-revolution? Where do computers fit into gear manufacturing *really*?

For answers to these questions, we went to the people in the field—the gear machine and cutting tool manufacturers, the gear companies and the manufacturers of the computer controls for the machines.

How the Machine Manufacturers See It

Gear machine makers have been building CNC machines for better than a decade and see no reason to stop now. If nothing else, market conditions demand it. "The progress has definitely been market-driven," says Gary Kimmet, The Gleason Works' Vice President—Engineering. "In the past twenty years, there has been a happy confluence of the needs of manufacturers for greater efficiency and lower production costs and the giant advances in the use of the computer."

What the market is asking for now is faster feeds and speeds, simpler, faster setups, more customization, simpler, more user-friendly controls, networking capabilities—in short, anything that will make the gear manufacturing process more efficient and less expensive.

"The next advance in machines will be in terms of speed," says Dennis Gimpert, President of Koepfer America. "Cutting tools today appear to be able to run faster than the machines that drive them."

Peter Kellenberger, Manager of Engineering for Reishauer, concurs. "I see a move toward faster and faster setup and easier operation."

One specific process where many of these issues are addressed is grinding. Kellenberger predicts that new machines will help make grinding decisions. Soon the operator will be able to put gear data into the machine, and the software will propose a specific grinding solution for the gear.

Another new computer-generated advance in grinding is the machine that not only makes the gears, but inspects them as well. A PC with evaluation software is a part of the machine. Brian Cluff, Vice President of Sales Engineering at American Pfauter, points out that this technology is a special boon to shops grinding large, expensive workpieces. Because the workpieces don't have to be removed from the machine, inspection time is shortened. The same PC-operated inspection probe can optimize stock removal and assist the operator in making grinding decisions.

But grinding is not the only place where gear machine manufacturers see software/hardware advances. Brian Cluff sees a demand, particularly among automotive manufacturers, for dedicated, single-purpose machines with even simpler controls. This demand is driven by the need to continue to lower production costs. "The more you can do on a single machine, the more you can reduce costs, time spent and product variation and, therefore, increase quality."

At the other end of the gear manufacturing market, job shops have a different set of needs, which also can be met by advances in CNC. Job shops need equipment that can do multiple tasks. They should be looking at machines with multiple heads that can shape, hob or mill. The software is resident, and the operator can select what he or she needs for a particular operation.

Gary Kimmet says, "We will be seeing a higher degree of customization in the future. Software can be written to meet a customer's unique needs." He also sees increasing user-friendliness in machines. Instructions and machines will be self-explanatory and intuitive.

What the market is asking for now is faster feeds and speeds, simpler setups, user-friendly controls, networking—anything to make the process more effective and less expensive.

Where Does the PC Fit in All This?

While many of us immediately think of the PC when we think about any kind of computer technology, gear machine manufacturers differ about the role it will play in gear manufacturing. Gary Kimmet says, "PCs and workstations will definitely play a role. The trend is moving toward network, cellular flow." But he also adds, "This development is all over the map, depending on the needs of particular customers. Some shops will never see themselves as needing this degree of sophistication."

On the other hand, Dennis Gimpert is less impressed with the potential role of the PC. "I don't see them as having much more use than they have today. They will not run gear making machines because they are not "hardened" for the [shop floor] environment. They don't allow real-time simultaneous processing of data from the different axes. They're just not designed to run machine tools."

Peter Kellenberger agrees. "You can use a PC for expanded memory, but there isn't really much call for this from our customers."

Manufacturers also disagree over the role of Computer Integrated Manufacturing (CIM). Brian Cluff says, "CIM is the way all gear manufacturing is going eventually."

But others disagree. Peter Kellenberger says, "I don't believe in the 'paperless office.' Everybody still wants a hard copy."

Dennis Gimpert goes even farther. "It's an extremely expensive option, and I don't think it's practical at this point," he says, arguing that CIM doesn't really apply to mass production situations and is too expensive for the average job shop. He adds, "I don't know of one CIM installation that is truly successful."

He would like the industry to address what he sees as more basic issues. "What's more important right now is that the American gear manufacturing equipment is so outdated. It's more necessary to get good new cutting, measuring and sharpening equipment. That's more important than glitzy computer upgrades."

The Bottom Line

One of the reasons that gear manufacturing has lagged behind other metal cutting process-

Dennis Gimpert
Koepfer America

Fred Sowinski
Falk Corporation

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

es in the integration of computers has been the smallness of the overall market and the price of new equipment. Computer hardware and software manufacturers have naturally gravitated toward larger markets first, and equipment buyers have sometimes been hard put to come up with the dollars necessary to upgrade their machinery. What are the chances that the fall of silicon chip prices will bring down the cost of new machinery?

Pretty small, alas. Gary Kimmet says, "Costs will drop, but not with the kind of dramatic force seen in personal computers. The global economy will demand this. The other thing you might see is holding the line on price, but incorporating more and more features for the same kind of money." The other machinery manufacturers interviewed either concur with this view or believe the cost of new machinery will remain stable.

Beyond The Black Box

One of the biggest changes in CNC gear manufacturing over the last few years has been in the machine controller or "the black box." Not so many years ago, every gear machine manufacturer built his own. The hardware and software were proprietary. Now driven by cost pressures and the increased power of generic CNCs, there has been a shift toward using commercially available controllers.

In the last few years controller manufacturers have begun to develop the unique algorithms required for gear making, the precise controls required to make an "electronic gearbox" and to customize the software for gear manufacturers. In the past, one of the most difficult parts of computerized gear manufacturing was the programming. The new CNCs allow the manufacturers to embed their own proprietary interfaces—the graphics, screens, special programs, etc.—into the CNC software.

John Turner, Manager of CNC Product Marketing for GE-Fanuc, estimates that as much as 95% of the controller can now be generic, with the remaining 5% customized for the particular gear machine manufacturer.

Mark Devonshire, Manager of Production Marketing at Allen-Bradley, sees the cost of controls coming down while their power goes up. "Machines are now able to do more in less time," he says. "For example, we can better control the tracking of the hobber and the workpiece. It used to be that you had to make a tradeoff between accuracy and time. You could make gears fast or accurate, but not both. Now that distinction is growing smaller."

"I don't believe in the 'paperless office.' Everybody still wants hard copy." – Peter Kellenberger, Reishauer

But there are some caveats to keep in mind when looking at the possibilities offered by the new CNC controls, particularly when considering the possibility of PC-based control systems.

According to John Turner, "The evolving control architecture may represent an investment risk for gear manufacturers. The real investment is in the software developed to interface the control and the machines. If PCs, which are consumer-driven in development, keep changing, manufacturers are running the risk that in 18 months or less, expensive programming they have written will be obsolete."

Turner sees a split developing. Motion planning, machine sequencing and interfacing, where big bucks are spent for programming, will continue to go in the "traditional CNC." The PCs will handle the operator interfaces, the data storage and communications.

Mark Devonshire sees another limitation. "We can do the paperless factory now, but the problem is people have a bunch of machines from different vendors and of different ages. And you usually can't upgrade your whole system at once. A company could sell a whole system that could speak together, but that's not the way companies upgrade."

The View from the Shop Floor

Gear machinery manufacturers naturally have a vested interest in the latest and greatest CNC upgrades for machines. Where do the gear manufacturers themselves see their place in the world of cybergearing? Not surprisingly, all of the gear manufacturers we talked to have

Yogi Sharma
Philadelphia Gear

integrated computers into their operations to a greater or lesser degree.

According to Paul Roberts, Senior Software Programmer at Cincinnati Gear, his company uses computers most in the area of production management and control—for scheduling, inventory, etc. CNC machines are also important in all the company's milling and turning operations, but it still uses a lot of manual gear cutting machines. Like many other manufacturers, Cincinnati is reluctant to turn over the manufacture of large, expensive workpieces to a computer.

Fred Sowinski, Vice President of Engineering and Technical Services at Falk Corp., which makes gears up to 46' in diameter, says, "Large machines are still mostly mechanical, partially because of the risk involved. We're still more willing to trust people and mechanics rather than computers to do the big, expensive workpieces."

According to Joseph Schulz, marketing manager at Milwaukee Gear, his company uses computers in all aspects of the design and manufacturing process. He sees CNC machines as most useful in turning, hobbing, drilling and grinding and least helpful in finishing processes like deburring and washing. He sees the greatest use for PCs and workstations in the areas of design and keeping track of inventory.

> *"We are still more willing to trust people and mechanics rather than computers to do big, expensive workpieces."*
> *—Fred Sowinski, Falk Corporation*

And what does the highly touted world of CIM look like from the shop floor? At Cincinnati Gear, there is no interconnectivity between engineering and production. Says Roberts, "We're still using blueprints and shoe leather." However, he adds that upgrading in this area is the only way to go. "Using a computer means less chance of screw-ups in terms of torn prints, lost documentation, etc. We're being driven by competition to upgrade computer use in all areas."

Yogi Sharma, Product Manager at Philadelphia Gear, concurs: "PCs and workstations are very much a presence in shops of all sizes. They are being used as interfaces between CAD systems and large machines."

Bill Maples, Marketing Manager at Star Cutter, the cutting tool manufacturer, adds: "You have to do it [use CNC and CAD] to stay on the cutting edge—no pun intended."

Falk Corporation is also working toward completely integrated manufacturing. "Manufacturing and production engineering are on the same mainframe and LAN," says Fred Sowinski. "There's a migration away from mainframes and toward PCs. IBM has made it clear they're not going to support the mainframe forever."

Sowinski also sees a definite trend toward CIM. He observes that machine controllers are becoming so powerful that they can support many functions themselves. Larger (100-200 MB) storage eliminates the need for DNC in some cases. He sees the next step as "a total closed loop—complete integration of design, manufacturing and inspection."

Whither the Job Shop?

This might all be well and good for the big gear manufacturers with lots of resources for capital improvements, but what about the little job shops? Will they disappear, run over by the computer juggernaut?

Not necessarily. Almost everyone we spoke with sees a future for the small shop. There will always be a need for repair services and orders of one and two gears. But the future won't be easy. Fred Sowinski points out, "The pressure is really on to computerize. If a small guy can possibly afford it, he should do it. The competitive and cost advantages will be worth it."

And Bill Maples warns: "Smaller shops will have to develop niche markets. In order to succeed they will need good management, good technology, good marketing and good timing." ○

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Bill Maples
Star Cutter Co.

John Turner
GE Fanuc

ADVERTISER INDEX

The "Paperless" Factory

The next step in efficient gear manufacturing.

Carl Watkins
J.N.L. Industries
Robesonia, PA

You're already a veteran of the computer revolution. Only you and your controller know how much money you've spent and only your spouse knows how many sleepless nights you've had in the last ten years trying to carve out a place in the brave new world of computerized gear manufacturing. PCs, CNCs, CAD, CAM, DNC, SPC, CMM: You've got a whole bowl of alphabet soup out there on the shop floor. Overall these machines have lived up to their promises. Production time is down, quality is up. You have fewer scrapped parts and better, more efficient machine usage.

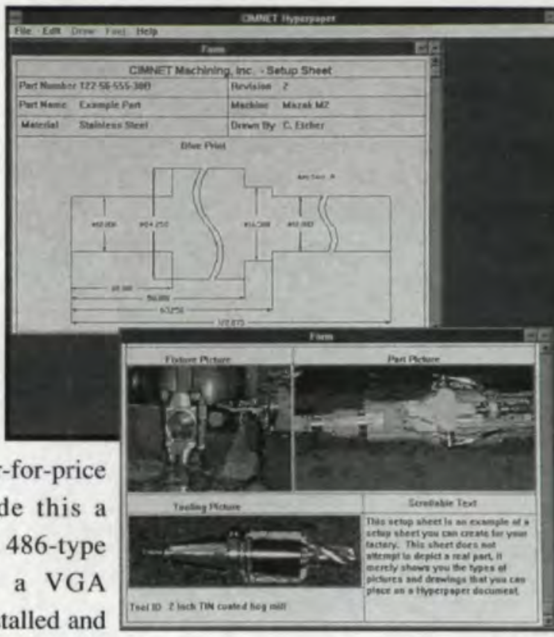
Still, there are glitches in the system—places where things come to a halt while someone brings the paperwork from the other side of the factory, looks for a lost blueprint or waits for a work order. And still your customers demand higher quality in less time and, ever and always, lower costs. So what's the next step?

Many say it will be the "paperless" factory—a production environment where information and data are transferred electronically over networked computers. Instead of having an operator walking around getting a blueprint or fixture, he or she stays at the machine, retrieving instructions on a workstation. At the very least, having the right information where it is needed, when it is needed, will increase machine usage significantly and eliminate errors.

Sounds good, but how feasible is it? Can you actually get to the point of "paperless" manufacturing, and if so, how?

The answer is "yes, you can," and the way you get there is step by step.

Converting to a paperless manufacturing operation is a gradual process. The basic premise to understand and accept is that eventually each operator stationed at a machine or machine cell will have a computer connected to a network. The astounding improvement in computing-power-for-price of PCs has made this a realistic goal. A 486-type computer with a VGA color monitor, installed and connected, can cost as little as $1000.



The machine operator's interface is critical to fast, effective implementation of a paperless factory. CIMNET™ Folders' WorkMan module has a button for each of the operator's primary tasks.

In the ultimate paperless office, these computers are connected to each other by a MICS, a Manufacturing Information Control System. Once this network is in place, all paper documentation is put in digital form. Hand-written pages, such as fixture drawings, are scanned into the computers with a simple inexpensive scanner. Word processors, spreadsheets, databases and planning programs all generate files that are stored on hard drives, if not on an existing network. All the data is available by means of a few keystrokes to anyone who needs it. Fundamentally, that's all there is to the "paperless" factory. Realistically, there are lots of details to work out.

The Machine/Operator Interface

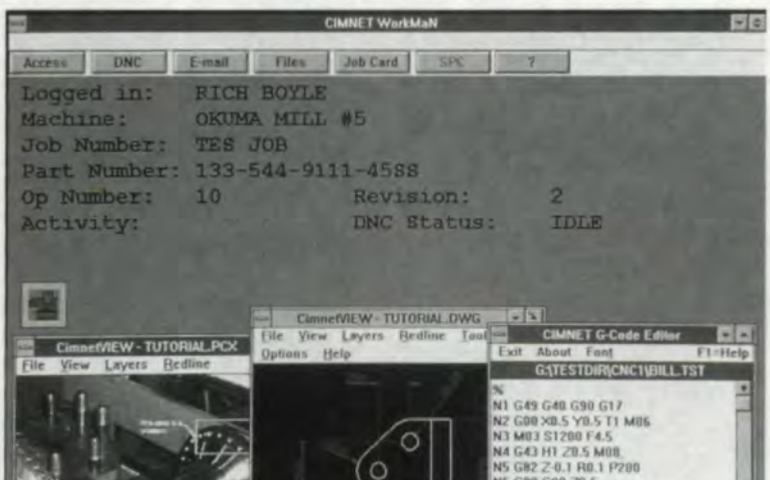
The first detail is winning over your machine operators. They are usually reluctant to use computers for many reasons. Expecting them to readily change and adapt to this new

Carl Watkins
is the Director of Marketing for J.N.L. Industries, manufacturer of computer integrated manufacturing networks in Robesonia, PA.

way of working without special consideration is unreasonable. The key to making the paperless factory work is to make it easy for the machine operators to learn and use the computers.

