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The Journal of Gear Manufacturing

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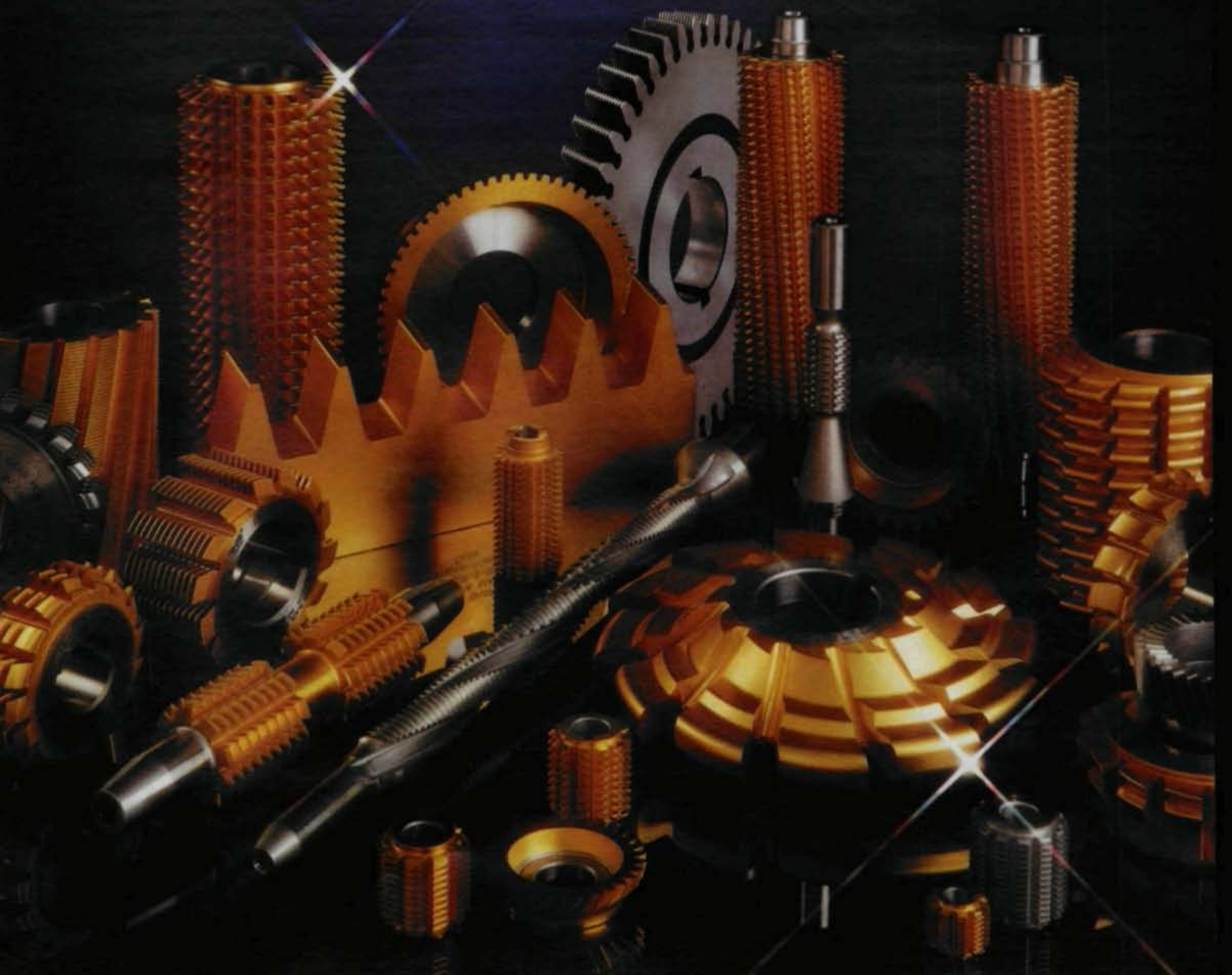

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GEAR TECHNOLOGY

MAY/JUNE 1996

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GEAR TECHNOLOGY
The Journal of Gear Manufacturing

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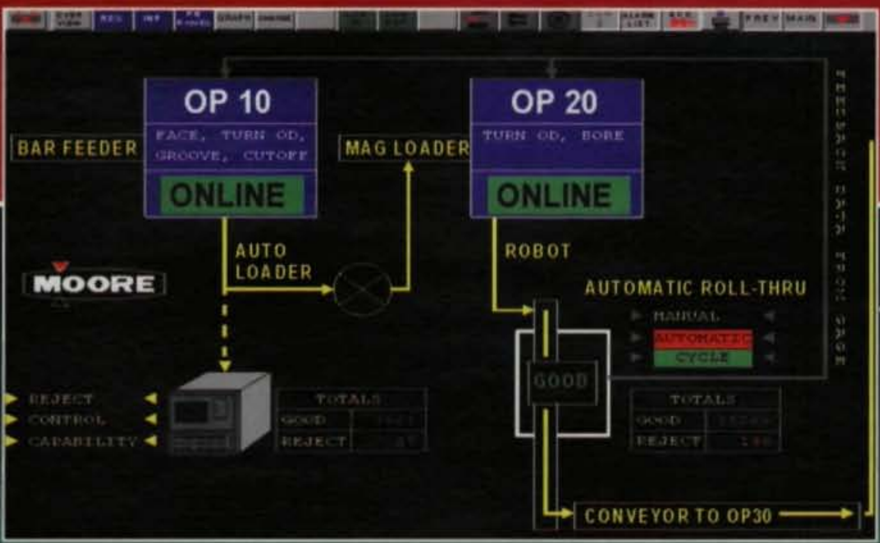

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Other People's Footsteps

Earlier this year, a relative of mine, Sidney Mandell, tragically passed away. I had the good fortune to serve with Sidney on the Board of Directors and the Executive Committee of the Machinery Dealers National Association (MDNA). Though he started before me, his MDNA career and mine overlapped for about 20 years. As I think back on the many things I learned from him, one of his favorite phrases keeps coming to mind: "We walk in the footsteps of those who have gone before us."

What Sidney meant to convey was a sense of obligation and an appreciation for our predecessors in our jobs, our companies and our industry. Industry standards, codes of ethics and professionalism, forums for learning and discussion, training and growth that contribute to the development of our industry are all a result of the work of those who came before us. They made the necessary sacrifices to make our work easier, more organized and more advanced. Sidney felt that because we have benefitted from those prior efforts, we have a moral obligation to continue these endeavors to benefit those who will come after us.

There are plenty of organizations—like MDNA, AGMA and SME—from whom we benefit. None of them are self-sustaining—they all need voluntary contributions of time, effort and thought from their memberships. Let's face it—somebody in those organizations spends hours and days in meetings to develop industry-wide standards or long hours on telephones and airplanes to make meetings successful and worthwhile. Somebody puts a lot of effort into contacting legislators to represent our interests in Congress. And all those "somebodies" are volunteers from whose work we benefit, whether we've made a contribution to the group or not.

All well and good, but most of us have more than enough to do in our lives without looking around for more tasks and responsibilities. Our usual response is something like, "Sure, maybe they made it easier, but what's in it for me?"

My observation in over 30 years of association and volunteer work is that volunteering is one of those odd paradoxes: It's a case of getting back far more than you give. The benefits to yourself, your company and your employer increase by the amount you put in—as a member, a committee chairman, a board member or a national officer.

Volunteering is a wonderful school for self-development, a way of learning skills that aren't always covered in our engineering and business courses, but still are vital to success in business.

Working within associations made up of volunteers hones your people skills. In such organizations, the first lesson is that you can't order anyone to do anything. If you want a project to succeed, you have to create the desire and convince others to be involved in the project. You have to lead, not give orders. What better skill can one cultivate in an era that demands teamwork?

(Continued on page 8.)

Another vital skill that volunteer work teaches is time management. When you have to work one more commitment into your already busy life, you have to make some decisions about what's important and what's not; about getting started on a task sooner, rather than later. Of necessity, you become more efficient, more effective, more organized in your thoughts, your words and your work. That's a task with which many of us struggle, and there's nothing like being in charge of a volunteer project to provide the motivation for getting one's act together.

Leadership in a volunteer organization will often put you in the position of having to direct a meeting or speak in public. Some of us never get completely comfortable with these tasks, but working in a volunteer organization provides the on-the-job training to make it easier. I've seen many examples of people who begin as hesitant and awkward speakers only to blossom into confident and interesting forces behind a podium by the time their terms of office end.

Another important gift that volunteer work gives, particularly for people who become involved at a national level, is a view of the larger industry picture. Interacting with associates from different companies, from different locations, maybe from different countries, helps give you a better perspective of your company and the industry at large, helping you to develop and maintain a sense of vision and direction.

This meeting ground also helps build a valuable network of business acquaintances (and friends). These people share common interests and can offer insights into common problems, and as time goes on, you will find these relationships will become some of your most valued.

Finally, I have seen the combination of all these acquired skills result in a positive personality transformation in numerous people who take on national leadership. Their self-image and their self-esteem grew in positive ways. It sounds a bit hokey, but the fact is, working in volunteer organizations made them better people. The public speaking, the organization, the sense of self-worth and self-confidence, the leadership skills, etc., are all attributes we carry with us for the rest of our careers.

Many of you have gone to college and participated in extended education, and you know you had to pay for your education with work and coin. The cost of volunteerism should be viewed as a further investment for the opportunity to get or improve many necessary skills that aren't taught in school and refine those that are. They make you more confident and a better leader, owner, manager and employee.

What seems clear to me, as it did to Sidney, is that each of us has a responsibility to our professions and our industry to continue to build them for the next generation, not only because it's the right thing to do, but because it's good for us personally and for our businesses. Remember, we walk in the footsteps of those who have gone before us. You too should leave your own footsteps for those who will follow.

Michael Goldstein
Publisher & Editor-in-Chief

What's News

Sales Up — Gleason sales for 1995 were up 53% to $197 million, according to a company spokesman. Sales of Gleason's 125GH CNC hobbing machines, used to produce spur and helical (cylindrical) gears have been increasing by better than 50% per year since 1992.

ISO Qualifiers — Etna Products Inc., a manufacturer of metalworking compounds, lubricants and specialty chemicals in Chagrin Falls, OH, has achieved ISO 9001 certification . . . **Computational Systems, Inc.**, a manufacturer of predictive maintenance products and services for large-scale facilities, and **Multi-Arc Inc.'s** Northeast Regional Coating Center have qualified for the ISO 9002 certificate.

Acquisitions — Midbrook Products, Inc., of Jackson MI, has acquired **Advanced Cleaning Systems (ACS)**, a former operating unit of Dow Chemical. Midbrook is a provider of industrial parts cleaning systems.

Facilities — Eagle Technology & Manufacturing, Inc. has opened a 38,800 sq. ft. facility in Roseville, MI, to service the North American automotive industry. It offers full-service OEM support for design and production of body assembly welding, tooling and fixturing . . . **Carl Zeiss IMT Division** has announced the completion of the expansion of its Brighton, MI, location. The Brighton facility has become the North American headquarters for sales, application development and training for Zeiss metrology products . . . **Abar Ipsen Industries** will be relocating its engineering department and the company's marketing and corporate headquarters to its existing manufacturing center in Rockford, IL. A new technology center for furnace development is also planned. The consolidation is scheduled to be completed before the third quarter of 1996.

New Moves — Fässler AG, a Swiss manufacturer of hard gear finishing machinery, has established an American division in Germantown (Milwaukee), WI . . . **Gosiger Inc.,** of Dayton, OH, has become the first full-line U.S. distributor of die-sinking and wire-cutting EDM machines made by **ONA Electroerosion, S.A.**

Promotions — Keith Liston has been promoted to international sales manager and **Robert Phillips** to vice president of manufacturing and engineering at **Pfauter-Maag Cutting Tools, L.P.** in Loves Park, IL. At the same time, **Hans Grass** has been promoted to vice president of manufacturing and engineering at **American Pfauter, L.P.**

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EDM Specialty Gears

From the Mars Lander to car doors, gears cut with EDM find their niche.

E. Bud Guitrau F.I.A.E.,
E & M Engineering

Introduction

The capabilities and limitations of manufacturing gears by conventional means are well-known and thoroughly documented. In the search to enhance or otherwise improve the gear-making process, manufacturing methods have extended beyond chip-cutting—hobbing, broaching, shaping, shaving, grinding, etc.—and their inherent limitations based on cutter selection and speed, feed rates, chip thickness per tooth, cutting pressure, cutter deflection, chatter, surface finish, material hardness, machine rigidity, tooling, setup and other items.

In this expanded search for improvement, EDM (Electrical Discharge Machining) has been utilized in more and more cases. EDM involves very few of the above criteria, thereby eliminating many of the problems associated with traditional methods. Granted, EDM can create some of its own problems, but on the whole, it makes design and manufacture of certain applications much simpler than conventional means. This article will examine a few examples.

The Process

Very briefly, EDM is a machining process that removes material by spark erosion. Using special generators, pulsed DC or AC current is used to vaporize and melt conductive material away instead of mechanically shearing a chip, as in conventional machining. The current is delivered to the workpiece via an electrode. Depending upon the application and machine, the electrode can be a small diameter alloy wire, as in the case of wire EDM or a pre-shaped, solid electrode that is used in a vertical or "sinker" EDM.

The spark gap of each machine type must be flushed with a dielectric fluid which is integral to the EDM process. The wire EDM uses deionized water that is regulated within a self-contained, closed-loop filtration and deionization system. The vertical EDM typically uses a specially engineered dielectric oil similar to kerosene, but with a high flash point. Both machines can use either as a dielectric, but as a rule, wire machines use DI water, and vertical EDM machines use a light oil engineered specifically for EDM use.

The Project

The first application is a gear assembly that is part of the drive mechanism that will retract the protective airbags, enabling other actuators to reorient the Mars Pathfinder Vehicle after its projected landing on Mars in July of 1997 (see sidebar). Since the lander may come to rest in any position, (upside down, sideways, etc.), this mechanism's task is to right the vehicle into its "heads up" position so it can function properly. The development and design of this complex and challenging project is being done by the Jet Propulsion Laboratory (JPL) in Pasadena, CA.

Four gears were required within one component of the Pathfinder Lander deployment mechanism called the airbag retraction actuator or ARA. Two of the gears were produced using a wire-cut EDM. This is a machine tool that can cut almost any conductive material using an electrically charged wire as a cutting electrode. The wire passes through the workpiece as the machine acts like an electric band saw. The wire electrode is usually made of various brass alloys and ranges in sizes from .001–.012" in diameter. For these gears, a brass wire of .008" diameter was used.

Because the wire electrode must pass completely through the part or outside of it along its periphery, spur gears are an ideal application for wire EDM, but gears located against larger shoulders or another larger diameter gear on the same shaft cannot be wire-cut. For them a vertical EDM or "sinker" must be used.

Instead of using a wire electrode, a vertical EDM uses solid, pre-shaped electrodes typically made of copper or a special graphite refined specifically for EDM use. These electrodes are made with the obverse shape of the desired details. For example, a free-standing male pinion gear located against a shoulder would be machined with a female electrode. The electrodes used for this project were produced on the wire EDM using the same tooth geometry macro from the actual wire-cut gear program, providing identical part accuracies and matching gear geometry. During EDM machining, these electrodes are "burned" into the solid blank, eroding the workpiece and leaving a finished gear impression requiring no additional processing.

Fig. 1 — Airbag retraction actuator (ARA) for the Mars Pathfinder Lander.

Fig. 2 — Exploded view of the ARA.

The Procedure

The decision to use EDM to cut the gears was based on several factors:

Workpiece Material—Initially, EDM was examined because of material properties. The gear loads will be quite high, and a tough, high-strength material was needed, so a maraging steel was selected. While this is a very tough material, its tendency to shrink during heat treating could affect the precise fit and mesh required for the finished gear assembly. Further, the final hardness specification would make any additional machining needed to correct any deformation cause by heat treatment very difficult. Using EDM allows the blank to be prehardened to its final specification and be machined "in the hard," eliminating any further processing.

Process Flexibility—Using EDM to manufacture gears allows for quick and virtually infinite adjustment of sizes and shapes of gear geometry without the need for custom hobs, shapers or broaches typically used in conventional gear manufacture. This degree of flexibility is especially important in any "cut-and-try" process of development.

Product Design—Besides having the ability to produce special gear assemblies quickly and economically, EDM can help steer the actual product design. Because the weight and size of components are primary considerations of space exploration, they must be as light and compact as possible. Unfortunately, some parts must be designed to be stronger and heavier than use specifications require merely to survive the rigors of their own machining and manufacture.

For example, sections of the part might be made thicker than necessary or have bosses added to facilitate tooling or clamping. The use of EDM on this part eliminated some of the tooling provisions typically required for holding the parts during conventional machining, because there is no physical contact of a cutter and workpiece. Material is removed with electricity instead of a mechanical cutter, eliminating the concerns of cutting pressures, clamping pressures, surface work-hardening, etc.

Since EDM is a "non-contact sport," part design and tooling considerations can be made without concerns for cutting pressures, setup rigidity, part wall thickness, etc. Part design can be optimized and manufacturing engineering can be simplified. This means that lighter, smaller parts can be made with more compact designs that help address the critical considerations of size and weight. In this case, a lighter launch and deployment vehicle will allow the use of a larger, heavier payload—the reason for the launch in the first place.

Product Testing—Since the gear hubs needed lightening, they were wire-cut with an internal hex bore which not only removed a significant amount of mass from the body of the gear hub, but also made dyno testing easier by allowing a common hex-shaft adapter to be used on all gears during speed and torque tests.

After careful analysis, engineers from the Spacecraft Mechanisms Engineering section of JPL concluded that gears made by EDM would fulfill all four of these criteria, and they then moved to contract that part of the project to an experienced EDM house.

JPL chose the Maroney Company in Northridge, CA. Maroney is a precision prototype EDM and machining facility with experienced EDM specialists, state-of-the-art machinery, a proven track record and the flexibility to shepherd through this kind of special project.

The Product

The wire-cut spur gear for the lander is made from Vascomax C300, has a .917" PD and a face width of 1 inch. The tooth form is modified and has a 25° pressure angle (see Figs. 1–2). Before machining, the blanks were prehardened to have a yield strength greater than 2000 Mpa (290 ksi). Using the vertical EDM, the remaining gear details were completed. Both processes (wire and sinker) provided gears of exceptional form and surface.

Extensive testing was done to analyze tooth form, surface condition and tooth thickness. For a 48-tooth gear, accuracies of the wire-cut parts had an average variance of only .00028" from a perfect tooth form. The parts produced on the vertical EDM have a .00028" taper across the gear face due to electrode wear, which resulted in a total average variance of .0005". These tolerances are equivalent to an AGMA class 10 gear.

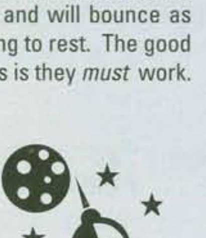
Concerns about recast, the very thin layer of thermally changed material remaining on the surface after EDM cutting, proved largely unwarranted. Maroney's experience and the use of a special anti-electrolysis generator with technology proprietary to Mitsubishi Electric (Japan) kept the finish and surface integrity well within specifications.

During these tests, it became obvious that making and testing custom

ROUGH LANDING

Here's your assignment, should you choose to accept it. Design gears to operate in a high-torque, low-temperature, dirty environment. They will be dropped from a vehicle traveling 13,645 mph and from 8,500 km in space. They will strike the rocky, low-gravity surface of Mars at approximately 50 mph and will bounce as high as a nine-story building as many as 15 times before coming to rest. The good news is the mechanisms have to work only once; the bad news is they *must* work. There will be no second chance.

Cushioning the landing and righting the lander are the tasks of the airbag retraction actuators and the lander petal actuators on the Mars Pathfinder Lander. Once on the ground, the airbags (made of a Kevlar-like material, Vectran, which may be ripped and deflated or still intact) have to be taken out of the way so the lander's solar panels can work. The lander itself, a tetrahedron roughly one meter in diameter, may land upside down or on its side and will have to be righted in order to function. EDM-cut gears are vital to the successful operation of both of these mechanisms.



gears by conventional means (hobs, master gears, etc.) would be both time-consuming and cost-prohibitive. While the EDM process is not necessarily applicable to everyday production gears, it proves invaluable for almost any experimental, R&D or specialty gear applications.

As with most experimental products, gears produced in this manner will cost more than the standard "off-the-shelf," garden-variety, but considering that, in the case of the lander, a multi-billion dollar investment will be over 140,000 miles away on another planet, gear failure is not an option. It simply *has* to work. Cost becomes a secondary consideration, with reliability being the primary concern. EDM has helped insure that.

Molded Gears

EDM has uses in more down-to-earth applications as well. A small (approximately 1" in diameter) helical gear to be used within the electric window mechanism of an automobile was needed. This gear needed to be quiet-running, long-wearing and have a natural lubricity because it was to operate within the auto's door panel and could not be easily lubricated. For this application, an engineered nylon was chosen to provide these characteristics.

If this had been a straight gear or spline, the mold cavity could have been machined using a wire EDM, but because the gear was helical, this became a CNC EDM application. A helical gear was machined from copper (slightly undersized to allow for the spark) and used as an electrode. The electrode was held in the spindle of a Mitsubishi CNC EDM equipped with a C-axis from System 3R that allows servo-controlled helical machining. Accuracies are virtually assured because the C-axis has a resolution of .001 of one degree and complements the servo resolutions of 0.1 micron or 0.000004".

Programming was very simple, requiring only a few lines of code commanding the machine head to advance in the Z-axis while simultaneously rotating the C-axis, literally screwing the electrode into the workpiece, eroding the material in front of it. After passing

Fig. 3 — Stacked spur gears in an EDM.

completely through the mold insert, the final finish was obtained by using low current settings and a small circular orbit of approximately .0100 per side. The final finish required no further processing or polishing.

Manufacturing Engineering

The decision to mold these gears instead of machining them was based on the part material, the quantity required and the part tolerances. The decision to use EDM to machine the mold cavity was arrived at after evaluating the time and expense of conventional machining. The following are a few considerations and observations.

Machining Plastic Gears—Machining each gear was not an acceptable avenue because of the large quantity of gears required and the reluctance to use an expensive metal-cutting machine to machine plastic parts.

Both the quantity and material requirements favored the construction of a plastic-injection mold to inexpensively mold the production parts rather than machine them. With this decided, next came determining the best way to machine the mold cavity.

Conventional Cavity Making—The usual method of machining an internal helical gear would be broaching or internal shaping. Both of these methods were ruled out for several reasons:

1. Because the part was to be molded, part shrinkage must be taken into consideration when making the cavity. In this case, shrinkage was factored at 16%, and all cavity-making methods must allow for this. This shrinkage factor precludes the use of "off-the-shelf" broaches, increasing costs and extending deliveries. Shaping this detail would require special guides to be made, making an already expensive proposition even more so.

2. Helical broaching must be done on special machines capable of twisting the broach through the part similar to the way rifling in firearms is produced. Shapers must rely on expensive guides and cutters to produce an internal gear. Both methods were deemed too expensive.

3. Whether the detail is to be broached or shaped, all conventional machining of the workpiece must be done while the material is soft. When machining is completed, the insert must be deburred and polished, and then it must be heat treated, which can cause the cavity insert to shrink, expand or otherwise move and possibly distort the geometry of the gear.

Results

EDM was selected to produce the cavities for injection molding because:

1. An inexpensive copper blank can be hobbed and used as an electrode. Electrodes are made undersized and as long as the tooth form and geometry are correct, size and finish are easily controlled by means of orbiting offsets during machining.

2. This is a routing job for a C-axis-equipped CNC EDM, requiring only the helical electrode and a few simple lines of programming code.

3. Parts made on an EDM are typically burned "in-the-hard," eliminating any post-machining heat treating operations and the resulting potential for part movement due to thermal influence.

Short Run Production

The last application we will examine is one that EDM can address very well; the making of replacement or discontinued gears for repairs or older equipment. These "onesy-twosy" or small lot, short-run situations sometimes do not warrant tooling up on conventional equipment.

In this example, multiple spur gears are produced with a single cut by stacking up the prehardened, blank material and wire-cutting them from the solid (See Fig 3). Internal diameters and keyways are typically machined first, then the gear shape. Since all operations will be done in a single setup, perfectly concentric ODs and IDs are guaranteed. After programming and setup, an application such as this could run almost totally untended with very little operator intervention. A wire EDM machine equipped with an automatic wire threader could move from part to part autonomously and easily complete the project unattended during a overnight "lights-out" shift.

Again, EDM provides time and labor savings on an otherwise expensive task.