Machine operators are used to computers that, for the most part, require the push of a few clearly labeled buttons. Having a lot of options, as is common in the newer graphic user interfaces (GUIs), such as Microsoft's Windows™, is unnecessary and confusing. The operator's GUI should consist of labeled buttons and word lists with familiar terms.

The paperless factory machine operator's module should be able to replace all the paper that previously flowed to and from his or her workstation. It should automatically manage the communication functions by linking information from the correct sources and to the appropriate destinations. The operators should be managing their machines, while the system controls the information, giving them quick access to any documents necessary to attain the highest levels of productivity. It should also provide the means to collect data and report information to manufacturing systems that perform as SPC and labor tracking.



Graphic viewers provide MICS users with documents, drawings and digital photos at their workstations. Electronic folders may access any pertinent information on the network.

A well-designed interface presents the next job "folder" ready to be accessed. Clicking on this in turn presents a few choices, such as "Look at the work order, the gear program, a gear drawing, routing sheet, setup sheet or fixture drawing"; or "Check the ISO 9000 procedures or the SPC measurements."

When the operator is confident that everything is in order, she chooses the DNC button and downloads the file. As she works through the jobs, she reports her activity in the "job card" menu by indicating current activity. She can also access SPC input screens to enter measurements or collect data. The operator now functions as the "manager" of her portion of the work flow. She no longer wastes time in non-value-added activity, but concentrates on making good parts.

Programmers and process engineers who build the electronic folders and managers who monitor the production process also are part of the network and benefit from GUIs that fit their needs. Again, the ideal interface is one that provides all the necessary data quickly with a minimum of effort.

Manufacturing Information Control Systems

The MICS is the heart of this kind of system. As files build up from continual use of CAD, CAM and other applications, a means is needed to efficiently manage and control this data. A MICS is that means. When the operator clicks on a file in the folder, the MICS "knows" where it resides on the network and displays the document on the operator's screen. The operator immediately gets the information he needs, while the system keeps track of files, formats and revisions.

In order to manipulate files effectively, the MICS should be based on a system structure known as a relational database. This is the fastest and most effective software design for manipulating large amounts of data. Document files on the network can be viewed without being copied, which saves system user time and minimizes storage requirements. CIMNET™ Folders, from J.N.L. Industries of Robesonia, PA, is a leading MICS with a relational database designed specifically for manufacturers.

The computer functions that relate to the tasks that the operator performs—file viewing, CNC, job reporting, SPC and e-mail messaging—work most effectively when they are all part of a single, integrated system. The primary reasons for this are that the operator GUI is consistent for each function and that the data is part of the same relational database.

This improves the interaction among system users in several ways. For instance, if a change is made to a gear design, the change immediately shows up in the folder, and the operator gets the correct gear drawing and program code. If there are questions from anyone on the system about a design or operation, messages can be immediately sent on the network, rather than through manually writing a message or walking somewhere to discuss the situation. DNC downloads and uploads can be initiated without switching to another system. Data can be collected about machine usage and operator time and immediately related to the job or operation. SPC instructions can be part of the folder, and as SPC measurements are collected, operators and quality control managers can monitor the accuracy of gears. Having SPC integrated into the same database allows for exceptional data analysis. For instance, if two machines are making the same gear, it is possible to compare each machine's and operator's performance and achieve the best production.

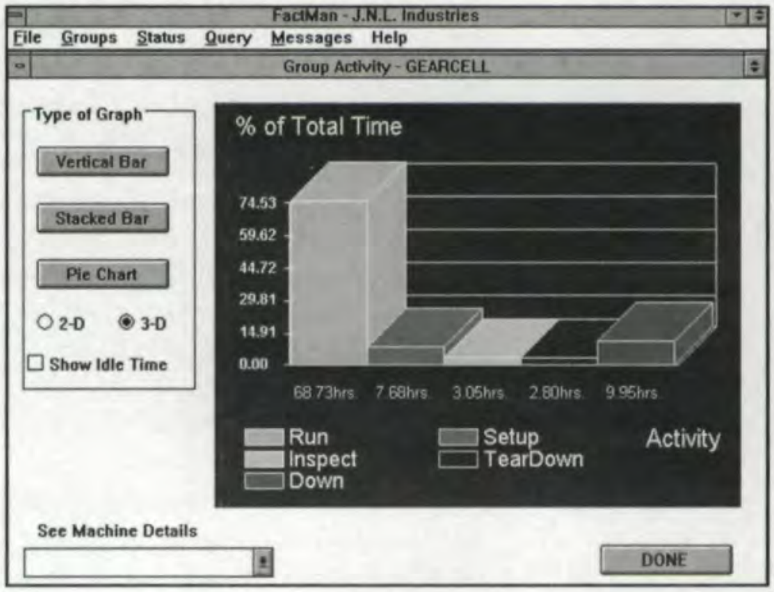
Open Systems

Very few manufacturing companies have not implemented some automation systems by now, so they have "legacy" hardware, software and archival data. These are valuable assets that cannot be allowed to become obsolete. It is not uncommon for a manufacturing company to have an existing Unix system, a mainframe and a PC network operating all in the same plant. A way is needed to maintain this data by getting control of these system files without throwing out the old systems. A good MICS, operating on industry standard computers and running within the popular networks and operating systems, will be able to work within this environment without requiring major changes.

The next detail to work out is to get everyone used to retrieving information on the network. First, the machine operators need to be trained on using the network system. A MICS, with its GUI and relational database, makes this a relatively easy task, but otherwise, it can be a fairly complex problem. The best way is to start with two or three types of files or documents and get everyone used to communicating over the network. The gear program, the work instructions and the drawings are good candidates.

Gear Manufacturing Implications

Some specific examples of how gear manufacturers can use a MICS involve the delivery of the necessary job information to the various operators. Each operation, such as roughing, hobbing, finish grinding, etc., will have an electronic folder where the operator retrieves instructions and reports progress. If SPC measurements are necessary, instructions are in the folder and data entry is accomplished by clicking on the SPC button. The system prompts for specific measurements, records data and makes sure the gears are staying within the required range. In the CIMNET™ Folders SPC module, the operator can collect data for measurement



The FactMan module of Folders displays data collected and stored in the relational data base to indicate machine usage and analyze activity.

over wires, root diameter and O.D. In addition, measurements for runout, lead and involute can be taken and combined into a series of graphs to conduct comparison analysis of hobbing and grinding operations.

By being able to compare the same operation on various machines, a gear manufacturer can know immediately if an aerospace gear requiring a .002" tolerance can be manufactured on his current equipment and which machine would do the best job. Only a MICS with a relational database would be able to make this kind of comparison.

Conclusions

So is the "paperless" factory for you? Maybe not this year. Maybe not next. But somewhere, not too far down the road, the next move in the game to stay competitive will be to unify all your various electronic systems to get them to work together better. At that point, a MICS and the paperless factory will become a part of your manufacturing future. ☼

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The ELIMS Project

CIM for gears sounds good, but how practical is it really? Arrow Gear Company's answer is "very practical indeed."

Joseph Arvin
Arrow Gear Company
Downers Grove, IL

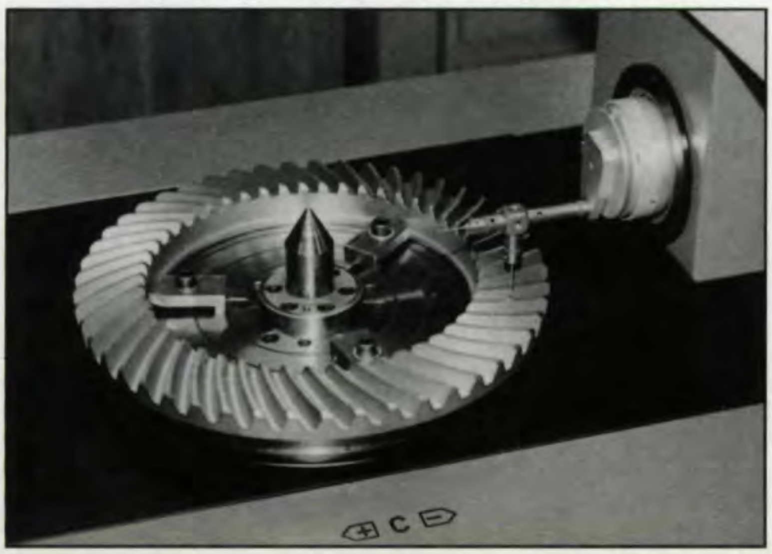
Arrow Gear Company of Downers Grove, IL, has implemented a computer system that fully integrates exchange between all of its computer applications. The ELIMS (Electronic Linkage of Information Management Systems) project has increased manufacturing productivity and reduced lead times.

The primary objective of the ELIMS project was to integrate all of Arrow Gear's business information and manufacturing computer systems, thereby creating a network of information between the mainframe computer, all PCs and CNC machine tools.

Hardware and Software

The hardware and software necessary for the system originates with Arrow's new computer platform, an MAI GPX 5150 computer system. This computer utilizes a Unix-based operating system, which allows for the networking between the main system, the PCs and the CNC machine tools. The computer is similar to most PCs, only much more powerful, as it can support more than 100 users simultaneously. Since all shop personnel routinely use computer terminals for shop-floor reporting, the capacity for this extensive volume was essential.

A spiral bevel gear inspected on Arrow's Zeiss/Höfler inspection machine running in conjuction with Gleason G-AGE software.



Equipped with 64 megabytes of RAM and 4.0 gigabytes of disk storage, it runs off an EISA bus, available in many PCs on the market today. This new computer, which is approximately 6" wide by 2' tall, replaces Arrow's $3^1/_2$-year-old computer, which was 7' wide by $4^1/_2$' high, a prime example of how quickly computer technology has advanced.

Application Integration

What makes the ELIMS project so unique is its extensive integration. As PCs have become more useful business tools, Arrow has been adding them to its information systems. Prior to ELIMS, access via PC to Arrow's main system could be achieved with a terminal emulation program, but files from different applications could not be shared. By utilizing the Unix-based system, users are now able to access information from the host system, the PCs and the CAD and CAM systems. This operating system is the key to the ELIMS project.

The technology that allows for this degree of integration has been around for quite some time, but because of the extensive work involved in system conversion, no one has taken full advantage of it. However, lower hardware costs have made it more viable.

Custom Programs

The most significant challenge in implementing ELIMS was the need to write custom programs for all of Arrow's applications. Because writing new programs for an entire operation is such an enormous task, most companies Arrow's size have not developed a system of this type.

The process of writing new programs involved detailed analysis of current systems and improvement of those systems and their methods. The defining of future needs was also an important factor in this process.

Implementation of the Project

With the ELIMS project expected to be completed by the end of 1995, Arrow has implemented it in a number of phases.

The first phase was the development of an order entry system. This system ties in purchasing, accounting and shipping. This also affects engineering backlog integration, which is then used for shop floor scheduling.

An important specification of the project was ease of use. All menus utilize X-Windows (a network windowing system), which is very user-friendly. Subsequently, very little training is required.

Numerous other modifications to Arrow operations have taken place throughout the implementation of ELIMS. The engineering department has been completely revamped and is now equipped with nine CAD/CAM workstations. Each terminal is linked to a DEC/Applicon computer system. With this system's on-screen information retrieval capability, similar parts and required tooling can be found and modified if necessary. This information availability can save up to 35% on manufacturing engineering time.

A significant benefit to ELIMS is the capability for Electronic Data Interchange (EDI). EDI is used for the transfer of purchase order information and technical data between Arrow and its customers. This method has already been implemented with several Arrow customers. If the customer is utilizing a CAD system, his files can be sent to Arrow's engineers for review and then on to sales for the entry of the customer's order. Next, design engineering receives the files for any necessary design work. Once this is completed, files are downloaded to manufacturing engineering for further analysis required for the manufacturing process. If the design is that of a bevel gear, Tooth Contact Analysis (TCA) is performed with Gleason CAGE software. TCA allows for simulation of the tooth contact pattern under load. Once this analysis is complete, gear summary settings are developed.

In the case of a spur gear, UTS 500 software is used to select or design a cutter and provide any missing gear data.

This development information then is used to update the CAD system, which draws the gear profile. Next, an engineer completes the gear drawing and the process information. The geometry of the CAD drawing file is then downloaded to Arrow's manufacturing CAM system, where it produces the information needed to run the machine tools. From there it is downloaded to the machine tools. When the operator is ready to run the job, he calls up the job number on his terminal and the program is loaded into the machine.

The time saved by this electronic method of downloading setup information is very dramatic. An example of the benefits of this capability can be seen in the Gleason Phoenix equipment used for producing cut and ground tooth spiral bevel gears. On conventional machine tools, setup and development is a very involved process taking up to several days. With the Phoenix machines, it is not uncommon to set up and develop a job in as little as three hours. The ability for fast setup and development time also allows for the economical processing of just-in-time lot quantities.

Information about the process, such as SPC figures, operator time and tooling, is captured electronically. Accounting information, cost information and productivity percentages provide analytical data, which may be required by the quality assurance and engineering departments.

The benefits of this comprehensive information system are numerous. Primarily, information is always readily available to anyone with terminal access.

In addition, job scheduling is made easier and more comprehensive with the reduction of paperwork and its associated errors.

Company officials believe Arrow is the first gear company in the country to use a system like this. Because of the substantial savings in processes and lead time reduction, ELIMS will give Arrow a competitive edge in the gear manufacturing industry. ○

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Joseph Arvin
is the Vice President of Arrow Gear Company in Downers Grove, IL.

Information Control

Shop floor systems tell you what you need to know when you need to know it.

Maureen Fischer
JobBOSS Software
Minneapolis, MN

What a Shop Floor Control System Can Give You

• Vital historical data to estimate more accurately and maintain quality on repeat jobs.

• A valuable audit trail to save on direct buys and keep a complex assembly on schedule.

• Up-to-date, easily accessible information to improve customer service. Knowledge of which jobs should have priority, their status and ship dates leads to on-time deliveries and better profits.