Summary

Obviously, we cannot conclude from these examples that EDM should always be used to prototype special gears, or that it should be used in all mold-making applications. There is, however, very strong evidence that EDM is a viable method for producing widely varying gear applications in a timely manner while reducing costs and eliminating secondary operations.

The scope of EDM gear use is very wide, ranging from the Mars Lander, a low-speed, high-torque application (0.7 rpm @ 100 ft/lbs), to the frenetic intensity of sustained, 1000 to 10,000+ rpms of a race car (see p. 34), to the relatively mundane task of occasionally raising and lowering a car window. These significantly different uses demonstrate the versatility and reliability of EDM-cut gears.

While EDM will never replace the traditional manufacturing methods of gear making, it has proven to be a worthy augmentation and a solution-finding process that has a valuable and rightful place in specific areas of gear development and manufacture. ✪

Reference:

Gillis-Smith, G. R. "Mars Pathfinder Lander Deployment Mechanisms." Jet Propulsion Laboratory, Pasadena, CA. 1995.

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CIRCLE 162 on READER SERVICE CARD

Cutting Tools Now

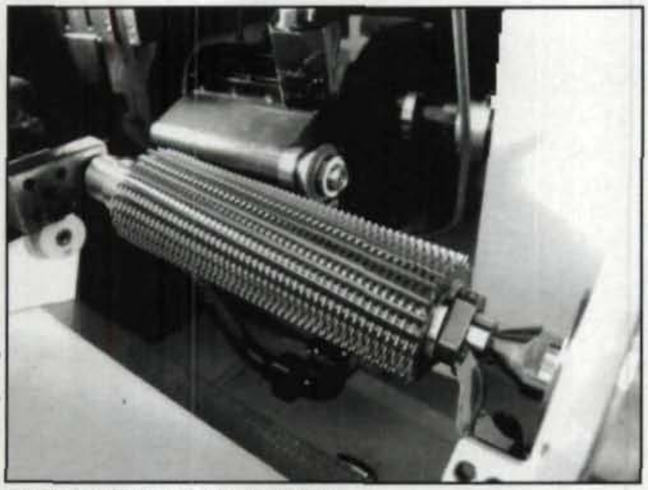
Carbides, Coatings & Other Hot Stuff

Nancy Bartels

The cutting tool is basic to gear manufacturing. Whether it's a hob, broach, shaper cutter or EDM wire, not much gets done without it. And the mission of the tool remains the same as always: removing material as quickly, accurately and cost-effectively as possible. Progress in the field tends to be evolutionary, coming gradually over time, but recently, a confluence of emerging technologies and new customer demands has caused significant changes in the machines, the materials and the coatings that make cutting tools.

What Customers Want Now

Like the Irish writer Oscar Wilde, cutting tool customers have simple needs: They want only the best. They also want it faster, cheaper, and with more technical and customer support.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A carbide hob ready for finish grinding.


© Pfauter-Maag Cutting Tools

Heat Treating is a crucial step in manufacturing cutting tools.

They are under pressure to produce gears of higher and higher quality and, as a result, they are demanding the same thing of their cutting tool suppliers. They want tools that are more durable, can cut faster and more accurately, but are still cost-effective. Ken Brewer, Sales Manager for Fette Tool Systems, suggests that the general push is toward tools with grinding quality tolerances. He says, "People want aerospace quality cutting tools without having to pay aerospace prices."

And everyone wants more and better customer service and warranties. "Machine customers are demanding longer-than-standard warranties," says Bill McElroy of GMI, distributor of a range of gear manufacturing machines, tooling and cutting tools. "And they want machines that are idiot-proof." Harvey Yera of National Broach concurs. "Price is always a factor, but consistent high quality and good, extensive customer support is even more of an issue," he says.

At Pfauter-Maag Cutting Tools, part of a nine-year-long redevelopment of the old Barber Colman facility in Loves Park, IL, has included installation of a new testing and analysis center. While the company uses it to check on its own work, its real purpose is to provide some of the latest equipment available to help customers solve their tool cutting problems. Says Bob Phillips, vice president of manufacturing and engineering "It's not a profit center. We do it for the customers. We have to be willing to do whatever it takes to have the customer satisfied with his cutting tool purchase."

Emerging Technologies

On the machine side, the latest development is dry hobbing. First introduced by Liebherr about two years ago, it has been greeted with a mixture of enthusiasm and skepticism, according to Ian Shearing, vice president of sales for Liebherr America.

For example, Carl Johnson, vice president, cutting tools, at Fellows Corp., cites the expense of manufacturing, handling and sharpening carbide tooling as a major concerns and calls dry hobbing an "emerging technology." Massimo Denipoti, managing director of SU America, echoes this skepticism, pointing out that it is the machine manufacturers who are pushing the technology and adding, "The tools are fragile, expensive, high-maintenance items. Many people are just trying it out now. It may be just a fad."

But while some manufacturers are waiting for more data before deciding about dry hobbing, the process is appearing in many high-production facilities, particularly in the automotive sector, and major players in the gear hobbing machine market, Liebherr, Gleason and American Pfauter, all have machines that offer dry hobbing capability.

Dry hobbing machines share certain characteristics. They are rigid and very fast, have speedy chip removal and are capable of both wet and dry hobbing.

According to Jerry Knoy, vice president of sales for Pfauter-Maag, "Most new machines have dry hobbing capability. Even if customers don't want to use it right away, they want it there for the future."

Beyond Hobbing

Improvements in shaper cutters will be following more or less the same trends as those in hobbing, according to Fellows' Carl Johnson. He sees continuing improvements in coatings and materials, including high speed steels, and more demand for disposable tools. Like hob manufacturers, shaper cutter suppliers will be confronted with a demand for longer tool life, better performance, higher speeds and more productivity.

Bill Maples of Star Cutter observes that improvements in powder metals will have an impact on cutting tools. "They are more homogeneous than other steels and provide a more even grain structure," he says, adding, "I think we're going to see less and less availability of wrought steel."

Makers of broaching tools have to meet the same demands from customers as hob manufacturers. In response to customer demands for longer tool life, quieter operation and longer times between sharpening, National Broach has introduced the SPIRALGLIDE broach bar, which offers continuous workpiece contact, virtually eliminating vibration and noise. The company says that the new tool increases broach life by 400%.

The other goal that broach manufacturers are aiming for, but have not yet reached, is the ability to broach parts after heat treating instead of before to increase accuracy.

EDM is another technology to watch. The jury is still out on how effective it is in cutting tool applications. Bill Maples says that his company used EDM to cut hobs for awhile, but was unhappy with the results. "We just couldn't get the accuracy or tool life we wanted," he says.

© Fellows Corporation

Shaper cutter manufacturing.

PFAUTER-MAAG GOES CELLULAR WITH CARBIDES

Carbide as the tool material of choice has undergone a renaissance in the last three years, and Pfauter-Maag Cutting Tools has primed itself to be in the forefront of this change. As part of an overall refurbishing and restructuring of the old Barber Colman operation it acquired in 1987, the company has installed a 9-machine (a tenth will be added by the time this article appears) carbide cutting tool cell at its renovated plant in Loves Park, IL.

Because carbide is a hard material already, and no heat treating is required, all the machines in the cell are grinders of one sort or another. Reineker form grinders are used for roughing and Reishauers for finishing. Huffman and ITM grinders do the gashing and threading from solid. Tropei grinders do face and bore grinding, and a Studer grinder is used for shank grinding. All the machines are less than three years old.

Lead times for production will depend, of course, on the application, but material removal time can run to roughly 50 hours with the new machines. (Actual lead times for carbide tools will run from 8–16 weeks, depending on design and availability of stock blanks.) The machines can all run unattended, and the cell operates seven days a week, 24 hours a day.

Flexibility and redundancy are important concepts on the Pfauter-Maag factory floor, and the carbide cell is no exception. While every effort is made to keep the equipment in the cell exclusively for carbide hob production, it does serve as backup for the steel cutting equipment. "But the carbide always has first priority," says *Bob Phillips, vice president of manufacturing and engineering.*

The carbide cell was one of the most recent renovations at the Loves Park plant for a number of reasons. P-M had other, more urgent issues to address first. And until three years ago, there wasn't sufficient demand for carbide tools to make setting up a separate manufacturing cell worthwhile.

Then in 1994, improved carbide material and coatings, developments in machine technology, including dry hobbing, and the pressure of environmental concerns combined to reach critical mass, and the demand curve for carbide cutting tools began to look like a 90° angle. In 1994, P-M sold 17 carbide hobs. In 1995 it sold 350. Projections for 1996 run to 50 carbide hob sales a week.

At that point it made sense to have a separate cell. "There were a lot of good reasons to separate carbide manufacturing from the other processes," says Phillips. "The characteristics of carbide are very different from those of steel; there are only hard operations, and the filtration process is different. We also *wanted to develop* awareness on the part of operators that this was a completely different process." ○

© Pfauter-Maag Cutting Tools

A finish grinder in Pfauter-Maag's carbide cell.

On the other hand, both Fellows and Pfauter-Maag successfully use EDM in certain niche applications. Rack cutting tools to AA quality can be made with EDM, and National Broach uses EDM to make pot broach and blind spline rings. Pfauter-Maag has purchased two AGIE-CUT™ HSS 150 wire EDM machines to make special rack and shaper cutters.

The Carbide Connection

Carbide tools go hand in hand with the new dry hobbing machines. Tony Spinks of Parker Industries in Bohemia, NY, calls carbide tooling one of the "hot trends" of the moment.

It wasn't always this way. Time was when carbide was known for its expense, its brittleness and its general unsuitability as a cutting tool material. But recent developments in microcarbides and their processing have closed up the pores in the material and made it considerably stronger and harder. According to Primo Pappafava, president of General Carbide Corp., the addition of more cobalt to the carbide has increased its strength, and finer particle size (down to less than .6 microns in some cases) makes for a harder part. Now carbides are available with 400,000 psi strength, no visible porosity and 91 Rockwell A hardness.

Not A Panacea

While a lot of people are jumping on the carbide tool/dry hobbing bandwagon, many are careful to point out that it's not good for every application. Dr. Walter Eggert, Managing Director of the Pfauter Group, says: "Carbide hobbing is an attractive approach in many applications, but it isn't always the best solution."

It seems to work best in high-production applications, such as automotive and hand tools, and in pitch ranges from 12 to 20 DP.

Dry hobbing, which in almost all cases uses carbide tooling, requires some means for disposing of hot chips quickly. In successful dry hobbing, 70–80% of the heat generated needs to be carried away in the chips.

The ability to do this, according to Ian Shearing, is a function of cutter diameter, number of cutter gashes, number of starts, the axial feed rate and the number of teeth in the workpiece. If the combination of these can be juggled to give the necessary chip thickness, dry hobbing will be successful. If not, it's not an option.

There are other drawbacks to carbide hobbing. In many cases, new machines, with their demand for huge capital outlays, are required. Cutting tools themselves are also very expensive—anywhere from 3–5 times the cost of high speed steel tools, and they require sharpening machines that use CBN/diamond wheels. For many applications, the selection of a good high speed steel with the proper coating may be a better choice than carbide.

Coatings

The third leg of the cutting tool triangle is coatings. The purpose of tool coating is to keep the heat generated in the cutting operation away from the material substrate. The right coating for the right application can be the difference between a good and a bad tool, and cutting tool manufacturers take their coating operations very seriously. Star Cutter is so particular about its tool coatings that it makes its own to ensure quality.

Introduced in the early 1980s, titanium nitride (TiN) is the workhorse of coatings. It is useful over a broad spectrum of applications and offers, conservatively speaking, an increased tool life of 200–300%.

But as with other parts of the cutting tool manufacturing process, research continues to improve TiN applications. Multi-Arc Inc. has been researching the interaction between surface preparation and the performance of coatings and has found a direct corollary between the amount of improvement provided and the quality of the preparation. A badly prepared surface (one with burrs, nicks, or one that is poorly ground) will not be improved by coating nearly as much as one that is properly prepared.

A result of this research is Multi-Arc's new Super TiN process for recoating hobs. It is a sequence of stripping the old coating, pre-coat polishing, an improved, smooth coating process and post-coat polishing, which results in doubling the tool life of hobs.

But newer materials and machines have also demanded newer, more efficient coatings; hence the appearance in the last 3–4 years of titanium carbonitride (TiCN) and titanium aluminum nitride (TiAlN). TiCN is a good coating choice for applications where moderate heat is generated. It is useful for machining abrasive or

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Hobs ready for coating.

adhesive materials, or those that are difficult to machine, such as aluminum alloy, tool steels and Inconel. TiAlN is the optimum coating for use with carbide tools. It offers much better oxidation resistance than TiN (up to 800°C). The heat generated during cutting creates a top layer of aluminum oxide, a thermal barrier coating with low heat transference, which is essential in dry cutting operations.

The other coating to keep an eye on is molybdenum disulfide (MoS_2). This is a coating for high speed steels which first appeared in aerospace applications. It is a solid film with a low coefficient of friction, and it is removed at a controlled rate. Work with this material in Europe suggests that applied by physical vapor deposition on top of a TiN or TiAlN surface, it has applications in hobbing. The material does not remain on the cutting edges of the tool, but flows into the flutes and spaces between the teeth, where it promotes chip flow away from the work.

Where To From Here?

The direction of cutting tool technology seems fairly clear: faster speeds, more exotic materials, and more hand-holding for customers as they learn to use the new technology. But some people suggest that the implications of these new developments are even more far reaching. Ian Shearing speculates that the faster speeds and feeds of dry-cutting-capable machines, which have dropped price-per-piece costs, may have effectively put the brakes on the development of chipless methods of gear production. He goes on to add, "The speeds in machines are now approaching direct motor speeds. If the trend continues, the days of kinematic drives may be numbered." ○

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Cylkro® Gears: An Alternative in Mechanical Power Transmission

H. F. Grendel

An alternative to bevel gears uses a cylindrical pinion and a face gear for power transmission in a variety of applications.

Introduction

Bevel gears have been the standard for several decades in situations where power transmission has to occur between shafts mounted at a given angle. Now a new approach has been developed that challenges the bevel gear's de facto monopoly in such applications. The concept is based on the principle of the crown gear; i.e., a cylindrical pinion mates with a face gear. Crown Gear B.V. in Enschede, Holland, is the developer of these specialty gear teeth, which are marketed under the trade name Cylkro®.

Features of the Cylkro Gear

The Cylkro transmission is an angular gear pair consisting of a cylindrical pinion with an involute tooth profile mating with a Cylkro gear. The upper gear pair in Fig. 1 is a normal cylindrical gear pair. Shown beneath it are three Cylkro gears using the same pinion with different shaft angles and gear ratios.

The geometry of a Cylkro gear is determined by the following factors: the geometry of the mating pinions, the relative positioning of the pinion axis in relation to the Cylkro gear axis and the pair's gear ratio. The pinion's geometry remains constant along its face width. The geometry of the Cylkro gear can be regarded as a rack; however, the pressure angle varies over the face width (See Fig. 2).

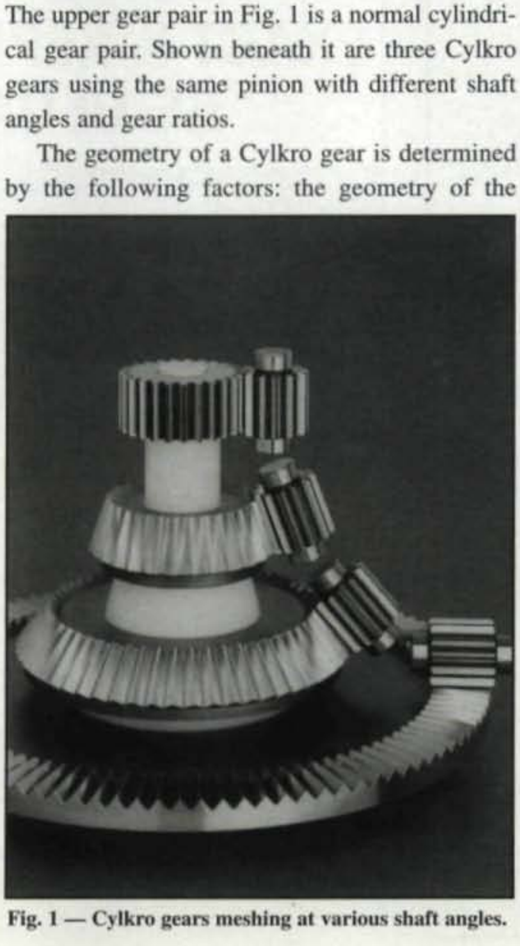

Fig. 1 — Cylkro gears meshing at various shaft angles.

Development

The general principles of face gear geometry and the necessary cutting techniques were readily available in the 1930s, but specific knowledge of the precise geometry and load distribution characteristics of face gears were lacking. These topics were the first to be researched and applied to the development of Cylkro gears. Advanced computer programs were used to develop and optimize the geometry. Many production methods were evaluated, and the generating hob process was chosen as the most efficient.

The next step in the development process was the design of a new generation of HSS and hard metal generating hobs. Initially the milling cutter profiles were pinion-shaped. During subsequent development rounds, the cutter shapes were gradually adapted for the production of Cylkro gears on commercially available CNC hobbing machines.

The power packing optimization abilities (minimal power transmission-volume ratios) of the first production batches were tested extensively. Testing and measurement methodologies and instrumentation were developed along with the production process. DIN 3962 and 3965 standards were applied. The manufactured geometry can now be compared exactly with the theoretical geometry, allowing a quality-controlled manufacturing process of the face gears.

It is now possible to manufacture Cylkro gears suitable for power-intensive transmissions. In this article the most frequently used form of Cylkro gear transmissions, i.e., 90° shaft angles using spur gear teeth, will serve as the basis for all examples, unless otherwise indicated.

Geometry. The geometry of the pinion, its position in relation to the axis of rotation of the Cylkro gear and the transmission ratio determine the geometry of the teeth. Formulas have been applied to calculate the geometry of the teeth in every possible application and for every shaft angle between 0° and 110°, with or without an offset pinion, and with spur or helical pinions.

Contact path lines. A transverse cross section of a Cylkro gear can be treated as a rack and pinion pair. The rack's pressure angle is a variable value along the entire face width of the gear. The variable pressure angle ensures that pinion and gear teeth keep smooth contact path lines between them (see Fig. 3).

Since contact path lines are skewed, the characteristics of Cylkro gear pairs are similar to those of helical cylindrical gear pairs with the same helix angle. This is true for the gear's rotation characteristics, its acoustic performance, its power transmission capabilities and its overlap ratios.

Transmission power packing density. The strength of material calculations for bending strength and pitting resistance meet DIN 3990 and ISO 6336 standards. Cylkro-specific factors in these standards were incorporated, and the newly emerging standards were verified and proven correct by means of finite element analysis methods (FEA/FEM) and with back-to-back life tests (see Fig. 4). All factors commonly used in strength of material calculations, such as the Ka factor, the dynamic Kv factor, etc., were also used with these gears.

These development efforts, especially gear tooth optimization, have resulted in transmission power packing densities equaling or exceeding those of bevel gears, depending on transmission ratios and shaft and helix angles.

Manufacturing. Cylkro gears are manufactured with standard CNC-controlled hobbing machines. This guarantees an efficient and continuous work flow, allowing high precision dimensioning. The production steps are lathing the blank, cutting the teeth in the non-hardened base material, hardening to HRc 61 ± 1, machining the locating faces (datum planes), finish-cutting the teeth flanks with hard metal milling cutters or grinders and honing a fine-finishing profile adjustment if necessary.

The new generation milling cutters developed by Crown Gear can be sharpened without running the risk of changing the cutting geometry. The geometry of the milling cutter is determined by the pinion's gear teeth characteristics, such as its module, number of teeth, helix angle and addendum modification. Cylkro gears can be manufactured with these milling cutters regardless of axis angles, transmission ratios or axis centerline offset.

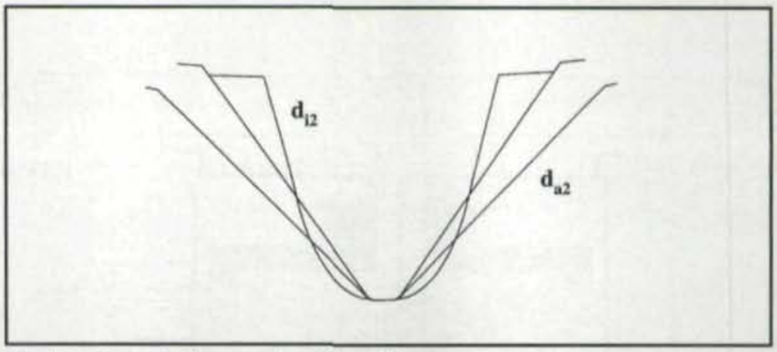

Fig. 2 — The variable geometry of the Cylkro gear.

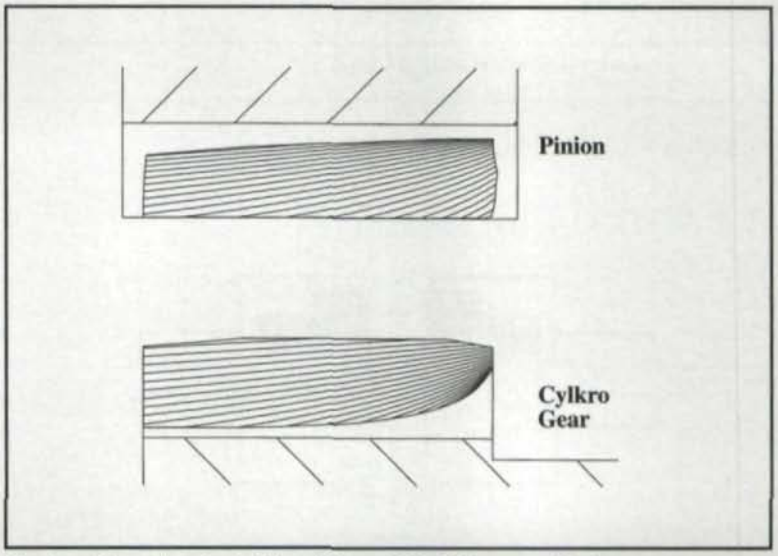

Fig. 3 — Lines of contact at the pinion and the Cylkro gear flank.

Fig. 4 — FEM stresses on a Cylkro tooth.

Cylkro gear verification uses 3-D, CNC measurement banks. The gear's calculated standard profile parameters are stored in the 3-D measurement bank and compared with the actual measured 3-D values. The deviation patterns are obtained in the form of a computer output with micrometer orders of magnitude (μ range). The patterns are directly related to the quality of production.

H. F. Grendel
is sales manager with Crown Gear B.V., Enschede, The Netherlands.

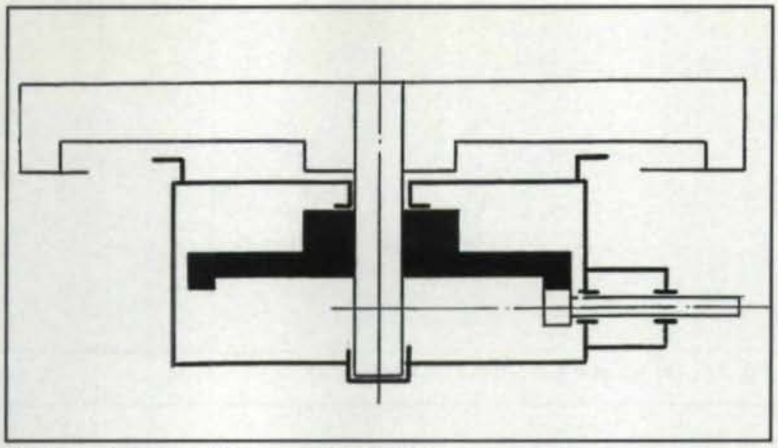

Fig. 5 — Single-stage driven turntable (i = 10).

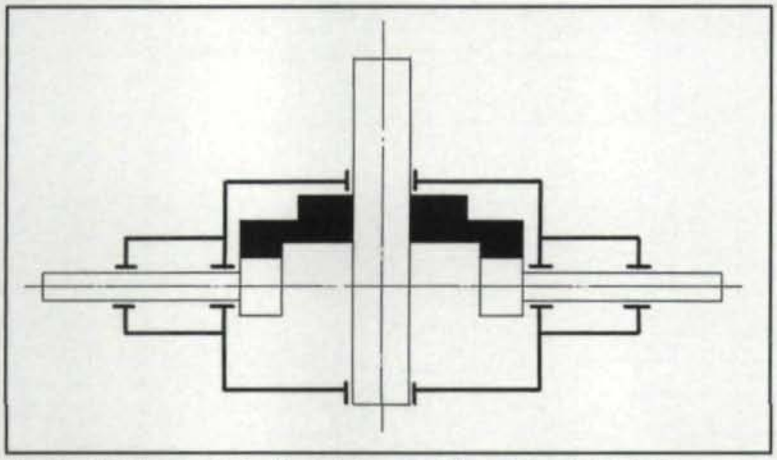

Fig. 6 — Multi-power design for a pinion as an integrated part of a shaft.