• User-friendliness. And the easier the system, the more employees will use it.

It used to be that a shop with hustle and plenty of big, fast machines could thrive using a manual system. But no more. Today's economic environment requires more and more in the way of top-notch service and quick turnaround—which frequently means a completely integrated shop floor control system.

The shift toward computerized business management of the office and shop floor can be dicey, but shops that find a system with the right fit reap big rewards.

• Cost control. An effective shop floor control system tracks costs of labor, burden, materials, subcontracted services and any miscellaneous charges that make up the total cost of the job. Actual costs are compared with estimated costs and the variance is calculated. Users can do a reality check on profitability.

• Instant job status information. Computerized job tracking allows an employee to peek into the computer and get a snapshot of the status of any customer order, be it a production- or finance-oriented view. Customers' questions can be answered immediately—exactly what today's nimble shop needs.

• Improved shipping performance. Typically, scheduling is a shop's biggest problem. With a computerized system, the scheduling function shows when a job needs to be at various work centers in order to be shipped on the promised date.

The stories of two gear shops illustrate how such a system can provide a powerful competitive advantage.

Fisher's Gear and Machine

Fisher's Gear and Machine, Los Angeles, CA, is a 12-employee, 20,000 square foot gear and machine shop, which handles 1,000 to 1,500 different orders a year, many of them as small as $500 jobs. Over the years, Fischer's Gear and Machine has developed a niche that keeps the business rolling in: It excels at reverse engineering. "If someone doesn't have a blueprint," says Dave Fisher, president, "if they've got a broken part and don't know how to replace it, we will do reverse engineering and produce it for them."

As early as the 70s, Fisher knew he needed to automate his shop, but the software he needed just didn't exist. He spent hours deciding on the parameters of a system suited to his specific business—and that was the easy part.

Initially, he used a custom-made system. It was costly and cumbersome and failed to meet his needs.

Years later, Fisher bought a time collection system from a company in Utah. "I put it online here," says Fisher. "It couldn't do what they claimed. They misled me. I'd bought hardware and software, and all this system did was put time onto a server. I wanted something that audited time and provided increased control over all aspects of the shop floor."

Fisher advises listening to software salespeople very closely. "They will usually tell you the system 'can' do what you want, not that it really does that. I've learned to distinguish between 'can' and 'do.' 'Can' means you're going to have to pay for custom programming."

Finally Fisher believes he's found the system that truly meets his needs—JobBOSS Software (Minneapolis, MN). In 1992, he invested in the accounting portion of the system, liked how it worked and in May of '94, added Job Control, which includes quoting, order processing, material management, scheduling, tracking, costing and shipping.

Though fully implemented only since June of '94, the new system is already proving itself. Cost control has been a major benefit. "We do the jobs," says Fisher, "and now we can review them. We now have a better idea of which jobs are really making us money." He hopes to add more software, including a data collection module, in the near future.

Now most paperwork has been eliminated. Instead, the information is all online and available with a few keystrokes, increasing accuracy and saving time and money. "We only have one chance at getting the job right," says Fisher. "There are usually no blueprints, only a broken sample. We have to reverse engineer it, plus be competitive. . . in a timely manner. It's important to document the processes on these jobs, and JobBOSS has filled the bill . . . so we can reproduce the part without mistakes. Before we had to write everything down. We'd lose the paper; different people would write things down differently. Now the computer keeps it all consolidated and accessible. It's helping."

With the help of the new system, the shop is reversing the downward spiral so prevalent throughout California's manufacturing community. Fisher's Gear is now seeking and winning out-of-state business. ". . . we're actually turning it around and should be in a growth mode during the next few years."

G & N-Rubicon

G & N-Rubicon Gear Mfg., Inc., Santa Ana, CA, is a 33-employee shop that produces anything with teeth—gears 15 feet in diameter to parts so small you can hold 30 in the palm of your hand.

By 1990, the shop's manual system was overwhelmed by the volume and complexity of its workload. "It was time for us to automate," says Mel Edwards, president.

Searching for the optimal software package meant finding a system that was high-powered, easy to use and affordable. "There are always cost parameters," says Edwards, "both the initial cost and the cost to operate the system. I find that with computer software, the purchase price is nothing compared to the cost to operate it." He adds, "In the past, we've found ourselves purchasing software that is actually more of a hindrance. It takes a genius to operate it. If that person isn't there, nothing can go on."

After evaluating several systems, G & N chose JobBOSS Software, a system so user-friendly that Edwards could quickly train several of the shop's employees to use it. "Several of us know how to use it. Any of us can write up a P.O., enter an order, print an extra shop paper if someone spills coffee on it. . ."

Though G & N chose not to integrate the new system with its accounting, Edwards considers the system a good investment. "I think this piece of software compares to packages that cost two-and-a-half times as much. There are things it won't do, but for the cost, it does more than enough. It's a good value."

With nine computers and 33 people, G & N employees can go almost anywhere in the shop and find the status of a job at any given time. Being automated also has dramatically cut down on meetings.

Edwards also likes the competitive advantage of having information available when he needs it. "A lot of benefits have resulted. Because it's easier, we all tend to use it more often. Now customer service is easy. If you have a question about a $5 or a $5,000 charge, it's easy to check on it."

Krista Rubio, who handles production control, input and job tracking at G & N-Rubicon, likes the cost control functions, particularly those keeping track of purchase orders on outside services and material purchases. "The system allows us to reference those fairly quickly. It's so much easier than trying to follow the paper trail."

Quality control is another benefit of the system. "If changes are made along the way, those changes are entered into the system and are very valuable for repeat jobs," she says.

In today's hypercompetitive environment, information alone is not enough. You need the information to be available when and where you need it with a minimum of hassle, and a good shop floor control system may be just the tool you need. ○

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Specific Shop Floor Control System Features

- Almost immediate credit information, part histories and job research.
- The ability to handle one operator using multiple machines.
- An inventory function that pulls multiple parts for one assembly.
- Estimates that originate from specs, a requote or an existing quote and transfer directly to the job.
- Additional fields for adding specs pertaining to certain customers.
- Instantly available job history for repeat jobs.
- Estimating that includes a routing—so the job process is developed before the job even hits the shop floor.
- Flexibility. For example, the ability to raise or lower a price when quoting a repeat job.
- Menu-driven and networkable integration.

Maureen Fischer
is a marketing representative for JobBOSS Software.

Multi-Metal Composite Gear/Shaft Technology

Raymond J. Claxton
Materials Analysis, Inc., Dallas, TX
Albert S. Wadleigh
Interface Welding, Carson, CA

Abstract

A research program, conducted in conjunction with a U.S. Army contract, has resulted in the development of manufacturing technology to produce a multi-metal composite gear/shaft representing a substantial weight savings compared to a solid steel component. Inertia welding is used to join a steel outer ring to a lightweight titanium alloy web and/or shaft through the use of a suitable interlayer material such as aluminum.

Fabrication is accomplished in a two-step inertia welding operation first joining steel to aluminum and then joining titanium to the aluminum side of the steel/aluminum weldment. The development program, carried out over a five-year period, included testing and metallurgical evaluation of torsion components, small fatigue test gears and prototype demonstration sun gears for the Allison 250-B17F gearbox. In addition to development of fabrication techniques, criteria were established to allow design of a new or retrofit component using the multi-metal welding technology.

A prototype multi-metal composite sun gear performed without incident when subjected to a 160-hour simulated flight endurance test in a gearbox test rig.

Introduction

Gears used in high-performance aerospace applications are typically forged from a single piece of alloy steel. Gear components for certain applications are then selectively or totally surface-hardened by techniques such as carburizing, nitriding or carbo-nitriding. This procedure imparts to the tooth contact surfaces the useful properties of high hardness, strength and wear resistance. The remainder of the gear component very often only transmits torsional loads and does not require the hardness and strength properties characteristic of the alloy steel contact surfaces. In a program begun in 1987 for the U.S. Army, a technology for producing lightweight gears and gear shafts has been developed that allows the use of hardened steel in the power transmission contact surfaces and lighter-weight titanium alloy in the non-contact areas of the web, hub and/or shaft. Since the density of titanium is 43% less than that of steel, significant weight savings are offered by the concept, provided the gear component geometry and contact surface configurations allow a significant titanium-for-steel substitution.

The use of lightweight, high-strength alloys for engine components is naturally an attractive proposition. Case-hardened steel alloys enjoy a well-established position of proven reliability and represent the very core of gearbox design technology. The objective of the program begun in 1987 was to develop a method for using surface-hardened steel where it was required and lighter weight titanium in other locations within the gear component. Metallurgical incompatibilities, however, have to date prevented titanium from being welded or otherwise metallurgically bonded directly to steel. This program developed a method for joining steel and titanium alloys by the solid-state inertia welding process using aluminum as a mutually compatible interlayer material between the two. The initial project was conducted over a period of five years by Materials Analysis, Inc., with its primary subcontractor, Interface Welding, under the auspices of U.S. Army AVSCOM, Ft. Eustis, VA. Additional contract assistance in the design, manufacture and test of flight-quality hardware was provided by Allison Engine Company (formerly Allison Gas Turbine Div. GMC).

Manufacturing Process Development

The five-year program to develop the multi-metal gear technology involved the design and fabrication by inertia welding of test specimens for the following purposes:

1. To develop the feasibility of the multi-metal approach,

2. To evaluate the metallurgical integrity of the multi-metal joint,

3. To generate the mechanical properties to be used in the design of test and prototype components.

The inertia welding machine which was employed by Interface Welding for fabrication of the majority of the test coupons, mechanical torsion test specimens and fatigue test gears is pictured in Fig. 1. A typical alloy steel test coupon ring is pictured in Fig. 2. In general these rings were 3.75" O.D. and 2.2" I.D. with a conical bevel machined in the I.D. on one side of the ring. The entrance diameter of the conical bevel on the face of the ring was maintained at 2.90". The conical bevel machined in the ring pictured in Fig. 2 was configured such that the beveled surface was inclined at an angle of 45° from the rotational axis of the ring. For the evaluation of joint geometry effects, which are discussed subsequently, the conical bevel on the weld surface was inclined at angles of both 45° and 30° from the axis of rotational symmetry. Although weld parameters and machine settings differed somewhat for the two different weld configurations, the technique employed for development of the weld procedures was similar.

Fig. 3 pictures a typical alloy steel ring chucked in the spindle collet of the inertia welding machine at Location 1. The steel mass surrounding the steel ring at Location 1 in the inertia welding machine is commonly referred to as the flywheel mass. Pictured at Location 2 in Fig. 3 is a section of 3.5". diameter 6061-T6 aluminum alloy round bar with a conical male bevel machined on one end. For the particular weld procedure pictured in Fig. 3, the mating surfaces of both the aluminum conical male bevel and the steel conical female bevel were inclined 45° from the axis of rotational symmetry of the parts.

After the two components to be inertia welded are properly machined, cleaned and chucked in the inertia welding machine, the spindle, containing the collet and attached to the flywheel pictured toward the left side of Fig. 3, begins to rotate. The rotational speed of

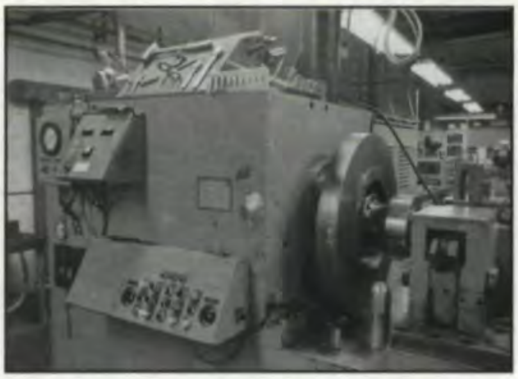


Fig. 1 — Inertia welding machine used in majority of welding trials.

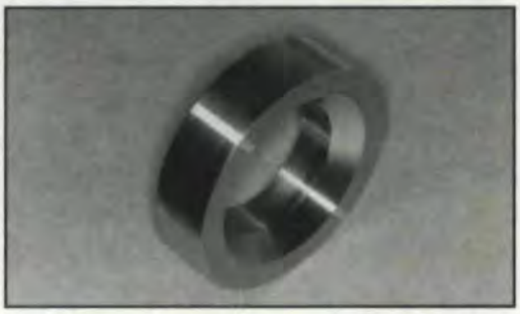


Fig. 2 — Alloy steel ring prepared for inertia welding with 45° conical bevel.

Fig. 3 — Inertia welding machine setup for welding aluminum bar to alloy steel ring.

Raymond J. Claxton
is the founder of Materials Analysis, Inc. The activities of Materials Analysis include metallurgical and mechanical engineering design, testing, failure analysis and research.

Albert S. Wadleigh
is President of Interface Welding, which is involved with design, metallurgy and production of parts using the inertia/friction welding process.

the spindle assembly is a variable parameter that is selected for the individual weld. After the spindle and flywheel assembly reaches a preset rotational speed (rpm), the spindle assembly is disconnected from the drive mechanism in the inertia welder and allowed to freewheel with only the precise kinetic energy (inertia) provided by the rotating mass of the flywheel assembly. The flywheel mass itself is variable and is selected during machine setup based on the material and configuration of the components to be welded. While the spindle and flywheel assembly are rotating freely, the tailstock, containing the premachined aluminum bar pictured toward the right of Fig. 3, is stationary. The rotating component is thrust against the stationary component by hydraulic pressure provided by the inertia welding machine. The freely rotating alloy steel ring, pictured at Location 1 in Fig. 3, surrounded by the spindle and flywheel mass, is thrust against the non-rotating component, pictured at Location 2 of Fig. 3. The resulting friction between the mating surface materials of the two components, D6ac steel and 6061-T6 aluminum, generates enough heat to raise the temperature of the aluminum component to

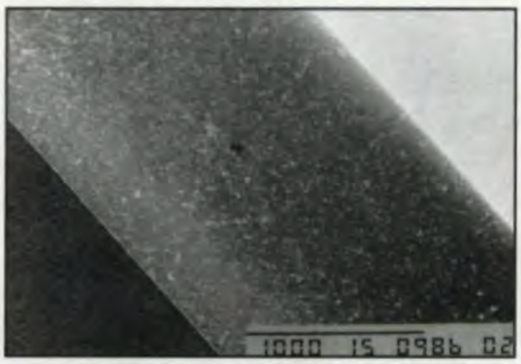


Fig. 4 — Electron micrograph of multi-metal weld cross section showing Ti 6Al-4V, 6061Al, D6ac steel components, lower left to upper right.