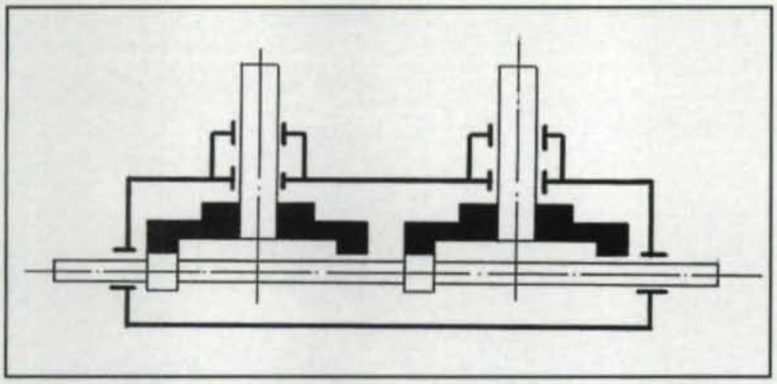

Fig. 7 — Centrally driven shaft with several distribution points.

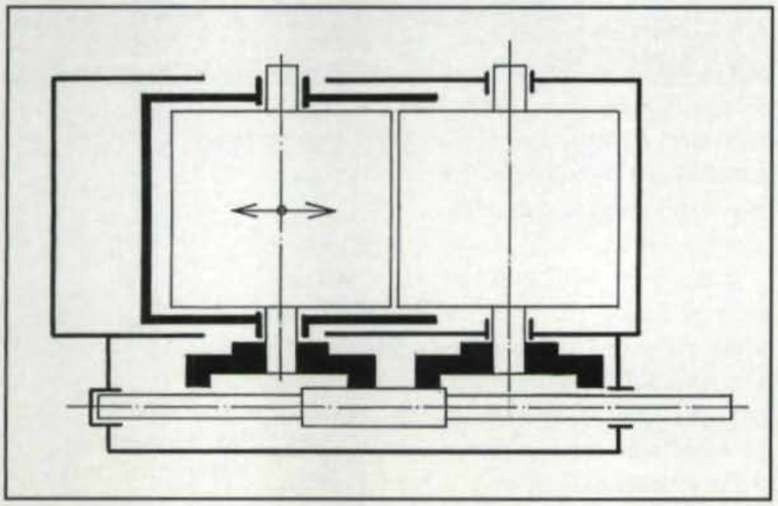

Fig. 8 — Rolling mill drums with adjustable throughput. (Patented by Crown Gear.)

Properties. Cylkro gear systems have the following characteristics:

• The pinion is a normal spur gear whose axial position has no influence on the meshing zone.

• Assembly time is reduced because only the axial position of the face gear needs to be set.

• Lapping is unnecessary because all gears irrespective of their tooth numbers or shaft angles may be interchangeably meshed with the common pinion upon which the particular generating hob geometry is based.

• Axial load on a pinion with straight spur teeth is non-existent.

• Meshing is smooth thanks to the system's oblique contact lines and high contact ratio.

• The systems offer high transmission ratios in one stage.

• Cost-effective manufacture on conventional CNC gear hobbing machines is possible.

• Using straddle-mounted pinions is possible.

• Zero backlash high-accuracy applications may easily be realized.

• High-strength teeth and good contact geometry give high torque capability.

Technical and economic benefits. The unique features of Cylkro gears bring certain economic and technical benefits that would not normally be possible with bevel gears or that would be possible only at great cost.

The absence of the need for any axial adjustment of the pinion shaft during mounting, repair or maintenance is a time saver, especially with high-tech assemblies. The construction of the pinion bearing can be greatly simplified thanks to the absence of axial loads. The use of bilateral pinion bearings is possible when the assembly requires extremely rigid construction. The Cylkro gear construction is characterized by a high degree of efficiency as a result of the sliding effect of generating tooth flanks while in motion.

Other economic benefits lie in the simplicity of the cylindrical pinion, which has obvious manufacturing cost advantages over conical pinions. Furthermore, Cylkro gears can be produced with much more economical tooling and machinery than bevel gears. The same machine tool can be used for coarse and fine machining, eliminating special machinery for finishing passes. The lapping process may be eliminated altogether thanks to the high tolerance finishing pass gears receive in the standard production process.

Applications. The unique properties of the Cylkro gear allow new approaches to design and manufacturing. Cylkro gear sets can be made in a wide range of gear ratios, with axial freedom of the pinion and a free choice of shaft angle.

A wide range of gear ratios. Theoretically the Cylkro transmission is suited for all possible gear ratios (i -> ∞). However, the effective face width of the Cylkro teeth in the area of the inner diameter will be reduced as a result of root undercutting when using small gear ratios (i -> 1.5) for a shaft angle of 90°. In these instances, the mechanical power transmission capability of Cylkro gears is smaller than in bevel gears of comparable size. Cylkro gears may definitely be used as power transmission gears when gear ratios equal or exceed i = 1.5.

No technical limitations exist regarding the production process for large gear ratios. A gear ratio of i = 12, for instance, would normally be designed in several stages, reducing the physical weight and, consequently, the material cost of the gear train. For some designs, however, it is advisable to design a single, large stage transmission.

The largest gear ratio achievable with bevel gears (i = 6 ~ 8) is determined by the production process itself. Cylkro gears, however, can handle large gear ratios in one single stage without any difficulties.

A typical application can be found in environments requiring a high degree of constant angular velocity. For example, Fig. 5 shows an application where a gear ratio of i = 10 is combined with tight angular velocity precision for the turning table. It is obvious that the total cumulative pitch error of this Cylkro gear is averaged over the largest possible gear diameter. With a diameter half the size or with a double-staged gear, the error deviation would approximately be twice as large. The Cylkro gear design combines both large gear ratios and precision constant angular velocity. Cylkro gear dimensions play a secondary role. Different gear ratios can be achieved simply by changing the number of teeth on the Cylkro gear. For some applications one gearbox can be used for several gear ratios with the same housing, bearings, pinion(s), etc.

Axial freedom of the pinion. Cylindrical gears may be offset freely in both axial and radial directions within reasonable limits without negative impact on the lines of action of the teeth. This degree of freedom in either direction does not exist in bevel gears. Bevel gears individually require precise installation and tuning to achieve a good bearing contact and the right backlash tolerance.

The Cylkro transmission combines both types of gears. It requires adjustment only in the axial direction to obtain a good bearing contact (the pinion teeth's base tangent lengths do not affect this). Axial pinion motion is perfectly possible.

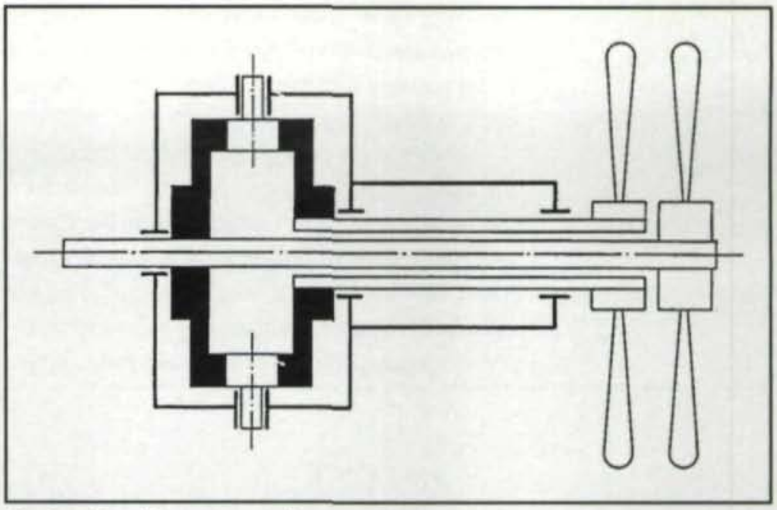

Fig. 9 — Coaxial counter-rotating propellers.

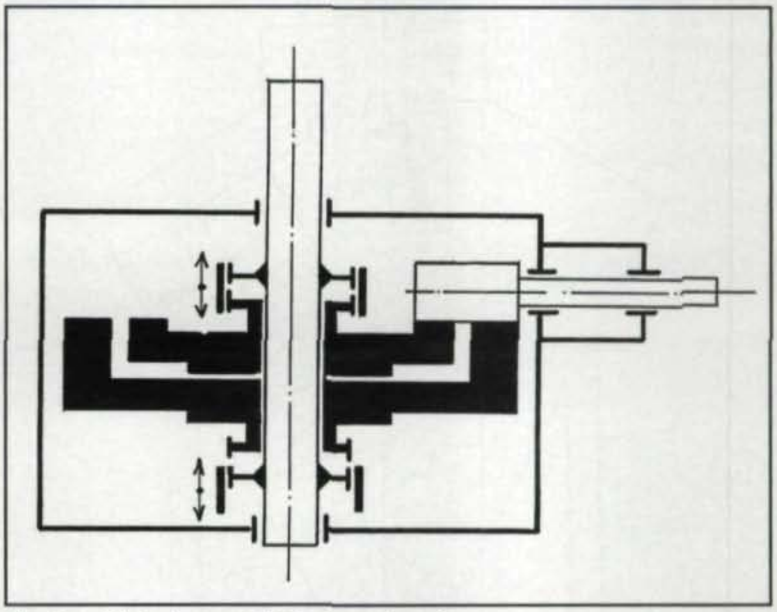

Fig. 10 — Ninety degrees (90°) dual-speed gearbox.

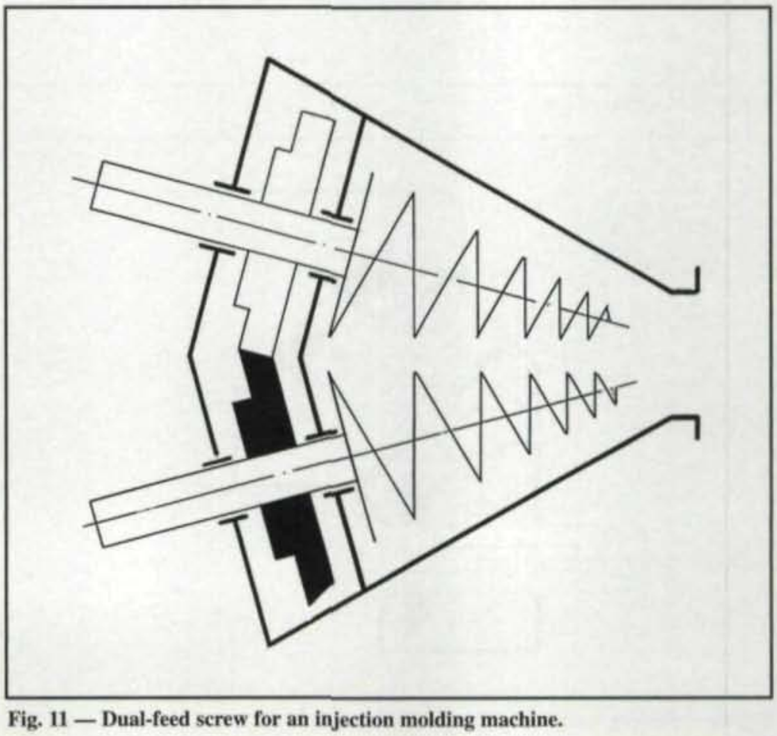

Fig. 11 — Dual-feed screw for an injection molding machine.

Adjustments are greatly simplified; moreover, the engagement of several pinions on one Cylkro gear or one pinion with two Cylkro gears simultaneously is made easy.

Another good example of the axial freedom is the pinion as an integrated part of a motor shaft. The motor shaft mates directly with the Cylkro gear; there is no requirement for any axial adjustment. The motor's own axial movement does not influence the bearing contact. Fig. 6 shows a multipower design, which is used in situations where one Cylkro shaft drives several rapidly turning pinion shafts or in situations where more than one motor drives one Cylkro shaft.

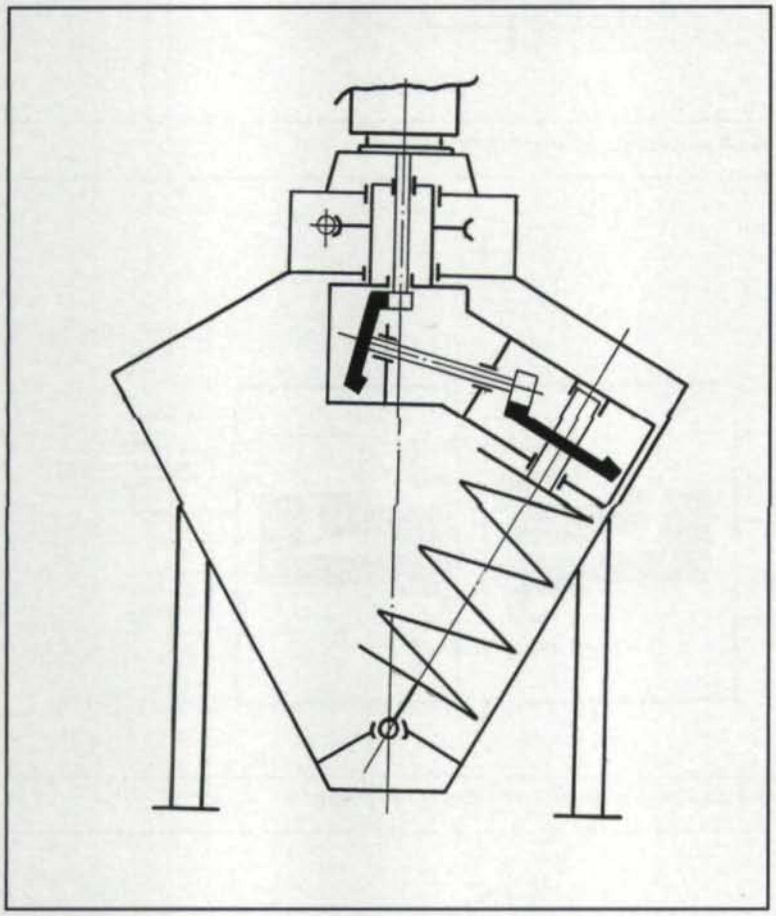

Fig. 12 — Conical mixer.

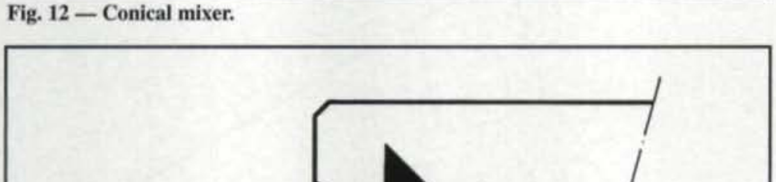

Fig. 13 — Milling machine heads.

Fig. 7 shows a common driving shaft onto which a set of pinions is mounted, each driving a Cylkro gear. This construction is commonplace in farming machinery. Axial dilations of the pinion shaft because of temperature changes, for example, have no influence on the lines of action of the teeth, nor on the rotational symmetry of the outgoing shafts.

The rolling mill drum design shown in Fig. 8 is an even better demonstration of the axial freedom of the pinion. Thanks to the possibility of the axial displacement freedom offered by the Cylkro gear design, the rolling mill drum's centerlines can be adjusted to accommodate milling material plate thicknesses. It is also possible to mount mill drums with other diameters. This does not affect the bearing contact or any relative motion of one drum against the other. When necessary, both drums may have different diameters. Of course, this would result in a similar requirement for different diameters of the respective Cylkro gears.

Fig. 9 shows a construction for distributing mechanical power to two counter-rotating propeller blades, where the propellers are mounted on coaxial shafts. Counter-rotating propellers are used in shipbuilding to get higher propulsion yields. Half of the available mechanical power is transmitted directly on the inner shaft, and the other half is transmitted to the outer shaft through a planetary setup of pinions mating with the second Cylkro gear. The design allows different rotating speeds on each shaft if required.

Fig. 10 shows a dual-speed perpendicular gearbox. Two Cylkro gears, each with different numbers of teeth, driven by a common pinion are coupled to a shaft through a clutch mechanism. The clutch ensures that the outgoing shaft stays connected to one Cylkro gear at a time.

Another application that takes advantage of the axial freedom of the pinion is the assembly that drives the pressure cylinder in a printing press. The position of the circumference of the printing press cylinder relative to the feed cylinder must be adjusted very precisely. A helical pinion with an adjustable (tunable) axial position on the driving shaft causes a proportional rotational offset of the Cylkro gear for a given axial pinion shift.

Shaft angle's freedom of choice. The freedom to select almost any shaft angle, as well as all other features and benefits of the Cylkro gear, is crucial to making optimal use of this design. The angular Cylkro gearbox does not affect the bearing contact in any way.

A typical application in gearboxes with small shaft angles is used for driving a ship propeller. Normally the motor is mounted horizontally, while the propeller shaft is mounted at an angle of 7° to 20°.

Fig. 11 shows a drive mechanism for dual-feed screws working under an angle of 15° to 20°, as commonly found in extrusion and injection machines for the plastics transformation industry. The dual-stage drive mechanism shown in Fig. 12 is part of a conical mixer with a still-standing reservoir. The drive mechanism could be executed in a different way. It could, for instance, be mounted on the bottom side of the reservoir.

The drive mechanism for the tool flange of the milling machine in Fig. 13 has a connecting shaft equipped with a pinion and a Cylkro gear. The milling machine's head can rotate freely around its drive shaft. The Cylkro gear on one end of the connecting shaft can be freely adjusted along its axial position; therefore, the pinion on the other end of the shaft will interfere with the tooth's contact path.

Currently several kinds of Cylkro gears are being tested in helicopter gear assemblies. A simple demonstration of the ease of adjustments for each Cylkro set is shown in Figs. 14 and 15, where the use of power distribution is shown. Note that the shaft angles differ from the classical 90°. Fig. 14 demonstrates power distribution in the first stage, and Fig. 15 does so in the second stage.

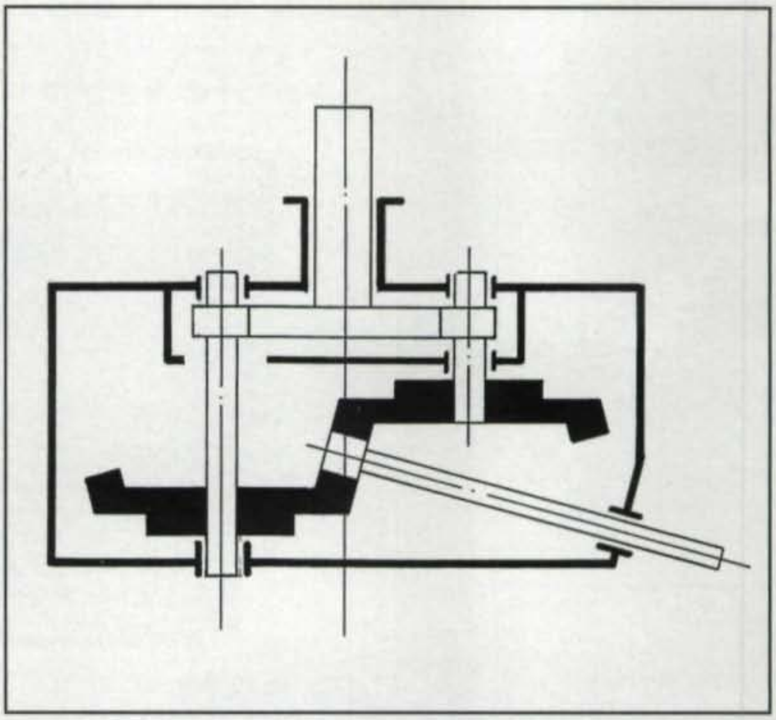

Fig. 14 — Helicopter gear assemblies. (Patented by Lucas Western, Inc.)

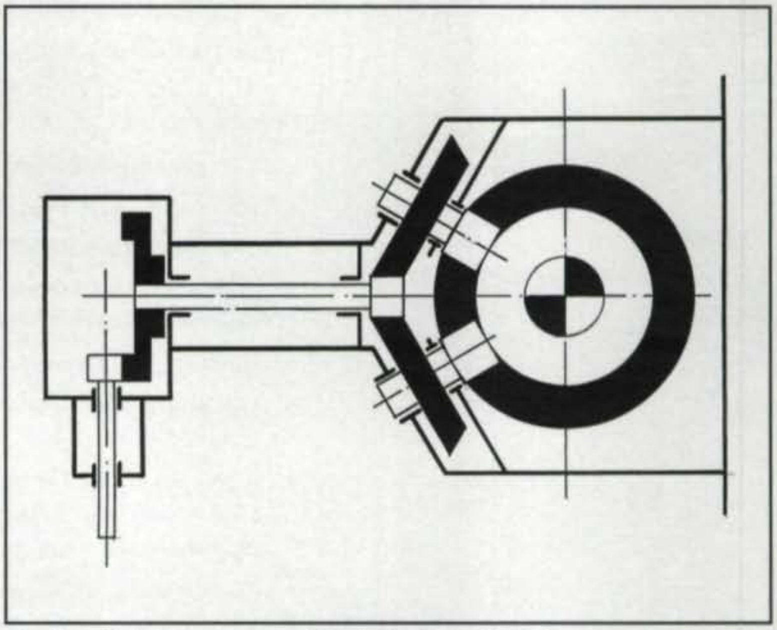

Fig. 15 — Helicopter gear assemblies. (Patented by Daf SP.)

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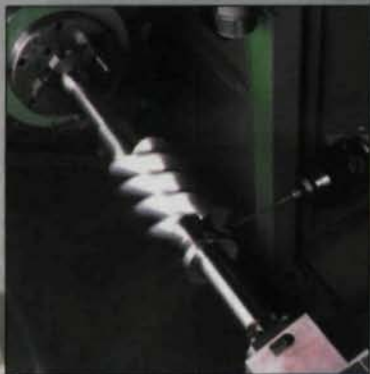

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RACING CIRCUITS

In Formula One racing, where reliability is everything, McLaren International counts on wire EDM to cut its gears.

William R. Stott

ZERO TO 125 MPH IN FIVE SECONDS. MAXIMUM SPEED OF 211 MPH. SEVEN-SECOND PIT STOPS.

Formula One racing is a high-adrenalin sport—one which demands peak performance from drivers and machines alike.

In their quest for speed, safety and performance, the racing teams are constantly pushing the boundaries of technology by testing new materials and manufacturing processes. McLaren International, one of the premier teams in the sport, has introduced a nontraditional gear manufacturing technique—wire erosion EDM—as a way to bring gear manufacturing in-house at a reasonable cost.

The transmission gears in a Formula One race car must be reliable. A single gear failure can mean the difference between the checkered flag and dropping out of the race. It is not uncommon for several cars in a 22-car field to drop out of a race because of gearbox failure. Because of this, each gearset is used only once for a race. Afterwards, the race team inspects the gears for damage and records the mileage. Then the gearsets are used for practice, qualifying and testing.

McLaren's cars use a semiautomatic six-speed (plus reverse) transmission, which means there are six change gear pairs in the gearbox. Before a race's practice session, the team chooses ratios based on previous experience at a circuit. Then, depending on weather and track conditions, they may have to adjust the ratios. Finally, on race day, they may have to make additional changes because of something as simple as the direction of the wind. If necessary, all six ratios can be changed in just 45 minutes.

Examples of change gears cut by wire EDM.

Overall, the team brings about 60 gear sets for each car at each race. With 3 race cars, 2 test cars, 16 races per year, and qualifying and practice sessions before each race, McLaren goes through as many as 1,000 change gears per year.

Traditionally, Formula One teams have used a handful of outside gear shops to design and manufacture their change gears, creating security problems. Because they already had a huge manufacturing facility in Woking, England, McLaren decided to bring the gear production in-house so they would have faster turnaround time, increased security and greater control over the design and manufacture. In addition, they could save money by not having to go through a subcontractor. But rather than purchase a dedicated hobbing machine, they looked to EDM as a more flexible, less costly alternative.

Wire erosion EDM uses a very thin wire to produce a high voltage charge that vaporizes material on the workpiece. By controlling the path of the wire, the machine can create a very complex form. Unlike a hobbing machine, the wire EDM machine requires no change in cutting tools for a change in gear design. You have only to change the program to generate a new part. There is no waiting for hobs to be designed, ordered or made—a process that could take as long as 12–14 weeks for a new design, says McLaren transmission designer Piet van Zyl.