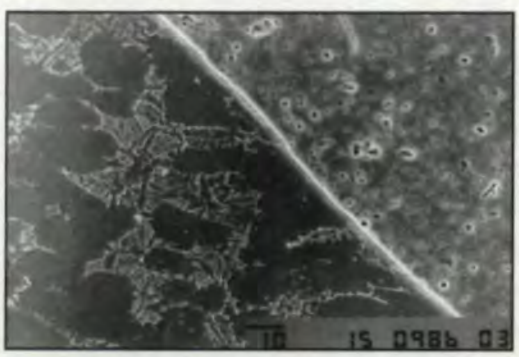


Fig. 5 — Electron micrograph of weld interface between Ti 6Al-4V, lower left, and 6061Al, upper right. (750X)

the forging temperature range, but not into the melting temperature range. In addition to creating heat and providing deformation, or flash, of the two components at their interface, the friction between the two components also brings the flywheel and spindle assembly to a stop. Thus the rotating (kinetic) energy of the spindle and flywheel assembly is transformed into thermal and strain energy, which causes the two components to be welded together without either component changing to the liquid phase during the process. The resulting weldment is then removed from the inertia welding machine, and the aluminum bar is cut off adjacent to the completed weld.

After completion of the first inertia weld, the aluminum center (interlayer) in the intermediate weld coupon was machined to create a conical female bevel on the inside surface of the steel/aluminum subassembly. At the conclusion of machining, the intermediate weld coupon with a newly machined aluminum surface was chucked in the inertia welding machine in a manner similar to that previously described for the steel ring component. Inertia welding of the titanium alloy bar to the aluminum interlayer was accomplished in a manner similar to that described for the aluminum-interlayer-to-steel weld, although different weld parameters were employed. This two-step inertia welding technique was employed with several variations to produce test coupons and components required in the R&D program.

For the coupon configurations described above, the inertia welding process generally produces welds of rotational symmetry. Machine settings, or weld parameters, which can be varied in the process, are flywheel mass, spindle rpm (weld speed) and weld pressure (the force with which the rotating weld component is thrust against the non-rotating weld component during the welding process). The length of total upset, or axial length loss, is a useful parameter to monitor; however, it is a variable resulting from the three machine setting parameters, the weld configuration and the properties of the materials being welded. All of these parameters are typically determined through a weld development program.

After development of the welding process parameters suitable for multi-metal weldment fabrication, metallurgical microsections were taken through the composite joints of each of the alloy combinations evaluated. Fig. 4 pictures at 35X magnification an electron micrograph showing the overall appearance of a joint profile of weldment materials Ti 6Al-4V, 6061Al and D6ac steel; lower left, center and upper right, respectively. The titanium/aluminum inertia weld profile is pictured at 750X magnification in Fig. 5 with the Ti 6Al-4V and 6061Al materials pictured lower left and upper right, respectively. Similarly, the steel/aluminum profile is pictured at 750X magnification in Fig. 6 with the 6061Al and D6ac steel alloys pictured lower left and upper right, respectively.

Mechanical Characterization

Mechanical characterization conducted on the multi-metal composite weldments consisted of microhardness surveys and static torsion testing. Microhardness surveys conducted on polished cross sections, such as the one pictured in Fig. 4, revealed that the heat treated properties of the titanium and steel alloy components were virtually unaffected by the inertia welding process. The aluminum alloy interlayer, however, being the lowest melting and the most sensitive to heat of the three materials in the stackup, was briefly subjected, during the inertia welding process, to temperatures which were at or near the solution treatment temperature for the alloy. Consequently, the 6061-T6 aluminum bar stock, which was the primary interlayer material used, experienced over-aging and thermal softening at locations immediately adjacent to the bond lines. Metallographic examination of these thermally softened regions did not reveal the presence of any defective condition, such as eutectic melting.

Specimens for mechanical torsion testing were designed and fabricated using the multi-metal inertia welding process. An example of one such torsion specimen is pictured in Fig. 7. Evident in the picture are the two inch-square drives machined into the titanium component to the right and the steel component to the left side of the photo. Specimens were made with interlayer thicknesses in the range of 0.020–0.050". A further joint geometry variable was evaluated by fabricating torsion specimens with the conical, aluminum interlayer oriented at 30° and 45° from the rotational axis of the specimen.

The torsion testing machine itself consisted of a drive shaft mounted in a sturdy set of bearings and operated through a 16-in. crank arm by a servohydraulic cylinder fitted with an LVDT and a 50,000 lb. load cell. The digital control system and hydraulic power supply were comparable to those that would be employed on a servohydraulic mechanical testing machine. Nine each of the 30° and 45° specimens were successfully torsion tested to failure in this program. The average maximum torque for the 45° weld specimens was 9,409 ft-lbs., while the corresponding value for the 30° specimens was 13,302 ft-lbs. Geometrical analysis of the surface area of the conical weldment in each of the two weld angle configurations revealed total weld areas of 3.96 square inches and 5.6 square inchs for the 45° and 30° configurations respectively. When the maximum torque values were calculated on a unit area basis, it was discovered that for both the 30° and 45° conical weldment configurations, the maximum torque values reduced to 2,375 ft-lbs. per square inch of interlayer material. This torsional strength consistency would prove useful during subsequent stress analysis and design activities associated with the manufacture of flight-quality demonstration gears.

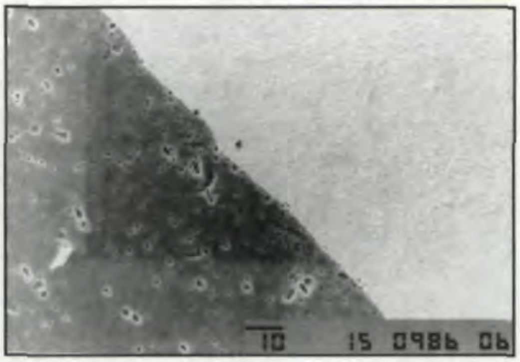


Fig. 6 — Electron micrograph of weld interface between 6061Al, lower left, and D6ac steel, upper right. (750X)

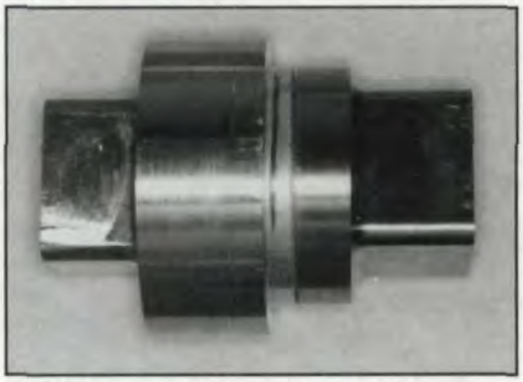


Fig. 7 — Typical composite torsion specimen prior to testing.

The 30° interlayer torsion test specimen, pictured in Fig. 7, is shown after torsion testing to failure in Fig. 8. The interlayer fracture surface was carefully examined on all torsion specimens to verify that fracture had occurred entirely through the aluminum interlayer, and that no de-bonding of the various components had occurred during the testing sequence. Fig. 9 is an electron fractograph, taken at 1000X magnification, showing the typical shear dimple microfeatures associated with the shear overload fracture mode in the aluminum interlayer material.

The fracture path through the interlayer material on specimens subjected to static torsional overload bore certain characteristics worthy of note. The shear fracture path in a thick-walled tube composed of a homogeneous and isotropic material would be predicted to occur on a transverse radial plane; however, in the case of the composite weldment, fracture through the aluminum is forced to occur along a line defined by the configuration of the conical interlayer. The longer the path of the fracture, the greater the strain energy required to create new surface during the fracture process. In appreciably thick interlayers, the fracture path occurred from one side of the interlayer on the O.D. to the opposite side of the interlayer on the I.D. in such a manner as to minimize the cross sectional area of the fracture. The fracture was simply passing through the path of least resistance, minimum area. In the eighteen torsion test weldments used for mechanical behavior characterization, an effort was made to maintain the interlayer below 0.050" in thickness. Once the interlayer was reduced to a thickness on the order of 0.050", and below, the tendency to fracture from one side of the interlayer at the O.D. to the opposite side of the interlayer at the I.D. was not as predictably observed. At the small interlayer thicknesses, other factors, such as local thermal softening of the aluminum alloy, probably exerted an influence on fracture path. This ameliorating effect of a thin interlayer configuration is consistent with the fact that the thinner the interlayer, the less difference in strain energy requirements for the very small angle of optional fracture paths through the interlayer. For this thin interlayer condition, other factors influencing fracture stress are probably of the same order of magnitude as the variations possible from available fracture paths. As the interlayer becomes thicker, the optional fracture path band increases, as does the percentage difference in strain energy required for separation along the various possible fracture paths.

In summary, joint geometry exerted a substantial influence on the static torsion strength of a composite weldment. This influence appears to be directly related to the cross sectional area of surface that the fracture separation is forced to create. For thicker interlayers there is a distinct tendency for the fracture to pass through the path of least resistance from one side of the interlayer at the O.D. of the weld to the opposite side of the interlayer at the I.D. of the weld. The tendency observed was for the fracture path to pass through the weaker interlayer material, but at the same time to cut corners and pass through the short-

Fig. 8 — Fracture surfaces of 30° interlayer torsion specimen after testing.

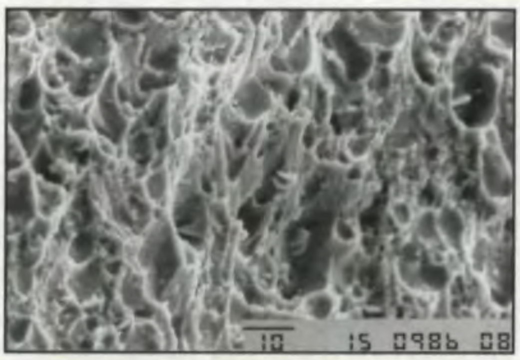


Fig. 9 — Electron micrograph of sheared aluminum interlayer from torsion specimen fracture surface. (1000X)

Fig. 10 — Pair of multi-metal fatigue test gears.

est, most nearly radial path possible. As the interlayer material becomes thinner, the strain energy difference between the optional fracture paths becomes less, as does the tendency of the fracture to predictably follow a given path.

Small Fatigue Test Gear Fabrication and Evaluation

One of the major goals of this project was to evaluate the performance of the multi-metal gear manufacturing concept in a gearbox environment. Simulation of such a gearbox environment had been successfully achieved by Allison using a four-square gear fatigue test machine. This machine, reportedly developed by Allison, was similar in design to rigs used at NASA Lewis Research Center. A standard gear configuration has been established for evaluation in the four-square test rig. The multi-metal inertia welding concept was incorporated into this standard gear configuration while maintaining all exterior dimensions of the gear. The multi-metal inertia welding process was employed to fabricate gear blanks suitable for subsequent machining of the test gear configuration. Several pairs of small fatigue test gears were manufactured with a pitch diameter of approximately 3.3". Fig. 10 pictures a typical set of these test gears with a titanium alloy hub, aluminum alloy interlayer and hardened alloy steel teeth. The small fatigue test gears were tested in the four-square rig under the following conditions:

1. Speed	10,000 rpm
2. Torque	400 in-lb.
3. Oil Inlet Temperature	119°F
4. Oil Type	MIL-L-23699C
5. Duration	50 hrs.
6. Max. Contact Stress	261 ksi

These test conditions were selected to be similar to those employed routinely by Allison to test steel gears. Employing this standard test gear design and test protocol did not subject the tri-metal weld joint to either temperature or torsional stress that would be considered severe. The test did, however, subject the tri-metal weld to vibratory loading similar to that experienced in an aircraft gearbox.

It is well-established that in most aircraft gearbox applications, oil supply temperatures of 175–250°F are normal. In this test, the oil supply temperature was maintained at 119°F to provide a thick lubricant film and prevent scuffing or scoring of the gear teeth. The actual surface temperature of the gears is usually somewhat higher than that of the oil supply. The web of the test gear is over-designed to provide rigidity and ease of manufacturing. Because of this, the maximum stress in the weld interlayer during the test was calculated to be 0.168 ksi. For comparison, the torsional design allowable stress utilized in the demonstration gear was 27.2 ksi.

Post-test inspection of the fatigue test gears after the scheduled teardown indicated a teardrop-shaped contact patch on the gear faces. This contact pattern, pictured on the visible faces of the right hand gear in Fig. 11, was uniform in size, shape and location. The gears showed no sign of pitting or other distress that would have prohibited continued testing. The tested gears passed magnetic particle inspection according to EIS 1169, Method D, and fluororescent particle inspection according to Method AMS 2640.

Aircraft gears are generally designed with contact stresses kept below 160 ksi. Using the American Gear Manufacturers Association Method 2001, the successful operation of this gear for 50 hours at 261 ksi is equivalent to 300,000 hours operation at 160 ksi. Although not statistically significant, the success of this test verified the soundness of the approach to a multi-metal composite gear and paved the way for design and manufacture of a full-scale, flight-quality, demonstration gear.

Demonstration Gear Design, Fabrication and Test

One of the primary goals of the project was to produce a sample quantity of flight-quality demonstration gears using the multi-metal inertia welding process. Selection of the gear to be manufactured included fabrication and

Fig. 11 — Contact surfaces of multi-metal fatigue test gears after testing.

application considerations. The completed part would be subjected to high frequency dynamic testing and simulated flight endurance testing.

It is necessary to consider several important criteria when designing a multi-metal gear or gearshaft, some of which can only be evaluated through testing of a prototype part. A few of these criteria follow.

1. Weight savings must be realized sufficient to justify increased manufacturing cost associated with the multi-metal process.

2. Weld geometry and strength must be considered. The lower-strength aluminum interlayer material may necessitate a larger shafting cross section at the location of the inertia welds.

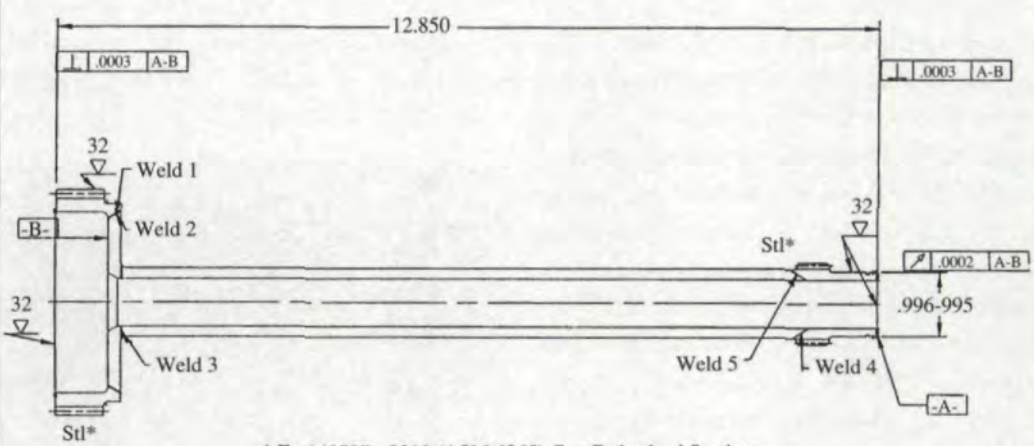
3. The difference in modulus of elasticity between steel and titanium introduces inherent stiffness differences between the multi-metal gear and an all-steel gear. Design modifications may be required to maintain satisfactory gear web or shaft dynamics when designing a composite component.