McLaren estimates that their wire EDM machine will pay for itself within 3–4 years. Also, the capital outlay for the EDM machine was far less than would have been necessary for a dedicated hobbing machine and all the tooling required for the various pitches and tooth numbers. In addition, the machine is used to make parts other than gears, including titanium seat belt brackets, splines on differential drive gears, front and rear anti-roll bar arms and clamp brackets for electrical items.

But before McLaren could implement wire EDM gear manufacturing, they had to test it to make sure it could produce gears durable enough to withstand as many as 3,000 gearshifts in a single race. "In my view the most important aspect of the gearbox in a Formula One car currently is reliability," says van Zyl.

Toward the end of 1993, McLaren began testing wire-eroded gears made by a subcontractor. They tested these gears for several race distances without problem.

After deciding that the wire erosion process could produce gears of acceptable quality, McLaren evaluated equipment from several manufacturers and chose the Charmilles Robofill 4020 submerged wire erosion machine, which proved capable of cutting DIN 4 quality gears (roughly equivalent to AGMA 14) when the gears were single-stacked. Charmilles became an official supplier in the middle of 1994.

For production, gears are stacked on the machine two high with four stacks on a tooling plate. Gear quality is approximately DIN 6 (AGMA 12) under these conditions. Even though each batch of gears takes 18-24 hours to complete, bringing the gear cutting stage in-house has actually given McLaren faster turnaround than sending them out to be hobbed.

The real advantage to wire EDM comes when design changes are required in the middle of the racing season, says van Zyl. "Toward the end of the [1995] season we were requiring a new ratio to optimize engine performance in sixth gear. I designed a new ratio, which would have required new tooling if manufactured by a subcontractor, with the associated delay in getting hold of the tooling, but we had the new ratios ready in about three weeks time. If really stretched, we could probably do it in less than two weeks, bearing in mind the number of operations involved."

While EDM has proven successful for McLaren, the company has had to overcome some small hurdles. For example, one of the initial problems was developing the software required to convert gear designs into CNC programming.

McLaren uses Computervision CADD5 software to construct parametric models of parts, including gears. In addition, they have created a program using TK-Solver software to calculate points on standard or modified gear tooth profiles. Once a new gear is designed, the program can be downloaded to the machine. "Although

there was a fair amount of work involved in creating the initial TK-Solver model and the parametric CAD model, it is now quick to produce data for a new design," van Zyl says.

Another obstacle was dealing with a new machine and cutting process. "Since wire erosion was new to us, most of our initial problems stemmed from a lack of experience operating wire erosion machines," says van Zyl. For example, Charmilles had to develop tooling to hold the gears in place for cutting. Unlike hobbing machines, wire erosion machines don't allow you to mount the gears on an arbor. Instead, they have to be supported from the outside. This is achieved by having bigger blanks and supporting them in a tooling plate with holes cut into it to support the blanks, van Zyl says. The blanks have three starting holes drilled in them from where the gear tooth profile can be cut, leaving tags on three of the teeth to support the gear.

The 1994 and 1995 racing seasons have demonstrated that wire erosion EDM is a reliable gear manufacturing process. Driver Mika Hakkinen drove one of the first McLaren-made, wire-eroded gear pairs in the 1994 Japanese Grand Prix. In the 1994 Australian Grand Prix, both Hakkinen and teammate Martin Brundle had second gears produced in-house by wire erosion. McLaren went through 16 races without a single gear failure in 1995. "We had good reliability before wire eroding them, and now we are improving further on that with our own design and manufacture," van Zyl says.

Overall, the company produced 726 change gears with their machine. "At the end of the 1995 season, McLaren can now conclude that wire erosion has been successful in meeting the required manufacturing schedule for a season's change gears," says van Zyl. ○

Precision machines, both on and off the track, contribute to Formula One success. Above, the Marlboro-McLaren car with drivers. Below, the Charmilles wire EDM machine used to make transmission gears.

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William R. Stott
is Gear Technology*'s associate editor.*

Generating Precision Spur Gears By Wire EDM

Roderick Kleiss, Jack Kleiss and Scott Hoffmann

Master gear accuracy is possible with this technique

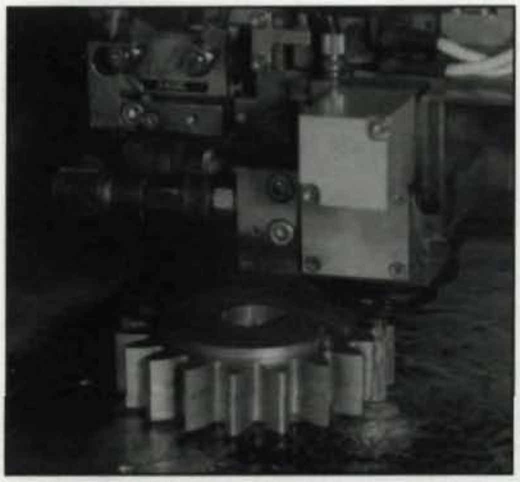

Fig. 1 — Wire EDM gear cutting setup.

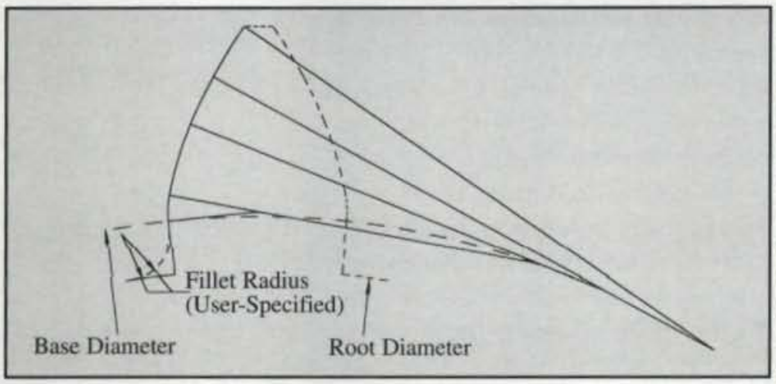

Fig. 2 — Typical EDM gear involute.

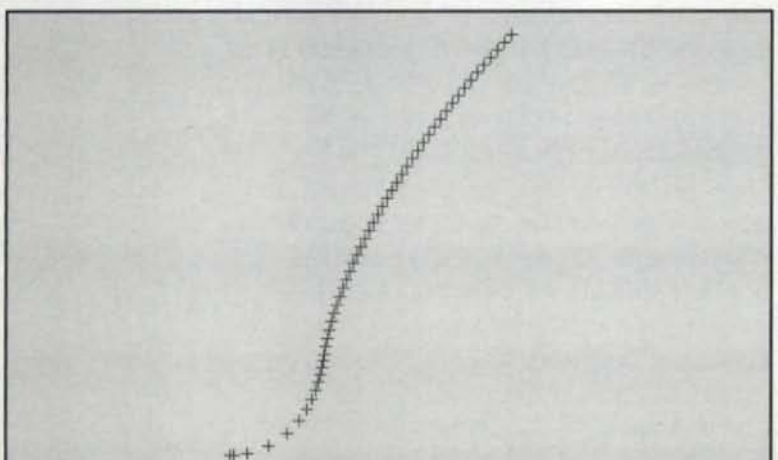

Fig. 3 — Gear surface coordinates.

Introduction

Over the past decade, the wire electrical discharge machine (EDM) has become an increasingly important tool for machining non-standard shapes. It has even been used to cut gears and gear cavities for plastic molds. While generally accepted as a quick and versatile method for cutting spur gears, the EDM gear has lacked the precision of a mechanically machined or ground gear. We suspected that many of the errors associated with these gears were caused by inexact setup procedures, poor tool path control and improper cutting parameters. We decided to test the potential for the wire EDM to make the most accurate gear possible.

Our experiment was, moreover, based on need. The plastic gears we designed for a gear-driven lawn sprinkler required unique master gears. Lead times for form-ground gears were unacceptable. With our customer's support, we developed a method of cutting these master gears that achieved the desired shapes on time and within cost constraints for fine-pitch master gears. We then employed the same techniques to cut a 19-tooth, 5 DP master gear in order to determine possible errors of scale. Profile inspection revealed that similar accuracy of tolerance was possible for large, coarse-pitch gears. In this article, we will present the methods we employed to achieve this level of accuracy, the inspection data from our work, comparisons with precision hob-cut gears and possible applications of this method to other forms of gear generation.

The EDM Process

Electrical discharge machining is based on the principal of erosion of an electrically conductive material by continuous spark discharge to its surface (Ref 1). With wire EDM, a metallic wire is continuously fed through arms suspended above and below the workpiece (Fig. 1). This charged wire is then guided through the specified tool path while cutting its way through the material.

The process is relatively slow, depending on wire diameter, workpiece thickness and machine settings. The servo-controlled tool path is quite accurate, typical for CNC machinery. The benign environment of the EDM machinery, with slow feed rates, extremely low forces, very little friction or vibration and controlled temperature, make an even finer accuracy possible.

The tool path can be drawn either point-to-point or in simple arcs. Advanced mathematical curves are not directly programmable by software; these must be approximated with arcs and/or line movements. Both the involute and trochoidal sections of a gear fall into this general category. Specified dimensional accuracy and repeatability of the more advance wire EDMs are on the order of .0001". Surface finishes are 16 microinches and can be attained through careful selection of machining parameters, along with multiple finishing skim cuts on low power settings.

Gear Cutting with Wire

Wire EDM machining is primarily a two-dimensional process, although the two wire guides can follow independent paths, allowing slight 3-D modifications. EDM software exists that claims to create a wire path for the spur involute. The software requires standard gear geometry to be input along with tooth thickness, root and outside diameters. Approximate arc segments are then fitted to the involute curve down to the root or to the base circle diameter, whichever comes first. If the base circle is located above the root circle, a straight radial line is connected from the base circle to the root diameter, and the user has the option of specifying a fillet radius for the intersection of those two features (Fig. 2).

Difficulties with this method of generation are immediately apparent: The trochoidal (or root) area is left arbitrary and undefined, and no provision is made for undercut even if it is required. One of the advantages of a hob-cut gear is that any gear will fit within the envelope created by the generating hob because the hob removes any possible interfering material in the root area that may physically interfere with another gear. A majority of non-undercut, standard gears are not sensitive to this possible trochoidal interference, since the standard whole depth provides sufficient clearance, and mating teeth never reach below the base circle. However, as designers modify gear geometry to maximize function or to allow for undercut, this area becomes critical because of possible interference or weakening by excessive relief. The mathematical generation of gear teeth must provide not only conjugate action, but also designed clearance with any mating gear.

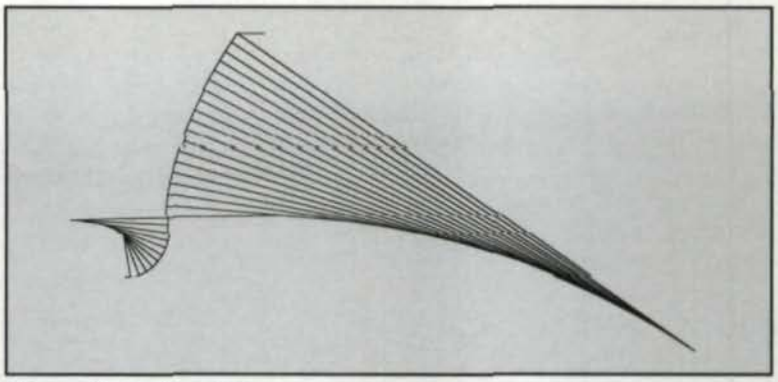

Fig. 4 — Optimal curve fit.

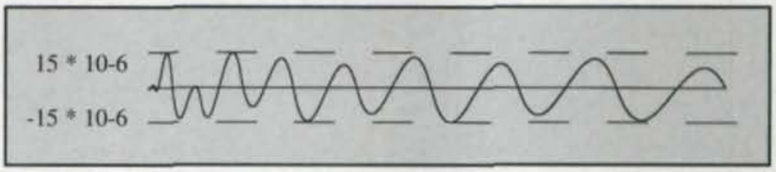

Fig. 5 — Deviation between splined arcs and involute.

Another not-so-apparent difficulty with the generation of approximate arcs to the involute concerns the nature of the involute itself. With its ever-increasing radius of curvature from the base circle, the involute is anything but a trivial curve-fitting exercise. The desirability of making intersecting arcs tangent at their endpoints compounds the problem of fitting these arcs to the involute. Without careful fitting, it is possible to have considerable error in the approximation, especially in the critical region of the base circle. The trochoidal surface can also be intricate and requires equivalent attention to detail in any generating curve-fitting scheme.