4. In some cases special tooling is required to control weld component concentricity during the fabrication process. Excess runout from eccentricities introduced during welding can lead to poor spline and gear loading and detrimental vibration.

5. The complexity of the component to be produced may simply require so many two-step inertia welds or so much specialized tooling that it may be impractical to replace in its current configuration with a multi-metal gear.

The demonstration gear was selected by a team from Materials Analysis, Interface Welding and Allison. The major consideration of the team in its final selection process was to select a gear that, when manufactured using the multi-metal inertia welding process, would subject the weld locations to relatively high loads and at the same time would be a relatively simple gear shape to fabricate. The intent was to select a gear shaft that was not overly complicated to fabricate, but that would challenge the ultimate performance of the welds by providing a high service load application. After careful consideration the sun gearshaft, P/N 23033882 from the Allison 250-B17F gearbox, was selected as the demonstration gear to be fabricated using the multi-metal technology. Prototypes would be subjected to a performance evaluation and comparison to the incumbent, all-steel sun gear shaft.

In order to evaluate the applicability of several manufacturing techniques, it was decided to produce a small quantity of flight-quality, demonstration sun gears using two parallel manufacturing approaches to produce the hardened steel portions of the gear shafts. On one set of demonstration gears, dual pulse induction hardening (DPIH), an Allison proprietary process, would be employed to induction surface harden the gear and spline teeth as the final step in the multi-metal sun gear manufacturing process. A second set of demonstration sun gears would be manufactured employing conventional gas carburizing to



* Ex 148797 - 9310 (ASM 6265) Gas Carburized Steel or
Ex 148798 - D6ac (AMS 6431) Induction Hardened Steel

Fig. 12 — Allison 250-B17F multi-metal sun gear shaft weld locations.

prefabricated 9310 alloy steel gear and spline components prior to the inertia welding fabrication process and finish grinding of the sun gear component.

Weld locations were selected within the gear shaft so as to maximize the amount of steel replaced with titanium and thus maximize weight savings. These weld locations are presented in the schematic gear shaft cross section of Fig. 12. The welds involving aluminum interlayers (welds 1 and 2 and welds 4 and 5), were designed as conical welds with the interlayer oriented at an angle of 30° from the rotational axis of the gear shaft. Weld 3, identified in Fig. 12, was simply a Ti 6Al-4V butt weld employed in the fabrication process to reduce machining costs and material waste.

The torsion test information previously described was used to determine the allowable torsional shear stress for the weld joints in the multi-metal sun gear. The failure torques for the 30° torsion specimens were compiled, and resulting torsional shear stresses were calculated. The resulting torsion design allowable stress within the interlayer was found to be 27.2 ksi. Analysis of the sun gear shaft predicted torsional stress in the shaft at the spline end to be 26.3 ksi. Since this was below the 27.2 ksi design allowable, no modification to the shaft section thickness was required. Since the service stresses at the location of the shaft spline were considerably greater than those in the region of the spur gear, the tri-metal weld in the spur gear web was also expected to be of sufficient strength without increasing the web thickness at the weld location.

A lateral and torsional dynamic analysis was performed at Allison. These dynamic studies were conducted to verify that the torsional and lateral natural frequencies were located well away from the frequencies associated with normal operation. Sufficient margin between the operating speed and both torsional and lateral natural frequencies assured no excessive engine vibration or dynamic loading of engine components.

Once the design analysis for the 250 sun gear was complete, manufacturing procedures were conducted in parallel for the D6ac and 9310 multi-metal gear shafts. The inertia welding process parameters were developed for each of the five welds cited in the gear shaft schematic of Fig. 12.

Two of the completed demonstration gears are pictured in Fig. 13. In that photo the gear shaft with 9310 alloy steel and gas carburized teeth is shown at the top of the photo and the gear shaft containing induction hardened, D6ac gear teeth is shown at the bottom of the photo. The geometry of the two gears is identical. Physical weighing of one of the finished composite sun gear shafts showed it to weigh 1.75 lbs., a weight savings of 28% over the 2.45-lb. weight of the incumbent all-steel component. The gear shaft with the 9310 alloy steel teeth was inertia welded into the tri-metal gear form using previously manufactured gas carburized steel parts. The gear shaft with the

Fig. 13 — Multi-metal demonstration sun gears with gear and spline portions composed of 9310, top, and D6ac, bottom.

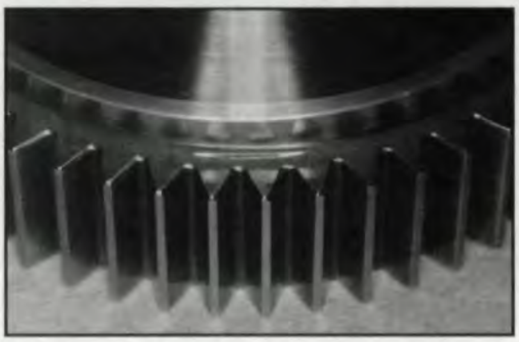


Fig. 14 — Spur gear end of 9310 multi-metal demonstration sun gear.

Fig. 15 — Spline end of 9310 multi-metal demonstration sun gear.

D6ac alloy steel components was fabricated by inertia welding and completely machined prior to induction hardening of the steel portions of the part. Close-up views of the spur and spline ends of the 9310 demonstration gear are pictured in Figs. 14 and 15, respectively. Figs. 16 and 17 picture the internal profile of the multi-metal weldments on the spur and spline ends of a demonstration sun gear.

One of the 9310 multi-metal sun gear shafts was subjected to dynamic stress characterization at Allison. This work complemented the analytical torsional and lateral dynamic analysis previously described. The physical testing associated with dynamic characterization was designed to further verify that the natural frequencies of the sun gear were located far enough from the operating speed frequencies so that no excessive engine vibration or dynamic loading of engine components would likely occur. Physical test results indicated the composite gear shaft exhibited natural frequencies very close to those observed in the all-steel production gear shaft. Since both the tri-metal gear shaft and the incumbent all-steel gear shaft exhibited very similar high frequency vibrational behavior, and since no problem has been observed in the long history of operation of the all-steel sun gear shaft, it seemed safe to conclude that no vibrational difficulties would be expected with the dynamically similar composite sun gear shaft.

Fig. 16 — Segment removed from spur gear end of D6ac multi-metal sun gear for metallographic evaluation.

Fig. 17 — Segment removed from spline end of D6ac multi-metal sun gear for metallurgical evaluation.

The high frequency vibrational behavior similarities between the multi-metal composite sun gear shaft and the all-steel version of that component was an unexpected finding in light of the significant difference in weight, 2.45 lbs. versus 1.75 lbs. for the all-steel and multi-metal sun gears, respectively. One possible explanation for this observed vibrational behavior similarity is that, although the density of titanium is considerably less than that of steel (0.160 lb/in.^{3} versus 0.282 lb/in.^{3}), the difference in the elastic modulus of the two materials (16.5 x 10^6 psi for titanium versus 30 x 10^6 psi for steel) results in a ratio of elastic modulus/density which is virtually identical for the two materials.

Finally, one of the 9310 alloy multi-metal sun gears was subjected to a 160-hour simulated flight endurance test by Allison in a B17F gearbox test rig. This test consisted of approximately 500 duty cycles, each consisting of idle, take-off, cruise and landing service segments. The multi-metal composite sun gear shaft performed without incident and was undamaged during the test. Successful completion of the simulated flight endurance test verified that the multi-metal composite gear technology is sufficiently mature for incorporation into a full-scale engine development program and is a viable candidate for retrofit, where feasible, into existing power transmission and accessory gearbox applications.

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CNC Basics

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NC and CNC machines are at the heart of manufacturing today. They are the state-of-the-art equipment everybody has (or is soon going to get) that promise to lower costs, increase production and turn manufacturers into competitive powerhouses. Like many other high tech devices (such as microwaves and VCRs), lots of people have and use them—even successfully—without really knowing much about how they operate. But upgrading to CNC costs a lot of money, so it's crucial to separate the hype from the reality.

So what are NC and CNC anyway? How do they work? What are their advantages? And is upgrading my mechanical gear cutting equipment really worth it?

What is NC?

Probably the most universally accepted definition of NC is offered by the Electronic Industries Association, which defines NC as "a system in which actions are controlled by the direct insertion of *numerical* data at some point." This control can be direct wire or a number of other input media.

Numerical controls are inherently more accurate than mechanical ones and usually even more accurate than the machines they control. It is important to emphasize that NC was born out of the need for mass production, but its greatest strength and efficiency is in the production of small lots.

What is CNC?

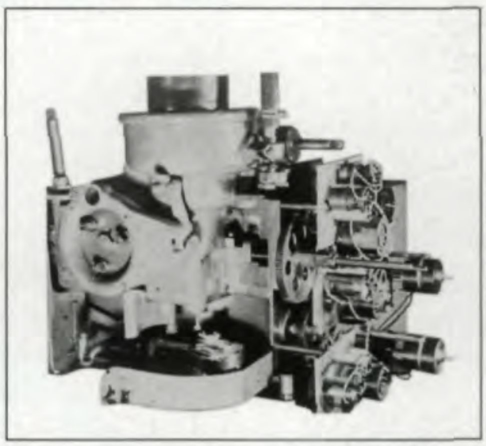
The term CNC refers to a computer attached to an NC machine. This improvement makes the machine more versatile, as programs can now be stored in the computer's memory. Instead of specially designed circuits executing instructions, a general purpose minicomputer is used, eliminating the specialized circuitry.

This "softwire" or more correctly "software" approach offers advantages over hardwired systems. For example, features such as canned cycles, maintenance diagnostics, storage of part programs and error compensation can be easily added via software. Some of the more important features of a CNC unit are memory, edit capabilities, an interface (usually a Cathode Ray Tube—CRT) with some sort of input device (keyboard) and built-in diagnostics capability.

CNC and Gear Machinery

Up until the mid-1970s gear generation equipment was controlled electromechanically. The position of the axes in the machinery was controlled by limit switches, and gear geometry was controlled by change gears. The first NC-controlled gear generation machines were relatively simple point-to-point systems.

Gear machinery manufacturers were slow to integrate NC/CNC technology into their machinery. The markets initially approached by the CNC manufacturers were the higher volume users, such as lathe and mill manufacturers, and not the low volume gear machinery manufacturers. As the lathe and mill market became saturated, CNC manufacturers looked for other markets for their controls. Even relatively small markets like gear machinery manufacturers were approached. In order to make the machinery work properly, some special functions were written by the CNC manufacturers in order to duplicate the work traditionally done by change gears. In the early years of CNC gear machinery, before these functions were freely available, manufacturers created their own hardware boards to duplicate the gearbox "change gear" functions.



Origin of the species: Modified Fellows 72 gear shaper with servomotors and film input.

Early NC hobbing machines (circa 1977) were manufactured by the gear machine tool builders utilizing proprietary electronic devices of their design, which were called electronic gear boxes (EGB), or less affectionately, the "black box." Some black boxes are still in use today in order to fulfill special functionality, but have been generally replaced with the electronic gearbox capabilities that are now built into modern CNC controls.

Elimination of the Electronic Gearbox

Up until 1980, hobbing machinery manufacturers who incorporated NC/CNC did so as an add-on to their machines designed for electromechanical control. In 1980 Pfauter introduced the first gear manufacturing machine redesigned for the CNC. Later, other gear hobbing, shaping and finishing machinery manufacturers introduced machines designed for CNC, but still used their own proprietary "black boxes."

Development of system software-based "black boxes" began at Siemens in the early 1980s. By the early 1990s, other CNC manufacturers, such as Allen-Bradley, Fanuc and NUM, got into the act.

Dr. Frederick Cunningham

The special electronic gearbox software controls the rotary functions of the gear manufacturing machines and is somewhat complex. The electronic gearbox functions needed to be built into the CNC system software before CNC machines could attain the reliability and ease-of-use of lathes and mills. After the incorporation of electronic gearboxes into the system software, the CNC systems became more "stable" and no longer relied on individual manufacturers' "black box" technology.

CNC and system software, as supplied by the CNC manufacturers, does not manufacture gears "as is." This functionality is programmed by the machine tool builders or other third party CNC system integrators. Nearly all the advantages of CNC are *software* functions, written to simplify the manufacturing process and to increase productivity.

Software and CNC

There are four different major software programs running in modern CNC machines. The first type of software is the operating system. CNC manufacturers have replaced "black boxes" and cumbersome change gears and have added an entire range of additional functions by building special software into the modern CNCs. These functions can be compared to the system software used in personal computers—for example, the DOS operating system.

The second type of CNC software is the user interface, or in PC terms, the "application software." This software is placed "on top" of the system software provided by the CNC manufacturers. Application software has many designs, names, shapes and forms: the user front end or menu, the conversational program, graphical user interface (GUI), feedback alarms, help screens. This entire range of bells, whistles, communication capabilities and graphics have made the modern machines easier to operate, given them better performance and enabled them to manufacture complex parts.

Each machinery manufacturer and CNC integrator offers his own design of application software. Gear machinery manufacturers are now beginning to introduce user interfaces that have a personal computer and Microsoft Windows™-based interfaces integrated with the CNC. Given the present level of technology and cost, the utility and economic return for these interfaces are now highly questionable. The PC front end is still more expensive, slower and more "buggy" than "CNC only"-based user interfaces.

System integrators have also been looking for a motion control system that will bypass the CNC altogether and use a personal computer for a truly low-cost motion control system. This solution has been elusive because of the need for processing speed, built-in machine standard hardware and software safety controls. Customers and equipment manufacturers currently do not wish to risk expensive workpieces and tooling on a less reliable PC system.

There is still little software standardization, and new versions are continually being produced. Gear makers will generally have an entire array of gear software on their CNC machines, which has led to some training difficulties. Today's software engineers have begun to design user interface software that is both intuitive and graphically based, reducing training from weeks to hours.

CNCs use real-time multiple operating system for multi-tasking. They are able to control multiple processes at the same time (machine functions, axis position, CRT display, etc.).

Continued on page 36.

E. Peter Kovar

is the Vice President of U.S. Tech Corporation and a recognized authority on CNC applications. U.S. Tech provides a variety of high-end services for CNC gear machinery systems.

In The Beginning Was the Weaving Machine. . .

The weaving machine and the player piano—what do they have in common? Believe it or not, they are the first true forerunners of modern numerical controls (NC).

In 1728 a Frenchman, Joseph Jacquard, saw a way to improve productivity in the highly competitive weaving business. He found that by punching holes in wooden strips he could efficiently arrange and change patterns on his looms by indicating when to change needles and threads. Jacquard patented his process and soon the entire industry changed—precision and quality improved and prices came down.

One hundred and thirty-five years later, in 1863, the Pianola, or player piano, was introduced. It used paper tape punched in patterns to play certain notes. This first known use of punched paper was the forerunner of NC tape.

Fast-forward again to the late 1940s. John T. Parsons of the Parsons Corporation (then the country's largest manufacturer of helicopter rotor blades) was working on a project for developing machinery that would manufacture templates used in the inspection of the contours of helicopter blades. Numerical control began with Parson's experimentation generating through-axis curve data and using that data to control machine tool motions. Modern NC history was made when Parsons later coupled his electronic equipment with a precision jig boring mill.

Parsons, together with IBM, proposed a development contract to the Air Force. In 1949, the Massachusetts Institute of Technology agreed to help him refine this technology. Together Parsons and MIT developed several design and safety checking features that are still in use today. (MIT actually coined the term *numerical control.)*

In 1951 NC technology was successfully demonstrated with a prototype one-axis machine. In 1952 Parsons demonstrated the first three-axis milling machine at MIT's Servo Mechanisms Laboratory. These early machines were capable of highly complex continuous path methods. (Only later were simpler point-to-point machines developed.)

Fred Cunningham's Garage

Another pioneer of NC was Dr. Frederick Cunningham. During World War II, Dr. Cunningham designed fire control systems and range finders for the Navy. Fire-control systems used the newly developed servomotors to correct the aim of the guns as the ships rolled at sea. The range finders used hard-to-manufacture, non-circular gears. After the war, being aware of the difficulty in producing non-circular gears and seeing that servo technology would be ideal in machine tool controls, Cunningham began his research in the development of NC machine tools.

Dr. Cunningham developed a non-circular gear manufacturing machine by modifying a Fellows 72 gear shaper, fitting it with servomotors and using film as the input medium. (See p. 33.) He designed a unique system to control the cutter and workpiece rotation and cutter feed simultaneously. One impulse from each control signal corresponded to one one-hundredth of one gear tooth, two minutes of arc and 0.00025". This stream of pulses would produce the gear.

The tape preparation process in Dr. Cunningham's NC was quite difficult and time-consuming. The program was manually calculated, put onto 16 mm film using a device he invented and read by photoelectric cells. This electronic device made this gear shaper the first *numerically controlled* gear manufacturing machine ever built (and the first NC machine put into commercial production.)

In the mid-1950s Dr. Cunningham put his continuous path three-axis machine to commercial use in the garage of his home. Several years later he quit his day job to devote himself to Cunningham Industries, which at the time consisted of two gear shapers, a small milling machine and some other machinery in a small shop run by his sons. Few people were interested in his gear shaper because it manufactured only highly specialized non-circular gears. However, the early continuous path NC did impress some observers, especially because of its simple elegance.

The original Cunningham NC machine is still in production today at Cunningham Industries' facility in Stamford, CT. Dr. Cunningham died in 1979, never having received due recognition in the United States for his pioneering work. But his son, Frederick E. Cunningham, continues the family tradition. He has modified the control on the original Fellows 72 gear shaper, and the original NC machine now uses a high tech, low-cost control of his and his father's design. The updated shaper is equipped with a Commodore™ 64 personal computer and stepper motors and incorporates parametric quadratic interpretation calculations to manufacture non-circular gears with the Cunningham trademark—simple elegance.

From NC to CNC

By the 1955 national machine tool show, early commercial models of numerically controlled machine tools were on display. (Commercially produced NC *gear* manufacturing machinery would not appear on the market for two more decades.)

In the 1960s the market shifted from mass production to smaller lots as consumer and industrial demand shifted toward variety. NC met the challenge of automating general-purpose machine tools for short-run production. Manufacturers began to produce universal machines to replace the highly specialized machinery previously used. (It is still a popular misconception that numerical control is justifiable only for large quantity production—just the opposite is true.)

Numerical control rapidly evolved in the control industry as well as in the machine tool industry. With the development of solid-state circuitry and modular integrated circuits, the control size became smaller, more reliable and less expensive. Although punch tape is still used as an input medium today, computer numerical control has largely replaced punched tape technology. (Even today CNC memory is measured in "tape feet" rather than megabytes.)

Today's CNC units evolved from the Direct Numerical Control (DNC) applications of the late 1960s. Early DNC systems were capable of controlling a large number of machine tools. They provided a form of tape editing at the machine tool site and collectively controlled production. With the DNC system, the tape reader was bypassed, and the machine was controlled by a host computer.

Many companies were reluctant to accept DNC because they felt it was nothing more than a replacement for a tape reader and because the technology was quite expensive and unreliable. As a result DNC was soon sidetracked by more sophisticated computer technology, which allowed control builders to incorporate computers into intelligent controls.

WHY CNC?

General benefits for both job shop and automated factory environments

- Mechanical kinematics are greatly simplified, providing easier maintenance; noise reduction; fewer parts for repair; easier and faster repair in case of failure; higher productivity; higher speeds and feeds; less heat generation and machine expansion; dry cutting capabilities due to higher speeds; quick setup; less idle time between changes in workpieces; easier, faster and more accurate entry of data parameters; easier repeated setup because data parameters are stored in memory.
- Complex workpieces can be made in one machine setup, using multiple (gear, tool, process, setup and cutting) cycles.
- Modification of tool path is simplified—standard canned cycles for crowning, end relief, taper, etc.
  Custom specific cycles can be easily edited.
- Machines have active (measured) or passive (estimated) compensation for tool wear and temperature stability.
- CNC machines are capable of implementing standard computing programs for the calculation of optimal tool usage with optimized feeds and speeds and the prediction of quality and part tracking.
- Inspection is simplified.
- Easier monitoring of machine status is possible.
- Machines have extensive diagnostic capabilities.
- Graphical user interface capabilities allow operators to view and input part, process and tool data on screen in the same perspective as they would normally view a blueprint.
- Easier operator training provided through help screens, graphical user interface and conversational input.
- Scrap reduced because of fewer errors in production.
- Production planning improved because machines are less specialized.
- Less space and smaller inventory required.
- Menu input is easily switched between inch and metric.

Additional benefits for automated factory environments

- Unmanned production capability; 12/24 hour production.
- Automatic retooling and refixturing capability.
- Networking capability (connection to host computer).
- Online gaging capability with corrective feedback.
- Tool management capability in the CNC or coded on the tool itself.
- Adaptive feed and speed control capability.
  Higher production output.
  Tool breakage monitoring.
- Machine diagnostics with graphing capabilities.
- Simplified interface to robot, gantry or other loading systems.
- Machines require less floor space due to simplified kinematics.
- Access to data entry screens can be optionally inhibited.

The third type of software used in CNC machines controls the tool path of the machine–the "parts program." This software is the heart of the CNC and is provided by the CNC manufacturers. (The program is in principle a code that in the past was fed by punch tape because the NC did not have sufficient memory.) The parts geometry is obtained by keyboard input or communicated to the system from a central computer and is fed to the parts program software to instruct the CNC.

The fourth software, called the programmable logic control (PLC), is integrated into the CNC and controls the machine logic. This software code polices the machine functions. For example, the PLC program will normally check all preconditions in order to start the parts program. It will also stop the machine if a door is open or if other safety devices are tripped. The PLC program utilizes a standardized coding scheme called the "ladder" program. The ladder is programmed by a system engineer who must fully understand the specific gear machine functionality.

What Does the CNC Do?

Without CNC controls, a machine operator must create a step-by-step procedure for making a piece by deciding which surface to machine first and planning all the motions, cutter speeds and feeds to make the final product. The product quality depends on the skill and speed of the machine operator.

With CNC, once the procedure and tools have been determined, the CNC machine operator makes the same part over and over in exactly the same way without human intervention. A skilled operator running a manual machine will be cutting a gear at most 30–40% of the time. With a modern CNC machine, cutting time can be improved to 70–90%.

CNC does not totally eliminate the need for skilled operators. If necessary, the operator may still manually control the machine with the use of jogging switches, hand wheels, or Manual Data Input (MDI). This versatility is a benefit of the technology. Machinery can be designed to run automatically or with a great deal of operator interaction, depending on the customer requirements.

Why Use CNC Gear Machinery?

Many gear shops are still quite happy with their old electromechanical machines and wonder why they should upgrade. Investment in new gear-making machinery is quite expensive, and there are arguments against it.

One problem with CNC is that the technological life cycle of each control is relatively short, only about 10 years. The actual usable life is of course much longer, but CNC, like any microprocessor-based device, advances in technology very quickly, and investment in newer versions of CNC technology will again be justifiable in about 10 years. This would not be much of an issue except that the mechanical portion of the gear machinery has a much longer life, up to 30 years, and can be extended almost indefinitely by overhaul and rebuilding.

One reason for changing to CNC-based machinery is that current electromechanical machines will not last forever. Furthermore, these machines simply cannot manufacture gears cost-effectively anymore. Parts for mechanical machines are also becoming harder and more expensive to locate.

Although change is inevitable, many users are putting it off as long as possible. Changeover to CNC machines is not so much a question of why as much as when. In order to stay competitive, more efficient manufacturing technologies need to be used, and in the gear industry that usually means updating of equipment incorporating modern CNC technology.

An analogy can be drawn by comparing the purchase of an old mechanical typewriter to a modern PC. The cost of PCs is low, and their reliability is acceptable; plus, the PC can do the word processing—and a great deal more! Furthermore, the development of user-friendly, easy-to-use graphical and conversational interfaces makes PCs easier to use all the time. Fewer and fewer reasons remain to delay the move to CNC.

Another reason why a switch is necessary is that the parts that gear manufacturers are producing are much more complex (as compared with only 20 years ago), and the tolerances are getting tighter. New gear designs always seem to push the envelope of the CNC's capabilities. Many of these advanced parts simply cannot be made on electromechanical machines.

The level of operator and engineering personnel skills required to properly manufacture these complex parts is considerable, and fewer skilled gear makers are available. CNC-based gear manufacturing, with the capability to program and modify the tool path, does greatly simplify the manufacturing process.

An additional incentive is ISO 9000. U.S. gear manufacturers who wish to improve the quality of their products know that CNC manufacturing techniques are a wise investment. CNC manufacturing systems are especially useful for shops that need to track each part as it moves through their facility.

What About Retrofitting?

The question many job shops now have is whether to buy a new CNC machine or perhaps one of the early generation of NC machinery. The answer may depend to a good extent on the kind of machine under discussion.

Converting a mechanical "change gear" machine into a modern CNC machine is a costly proposition because of the relatively complicated kinematics that need to be redesigned. Only unusual configurations or larger-sized versions of these mechanical machines, which are generally expensive to replace with new machinery, can be cost-justified. On the other hand, updating an early NC/CNC machine already designed for NC controls is a much less painful proposition. Modern CNC machine kinematics are much simpler (think of a mechanical watch with gears compared with the much simpler kinematics of an electronic quartz watch), and therefore easier to build. As CNC technology has advanced, the mechanical portion of the machines has decreased.

Conclusion

Gear makers will not be able to avoid the switch to CNC machines much longer. When the mechanical machines in shops are scrapped, CNC-controlled machines will take their place. Gear makers who do not invest in the technology are falling further behind and widening the technology gap that will eventually need to be bridged. ○

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How Many Mice Does It Take to Design a Gear?

or the Manager's Guide to Gear Design Software

You can use anything from pencil and paper to an "expert" system. Which is best for you?

William R. Stott

Gear design has long been a "black art." The gear shop's modern alchemists often have to solve problems with a combination of knowledge, experience and luck. In many cases, trial and error are the only effective way to design gears. While years of experience have produced standard gearsets that work well for most situations, today's requirements for quieter, more accurate and more durable gears often force manufacturers to look for alternative designs.

Many have hoped that faster computers and more powerful software would prove to be the philosopher's stone that could turn so much guesswork into design gold. While no computer program can replace a qualified gear engineer, many software packages can help him or her calculate equations, perform stress and materials analyses, produce computerized gear prints andeven suggest ways to optimize a design.

Most of the manufacturing design world has embraced the computer age wholeheartedly, but the gear industry has lagged behind. One reason is the esoteric nature of gear design—only a handful of people across the country know and understand it. Most of the programs that are useful for gear design have been developed by this handful for their own use.

But no matter how hard its members kick and scream, the gear industry is being drawn into the computer era. While many smaller gear shops—and a fair number of large ones—still calculate gear designs with pencil and paper, a lot of high-end, high-volume shops have gone to full automation, with CNC machines, PCs, CAD programs and other computer design tools.

Two of the engines driving these changes are the

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automotive and aerospace industries. Earlier this year, Chrysler announced a new corporate-wide strategy centered on IBM's CATIA software package. One of the goals of the strategy is to design their automobiles completely on the software. Already, Chrysler exchanges CAD data with more than 300 suppliers and produces several of its models entirely on the CAD system. Also this year, Boeing unveiled its new 777 airplane, the first commercial airliner designed entirely on a CAD system.

Computer programs that would be of use to gear designers can be divided

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William R. Stott
is Gear Technology*'s Associate Editor.*

into three basic categories: CAD programs, gear calculation programs and gear analysis or "expert" systems software.

A CAD Software Primer

Essentially, CAD programs computerize the drawing board. Instead of drawing mechanical blueprints with a pencil and paper, design engineers use a mouse, electronic stylus or other input means to draw a part on the computer screen. Some of the more popular software packages include *AutoCAD* from AutoDesk, IBM's *CATIA* and *CADAM* programs, Intergraph's *Engineering Modeling System* and *CADDS* from Computervision. Versions are available for PCs, workstations and mainframes.

This digitization of the drawing process enables the designer to save a design, modify a portion of it and print it without having to redraw the entire part each time. It also allows direct downloading to machine tools via CAM software.

In addition to standard two-dimensional drawings, many CAD programs today are capable of 3D solid modeling, which allows the designer to fully visualize the part from any angle, making obvious such errors as interference.

CAD systems have definite benefits to someone laying out a transmission or an entire gearbox. By placing the gears, shafts, bearings and seals with a CAD system, the designer can determine whether proper clearances are given for each part and ensure that the entire product is manufacturable and easily maintained once produced.

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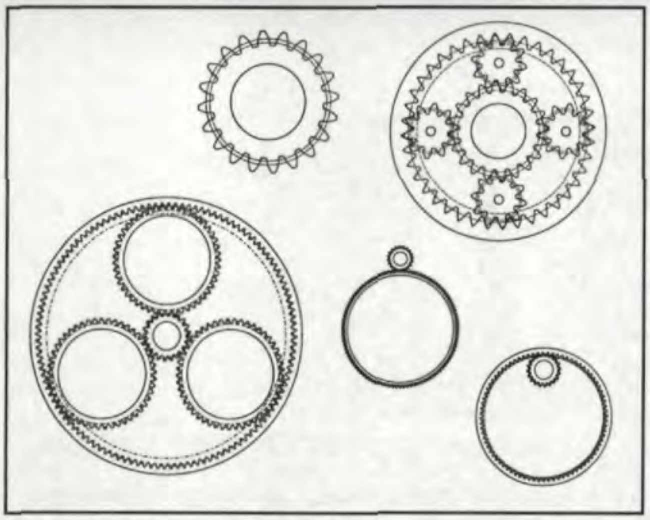


Sample gears drawn with *PC Gears* software.

Some vendors have developed add-on modules for gear design in conjunction with CAD programs. One example of this is CIMLOGIC's *Power Transmission* package, which works with the popular *AutoCAD* program. *Power Transmission* selects appropriate standard gears based on the user's specifications, including horsepower, speed ratio and input rpm. However, this program will not perform calculations to determine load, stress and life capabilities of the gearset. *Power Transmission* requires the CIMLOGIC *Toolbox* program, a general-purpose geometry design enhancement for *AutoCAD*. The price for the package is $1,595 for DOS-based PCs.

However, the consensus among gear experts is that CAD systems are not all that useful for designing gears. While these programs are extremely powerful and have been a boon to mainstream manufacturing design, they do not come equipped with the formulas necessary to compute gear geometry. Given the appropriate geometry, a CAD system can draw the gear, but this is an unnecessary step, says Kent Reece, vice-president of Van Gerpen-Reece Engineering in Cedar Falls, IA. "There is no use for each tooth drawn on a gear drawing," Reece says. "There's nothing you can do with it. It's a waste of the engineer's time."

What's Out There?

The number of kinds of software available to design engineers may seem overwhelming. Prices can range anywhere from $100 to $10,000 or more, not including the required hardware, which can range from PCs to workstations to mainframes. There has been no effort to produce a standardized gear design package for computers. A number of gear shops, universities and consulting firms have developed their own software over the years to suit their own needs. The result is that there is a great variety of gear design software available, each package with its own approach to the gear design problem. With so many choices, and with so few of them aimed directly at gear manufacturers, computerizing the design process can be a daunting and confusing task.

While no one has written a program that could be the industry standard, most of the commercially available gear design programs are based on formulas found in the AGMA standards. In addition, AGMA's Computer Programming Committee has been working for about a year and a half on a program that will perform calculations based on the proposed ISO 6336 standard. This program will make it easier for manufacturers to compare AGMA ratings with ISO ratings, said committee chairman Michael Antosiewicz of Falk Corp. It's important for AGMA to develop such a program because the standard itself is subject to interpretation, and different programs might produce different results, Antosiewicz said.

AGMA plans to sell the ISO 6336 software sometime after the standard is approved by ISO and the program itself is finalized.

Gear Calculation Packages

If you want to start small, there are a number of commercially available packages created to perform some of the routine calculations of the design process and provide easy answers to certain design-related questions.

One of the simpler programs available is the *Gear Professor* from Computer Sales & Maintenance, Inc., in Arden, NC. The program is primarily designed for manufacturers rather than designers. It calculates the appropriate change gears required on conventional gear hobbing machines according to the gear geometry provided. In addition, the *Gear Professor* will calculate the appropriate pin measurements of a gear, allowing the design department to better communicate with the manufacturing department the exact geometry of a gear. The program costs $595 for the first copy and $295 for additional copies. A new release that will perform calculations for bevel and worm gears as well as spurs and helicals is due out sometime in 1995.

PC Gears, from PC Enterprises in Sedona, AZ, takes gear geometry and cutting tool information and produces animated drawings of spur and planetary gearsets in mesh, providing the designer with an immediate idea whether there will be interference, backlash or undercut in the mesh.

PC Gears, at $250, is a relatively inexpensive tool that can be of help to gear engineers who need a fast and easy way to check for problems in their designs. In addition, a new release of the software, *GearWorks for Windows*, will be available early this year.

Another program that will handle many of the routine calculations involved in gear design is *Gearpack* from Software Engineering Service in Rockford, IL. *Gearpack* helps the engineer design single gears or mating gear pairs. The program will calculate tooth thickness, outside diameter, root diameter, gear lead and normal diametral pitch from the center distance and number of teeth for spur or helical gears meshing at parallel or crossed axes.

In addition, *Gearpack* presents a graphics screen showing the gears in mesh and demonstrates a step-by-step rotation of the gears in motion. *Gearpack* is available for $250. Software Engineering Service also offers software to select change gears, calculate the tooth form of a gear when the meshing gear form is already known, and perform many other functions related to gear hobbing, inspection, grinding wheel dressing and gear tooling. All the programs from SES run on a PC.

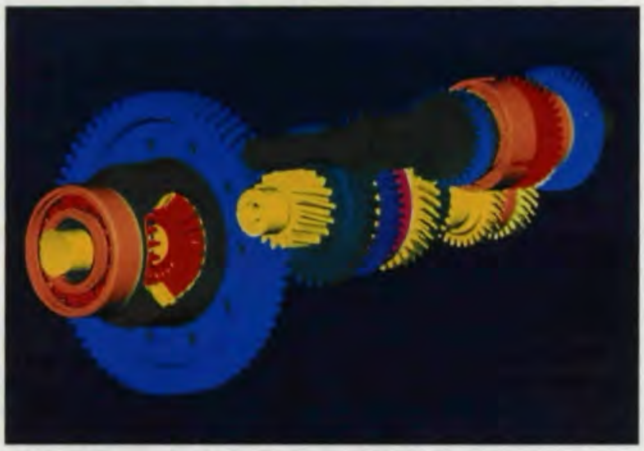
Expert Systems

While programs that perform calculations based on AGMA standards can be of great help to engineers, designing gears based on these formulas might produce gears that are noisy, short-lived or prone to pitting, bending, breaking or fatigue. Several companies have produced more comprehensive, "expert" systems for gear design, which help designers produce the optimum gear design for specific applications.

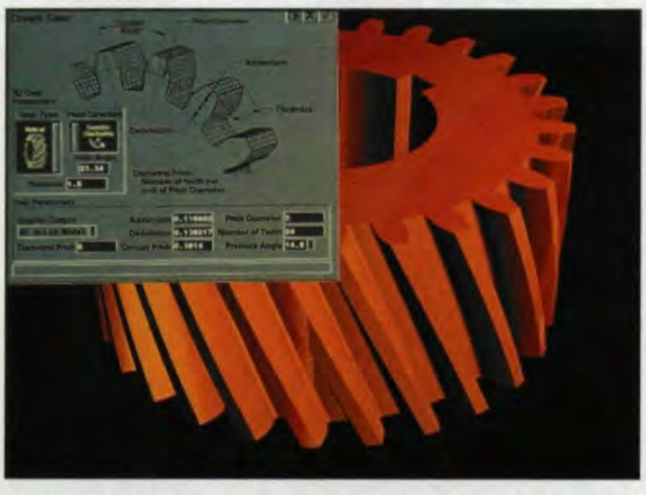
Expert systems help designers along the way by providing default values for certain gear geometry factors. Also, they are capable of performing stress, load and life analyses of gear pairs. Finally, expert systems will present the engineer with warning signals if obvious problems, such as low contact ratios or excessive interference, arise.

Fairfield Manufacturing Company, Inc., of Lafayette, IN, is one of the country's largest suppliers of gearing and power transmission systems. Over the past 25 years, Fairfield has developed its own *Gear Design Software*, beginning with simple calculation programs designed to run on a mainframe system and evolving to version 6.2, which runs on a PC and is available from the manufacturer or through AGMA for $850.

Fairfield's *Gear Design Software* performs data, rating, stress and life calculations for spur, helical, planetary, bevel and spiral bevel gears. Calculations are based on AGMA 2001-B88 and publications of the Gleason Works. In addition, the program has a quick pin size routine, an AGMA quality calculation routine and a two-bearing shaft routine to estimate bearing life and help determine which bearings to use.



Many CAD programs can be adapted to the users needs. Above is a gear train designed on Intergraph's EMS. Below, a customized application for creating spur & helical gears.



Despite its calculating abilities, however, *Gear Design Software* is not an automatic design tool, says Jim Dammon, vice president of engineering. The program will warn you, however, when obvious problems in the design come up—for example, contact ratios less than 1, excessive interference, etc. However, it is entirely possible to design faulty gears with the program, Dammon said. The gear designer still has to know what he is doing.

Geartech Software, Albany, CA, sells a trio of programs for designing and analyzing gears. *GearCalc* designs spur and helical gears for optimum surface durability and bending strength. *AGMA218* calculates power ratings and tooth pitting and bending fatigue life ratings for gears. Although the program uses AGMA standard 218.01, which has been superseded by AGMA 2001-B88, developers say the calculations are still acceptable for all gears except those made of Grade 3 carburized material. Finally, *Scoring+* analyzes the scoring and wear probabilities for a gear set.

Geartech's programs work closely in conjunction with one another. A single keystroke will take you from one to the next. For example, you could design a gear set with *GearCalc*, check to see that it will perform as required with *AGMA218*, and determine if there are likely to be any lubrication, scoring or wear problems with *Scoring+*.

Geartech's three programs are available in a single package for $2,490. The software will run on a DOS-based PC.

Like the other expert systems, *Diseng* gear design software from CIATEQ, Queretaro, Mexico, tries to make suggestions for the best possible gear based on the parameters provided by the user. First, the designer defines either a single explicit value or a range of possible values for gear parameters, including ratio, center distance, pressure angle, and so on. This allows the user greater flexibility in defining the design problem. When starting from scratch, there is even a subroutine to help the designer in the initial sizing of the gears when only factors such as power, torque or speed are known. Second, the designer defines the performance requirements of the gearset, including pitting life, bending life, scoring probability, reliability level and the potential operating conditions. Third, the software performs calculations based on AGMA 2001-B88 and supporting standards to produce the gear design.

With the *Diseng* software, optimization of a gear design means going back to the first and second steps and changing the variables. The software saves the results for each iteration, and it will produce a graph showing the relationship between different iterations for each variable. This allows the designer to see exactly how changing each variable will affect the various aspects of gear performance.

The goal of the software from Van Gerpen-Reece Engineering Co., Cedar Falls, IA, is to produce gears that are quieter, longer-lasting, more efficient or less expensive. A typical approach for Van Gerpen and Reece is to take a gear set that works and make it better, Reece says.

Van Gerpen-Reece's complete gear design system calculates tooth beam strength factors, surface durability factors and all the dimensions required to manufacture the gears. The designer can create non-standard gears with either standard or non-standard tooling. In addition, modules are available for selecting the appropriate shaper, shaver or hob for a gear, designing new tooling, selecting the appropriate master gear for inspection or designing a new master gear if needed.

The basic Van Gerpen-Reece gear design module sells for $5995. A package that includes modules for cutting tool searching and design costs $10,000. Additional modules are available.

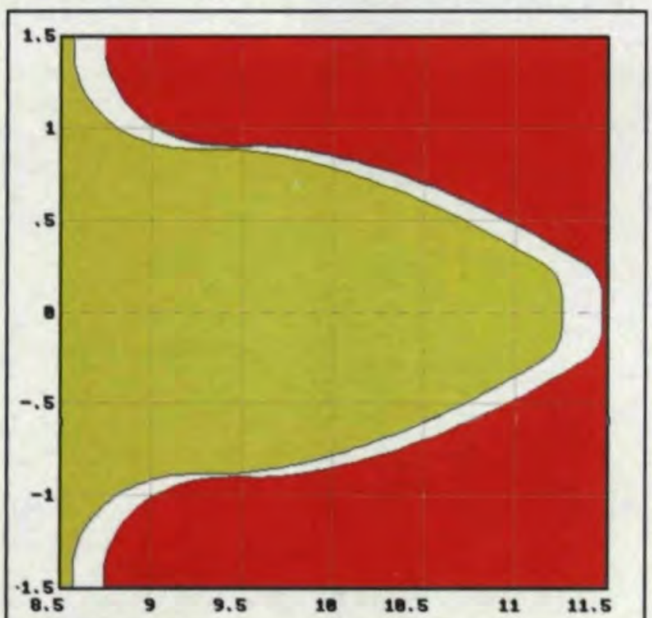
Universal Technical Systems in Rockford, IL, has more than 75 programs for the design, analysis and manufacture of gears. UTS's *Program #500* is its main program for designing gears. It can be modified according to the user's needs, with options for optimizing hobbed and shaped gears, for calculating sliding ratios and profile modifications, and for a number of other functions. In addition, the company offers an engineering calculation package called *TK Solver*, which can be combined with a large number of gear-specific calculation modules, including programs to calculate K Factors, determine tooth thicknesses, perform stress analyses, and calculate the load and life ratings of plastic or powdered metal gears.

UTS's software allows an engineer to modify existing gear designs to produce non-standard gears that are better than their off-the-shelf counterparts. The complete package for *Program #500* with all the options installed costs $12,000. The price for the basic hobbed gear and tooling design software is $1950. *TK Solver* sells for $595, with additional modules relating to gear analysis available for $50 to $1,200 per individual module.

In spite of the capabili-

Expert systems often use graphics to demonstrate potential problems. A screen image from UTS Software shows gears in mesh.

A blown-up section of the image reveals interference in the design.



A design module from UTS Software adjusts the mold cavity for plastic or powdered metal gears to allow for shrinkage.

ties of these "expert system," none of them is capable of replacing the gear design engineer. Too much of the gear design process relies on experience and knowledge of the field.

All Right. I'm Still Confused. How Do I Choose?

Unfortunately, choosing a gear design system is no easy task. The programs mentioned in this article are just some of the software packages being used today. Many individual companies use proprietary software in-house, and some consulting firms use their own software to design gears for clients.

What this means is that it's going to take some research to figure out exactly what will meet your needs. Not everyone needs to go out and buy an expert gear system. The engineers at your company may be doing just fine on their own, but a simple calculation program might help them do their jobs better. On the other hand, your company may be designing cutting-edge gears that require non-standard forms, in which case you might benefit greatly from an expert system. In any case, it's important to check as many sources as possible before deciding.

Once you have determined what type of software you need, choosing an individual package or combination of packages will also require a bit of research. Each piece of software is in effect a computerization of the design technique favored by the programmer, especially with the more advanced expert systems. It is important that you be familiar and comfortable with the approach taken.

Other factors that should be considered before buying software include the amount of training it will require and the type of hardware required to run it. While most gear-specific design programs are written for the PC, many high-level CAD programs require workstations or more powerful systems. ○

If you would like additional information about any of the companies or products mentioned in this article, please circle the appropriate Reader Service number listed below.

AutoDesk..........A-52

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If you found this article of interest and/or useful, please circle Reader Service **Number A-51**.

What's Going On Around Here!

Metrology Update

A formal gear metrology research agreement has been finalized between **Penn State's Applied Research Laboratory**, the Office of Naval Research, the National Institute of Standards and Technology and the Department of Energy's Y-12 Plant at Oak Ridge, TN.

The collaborative arrangement will work toward establishing a calibration service for master gears, developing advanced gear measuring techniques, providing education and training regarding the use of metrology in gear manufacturing and promoting the development of a formal laboratory accreditation program for gear-related measurements.

Elections

James S. Gleason, chairman and C.E.O. of Gleason Corporation, Rochester, NY, was elected to a three-year term on the board of directors of the Association for Manufacturing Technology at the annual meeting in Tucson, AZ. In addition to serving on the board, Gleason will serve as second vice chairman for 1995.

The American Society of Mechanical Engineers announced the election of its next president at the ASME International Mechanical Engineering Conference and Exposition in November. **Daniel T. Koenig**, senior vice president for manufacturing technology of AAVID Engineering, Laconia, NH, will take office in June 1995.

Acquisitions

Santasalo North America Inc. has acquired **Moulder Harwell Machine Company** of Doraville, GA. Santasalo North America, based in Cambridge, Ontario, purchased the Atlanta-area gear company to provide a regional service center for the southeast United States.

Moulder Harwell has 12 employees and sales of $1.2 million. The company will continue to operate under its existing name, but as a division of Santasalo North America.

New ISO 9000 Certification Office

The **Quality Assurance Association of France (AFAQ)** has established a U.S. branch in the Chicago suburb of Schaumburg, IL, to provide ISO 9000 certification for companies in the United States.

AFAQ, an independent, non-profit organization, is recognized as an ISO 9000 auditor by certification bodies in North America, Europe and Asia. ○

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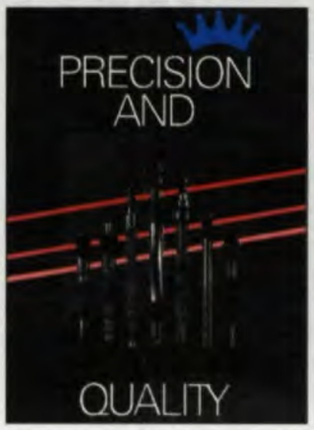

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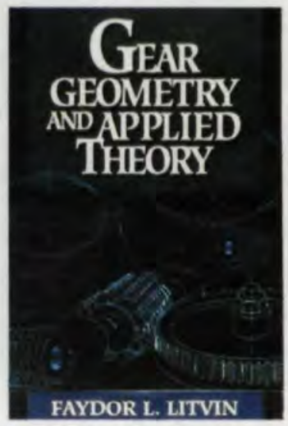

The Complete Gear Book

Gear Geometry & Applied Theory, by Faydor L. Litvin, covers the modern theory of gearing, geometry, design and computerized simulation of meshing and contact for almost all gears; the geometry for face-gear drives, double circular-arc helical gears; CNC applications and new approaches for tool design. **Prentice-Hall**, 1994. $72.00. To order call (800) 947-7700.

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Total Distribution	11,469	12,350
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Total	12,427	15,110

Watch This Space

Addendum, Gear Technology's *bimonthly aberration, will appear in this space. It is a collection of gear trivia (as opposed to trivial gearing), humor, puzzles, weirdnesses and oddments for the edification and amusement of our readers. Contributions are welcome.*

Good References

In the 7th Edition of the *McGraw Hill Encyclopedia of Science and Technology*, 10 pages are devoted to the subjects of **Gears, Gear Cutting** and **Gear Trains**. The entries are found between those on *Gaviforms*—"a small order of aquatic birds that contains a single living family, the *Gavidae* (loons)" and *Gecko*—"the name for about 300 species of reptiles that form the family *Gekkonidae*. . . ." We trust the placement of gears between loons and lizards was the result of the constraints of the alphabet and not an editorial comment. Where's the SPCGE (Society for the Prevention of Cruelty to Gear Engineers) now that we need them?

Gearing gets more thorough treatment (and more propitious placement) in the 9th edition of *Marks Standard Handbook for Mechanical Engineers*, where 22 pages are devoted to it. The 24th edition of *Machinery's Handbook* contains practically an introductory gear course with a whopping 247 pages devoted to the subject.

Don't Throw Away Those Blueprints!

They could be worth money someday, say, $30.8 million. That's what Microsoft's Bill Gates (who by the end of the year will announce the purchase of the entire world) spent last November for one of Leonardo da Vinci's notebooks containing ideas on hydraulics, astronomy, geography, geology and mechanics. The notebook, written between 1506 and 1508, contains more than 300 illustrations.

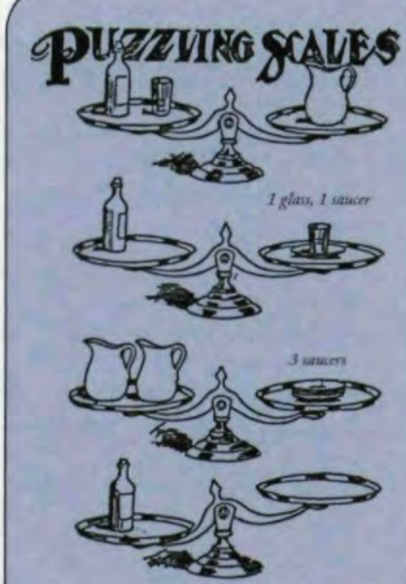
Among other things, the *Codex* contains discussions of the principles of steam power and engineering designs for the snorkel and the submarine.

Christie's of London, the auction house that handled the sale, earned a $2.8 million commission on the deal.

Yes, but Can He Play on the Company Softball Team?

The first gear-cutting machine on record was built by one Juanelo Torriano of Cremona, Italy, who went to Spain in 1540 to build a large planetary clock for Emperor Charles V. It took him 3½ years to build the clock, which contained 1,800 gear wheels. According to a contemporary report, "Every day he had to make . . . more than three wheels that were different in size, number and shape of teeth, and in the way in which they are placed and engaged. But in spite of the fact that this speed is miraculous, even more astounding is a most ingenious lathe that he invented . . . to carve out with a file iron wheels to the required dimension and degree of uniformity of the teeth . . . no wheel was made twice because it always came out right the first time."

(From Daniel J. Boorstein, The Discoverers, *1983, Random House, p. 65.)*



How many glasses will balance the bottle?

Get Out Your Calculators. . .

The following puzzle appeared in Sam Loyd's *Cyclopedia of Puzzles* in 1914. Can you find the solution? If not, the answer will appear in our next issue.

(From *More Joy of Mathematics* by Theoni Pappas, ©1989. Reprinted by permission of Wide World Publishing/Tetra, San Carlos, California.)

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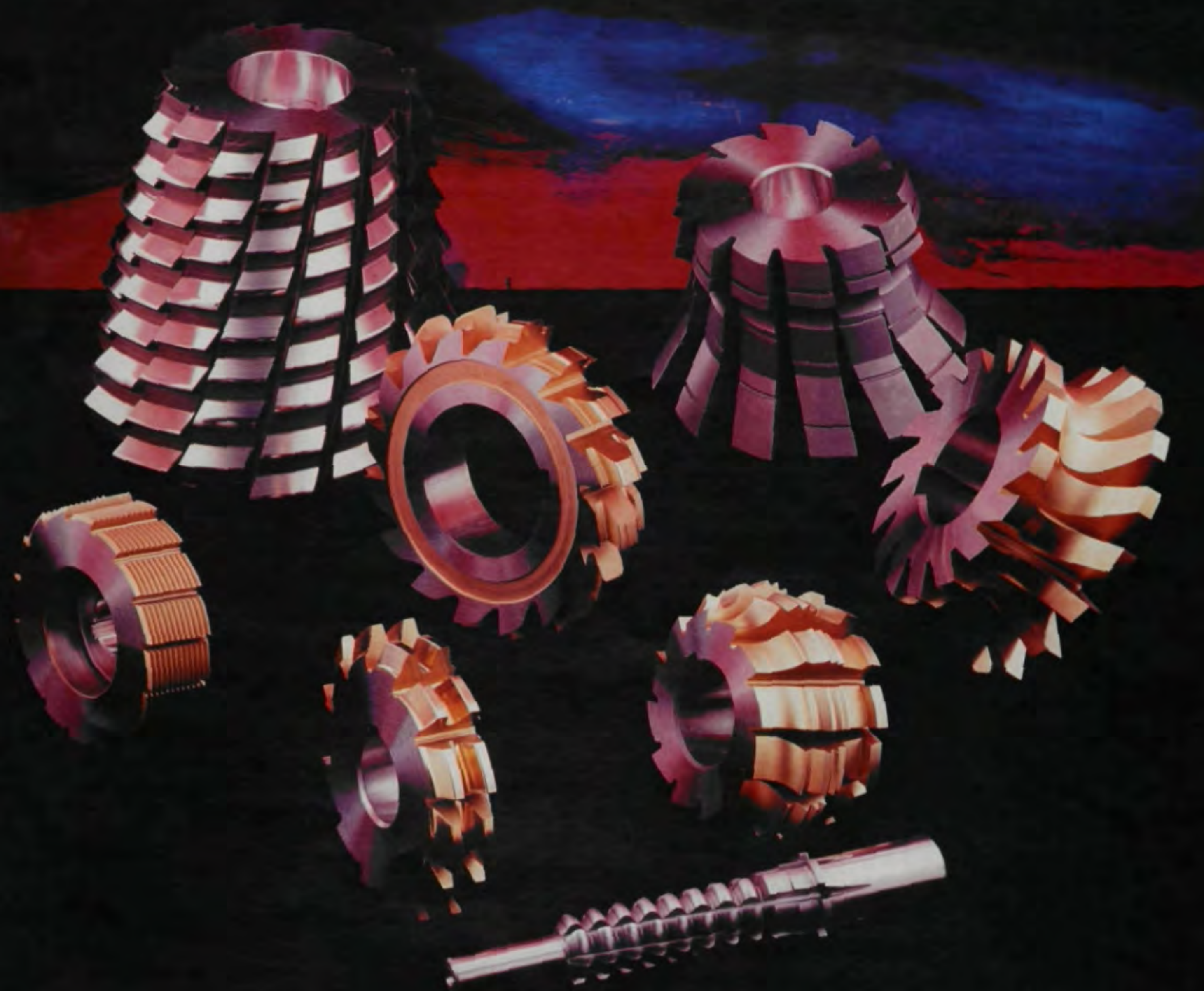

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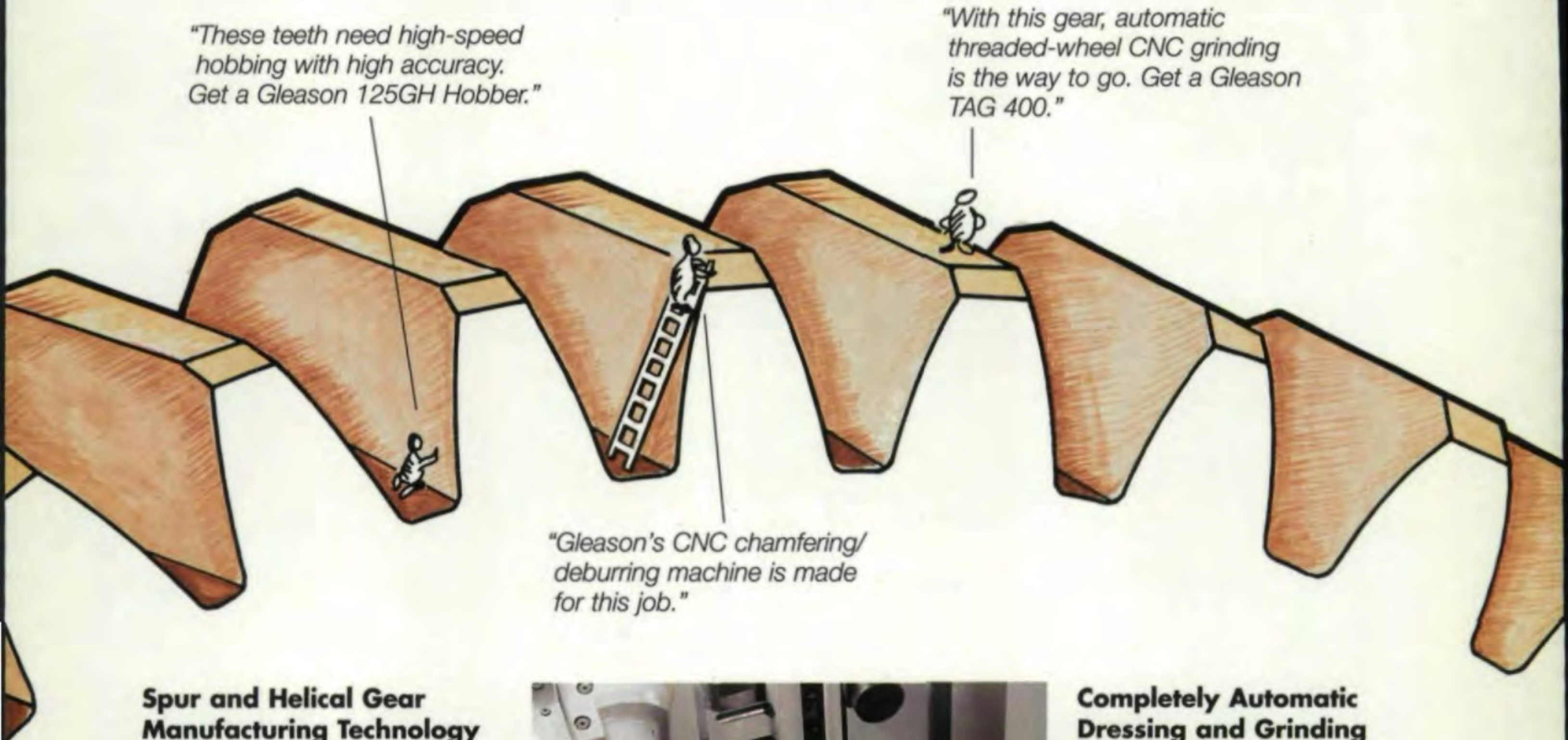

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