Mathematical Generation

Many texts describe the mathematical generation of the involute. Buckingham (Ref.2) described both polar and Cartesian equations for the involute profile. Point-to-point development of the generated trochoidal region is less well-documented. However, Khiralle (Ref. 3) and Colbourne (Ref. 4) have both published methods to find points on the trochoidal curve for any involute rack. They also describe the necessary iterative schemes to determine the exact involute form diameter for undercut gears. Solving these equations yields an array of discrete coordinate points that exactly describe the entire surface of the gear tooth (Fig. 3).

Curve Fitting

The wire EDM tool path is constrained to follow either straight lines or simple single-arc segments. The involute and trochoid, however, are curves with continuously changing radii of curvature. The designer might create a tool path with infinitesimally small linear moves to maximize the EDM's resolution, but the resulting NC program would be excessively cumbersome. A more

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Scott Hoffmann
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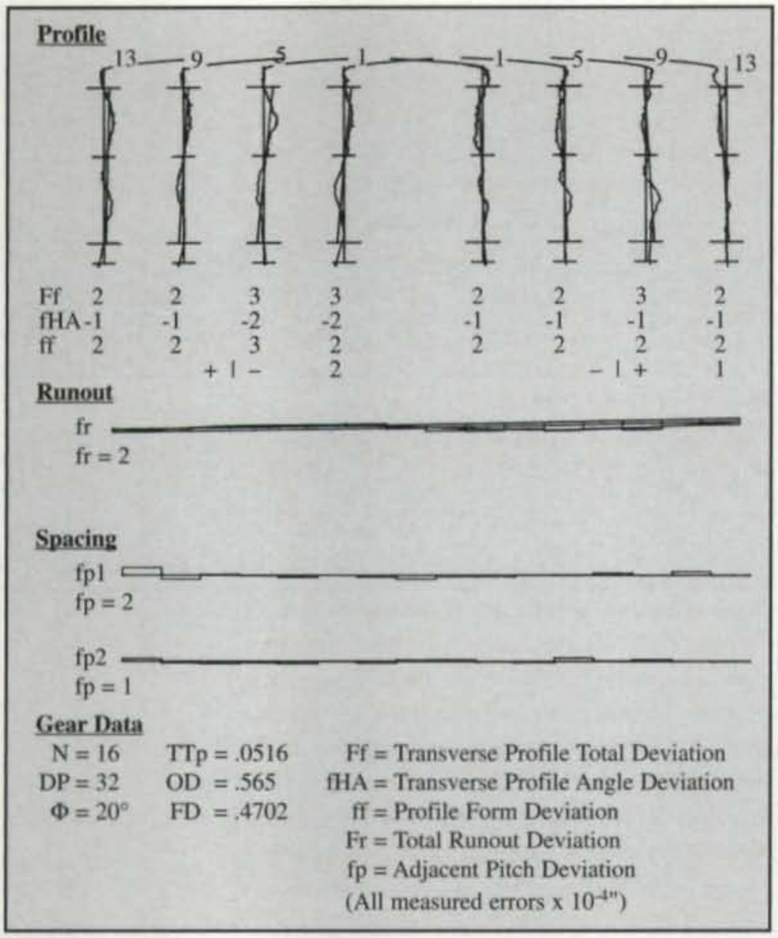

Fig. 6 — 32 DP hob-cut gear data.

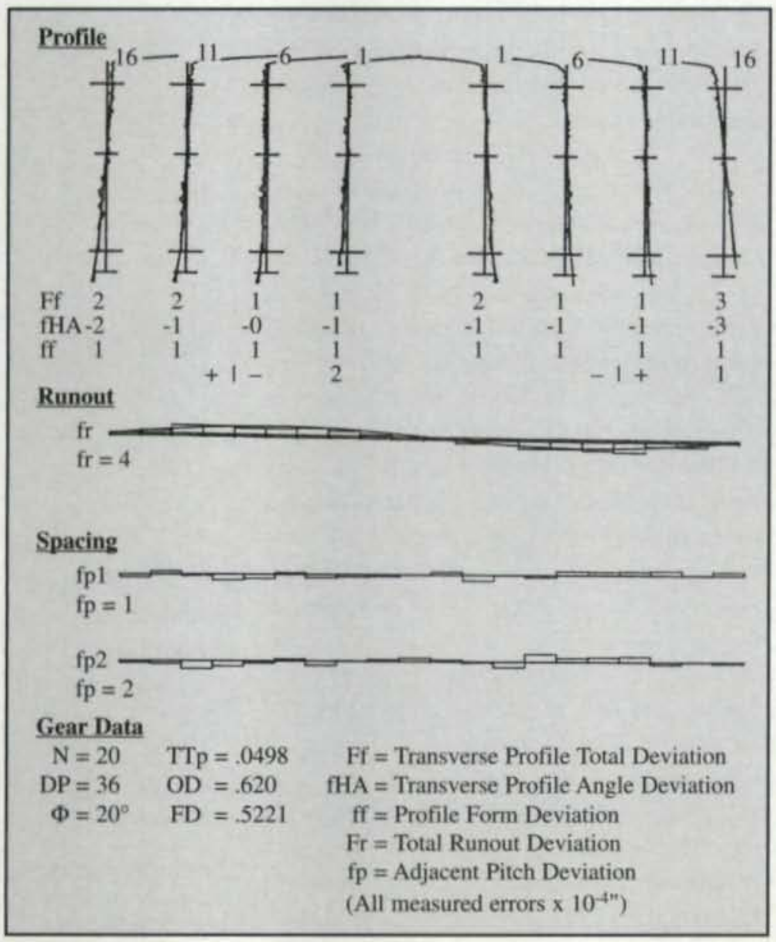

Fig. 7 — 36 DP wire EDM gear data.

efficient approach would be to allow the machine's own software to optimize the cutting path. A mathematically satisfying curve-fitting routine would link approximated arcs with common tangents to the profiles (Fig. 4). The machine tool would then follow the nearest *x-y* path to this profile.

At first glance, it would appear a simple task to approximate the involute and trochoidal curves with splined arcs in the minimum least-squared sense; however, since any arc segment is mathematically nonlinear and multivalued, and because the function that represents a splined series of arc segments includes nonlinear parameters, this is not the case. The curve-fitting task is difficult, but not insurmountable. Numerous general purpose optimization algorithms can be adapted to solve this kind of problem (Ref. 5). The use of these methods to solve curve-fitting problems is not an exact science and has sometimes been called an art. With careful selection and tuning of methods, we have been able to generate splined arc approximations of the involute and trochoid with arbitrarily specified maximum error criteria (Fig. 5).

Initial Setup

Four external gears were made. The diametral pitches were 32, 36, 40 and 41. Inspection equipment included a Mahr Model 896 gear roll tester and a Zeiss ZMC 550 gear coordinate measurement machine for profile, lead and spacing checks. The 36, 40 and 41 DP gears were cut by EDM, and the 32 DP gear was cut with a 1" diameter Grade AA precision hob in order to get a sense of the relative accuracy possible with each method. Two of each gear were made so they could be roll-tested against themselves to examine close-meshed conjugacy. They were then inspected independently on the CMM for absolute accuracy. We felt that roll testing was imperative for wire-cut gears, since the cutting process was purely mathematical in function. Any local aberration in the cutting or fixturing of the gear that might not be detected by the single point of a profilometer would be more easily seen on a double-flank roll tester.

Discussion of Results

Figs. 6, 7, 8 and 9 show the profilometry of the fine-pitch gears as measured on the Zeiss CMM. Total profile deviation (*Ff*) for the EDM gears in Figs. 7, 8 and 9 varied between .0001" and .0003", while the profile form deviation consistently stayed within .0001". The hob-cut gear in Fig. 6 maintained profile deviation between .0002" and .0003", however total form deviation also varied by that amount. The EDM profile traces appear as more nearly straight lines, while the hobbed profile exhibits waviness. The lead error on all gears was .0001" maximum, and the adjacent pitch deviation (*fp*) remained less than .0002" for all gears. In total runout, the hobbed gear held .0002", while the EDM gears varied between .0003" and .0005".

Roll tests of the gears against themselves are presented in Fig. 10. A comparison trace of 32 DP form-ground master gears rolled against each other is included as reference. The scale is identical for all traces at .0003" per large division. These traces were taken when the gears were new without running them in lightly first. Later traces were more uniform. Unfortunately they were not retained. We believe that light running-in of EDM gears is desirable to polish the matte surface and deburr edges.

A Coarse-Pitch Example

The remaining question was whether EDM errors would be magnified by scaling the generation process for coarse-pitch gearing. We decided to wire-cut a 5 DP, 19-tooth gear and concentrate on improving runout and optimizing the curve fit. This gear would be roughly 8 times the size of the previously cut fine-pitch gears. We generated 15 arcs for this involute with a maximum mathematical error of ± 15 microinches. The material was through-hardened 420 stainless steel. A complete profile inspection was done for each flank of this gear. A representative sample of results is given in Fig. 11. Total profile and form deviation stayed within .0001" and .0002", and total runout was held between .0002" and .0003" Spacing and lead were both held to .0002". In effect, we were able to improve the dimensional characteristics of the larger gear by improved cutting methods and closer mathematical approximations. This wire EDM gear was ultimately used to monitor a production run of thread-ground spur gears.

Conclusions

Wire EDM is suitable for producing accurate spur gear shapes. These early fine-pitch gears were adequate for their intended purpose of plastic gear inspection. Both profile and form deviation for these gears were generally improved over their hobbed counterparts. Total runout of these gears was slightly greater than for the cut gears, but further modifications in fixturing and machine setup should improve this feature. At present, this method has not reached the same accuracy as form-ground masters, but gears cut this way cost less and can be cut in a week. For certain applications, that can be the deciding factor. The coarse- pitch gear in this experiment benefitted from the lessons learned on the smaller gears. It suffered no degradation in tolerances despite being 8 times larger.

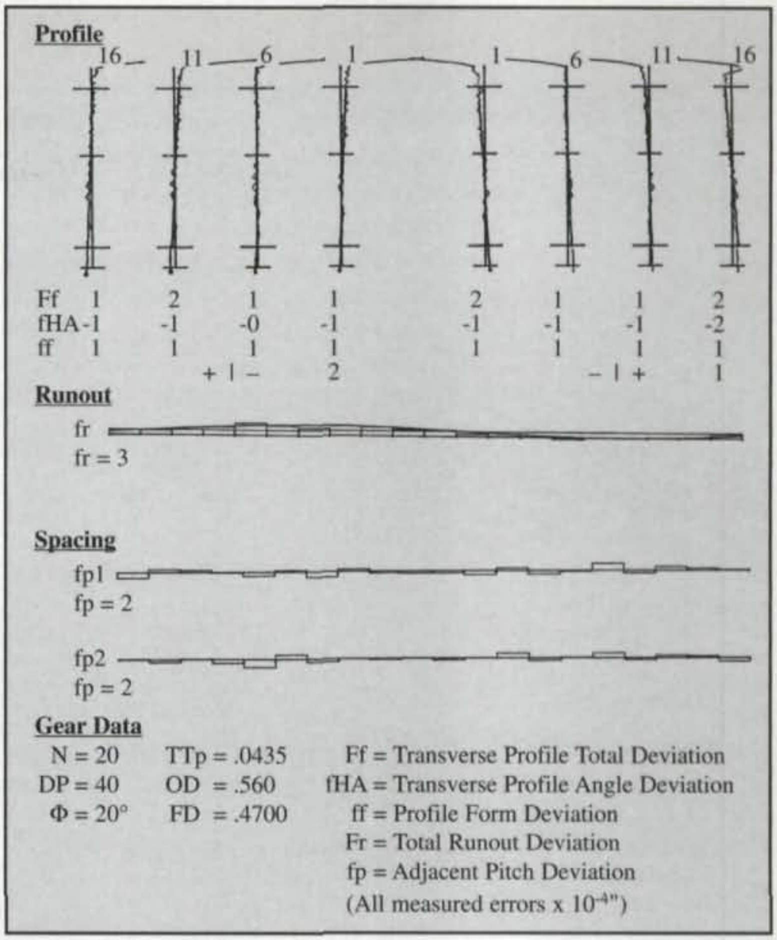

Fig. 8 — 40 DP wire EDM gear data.

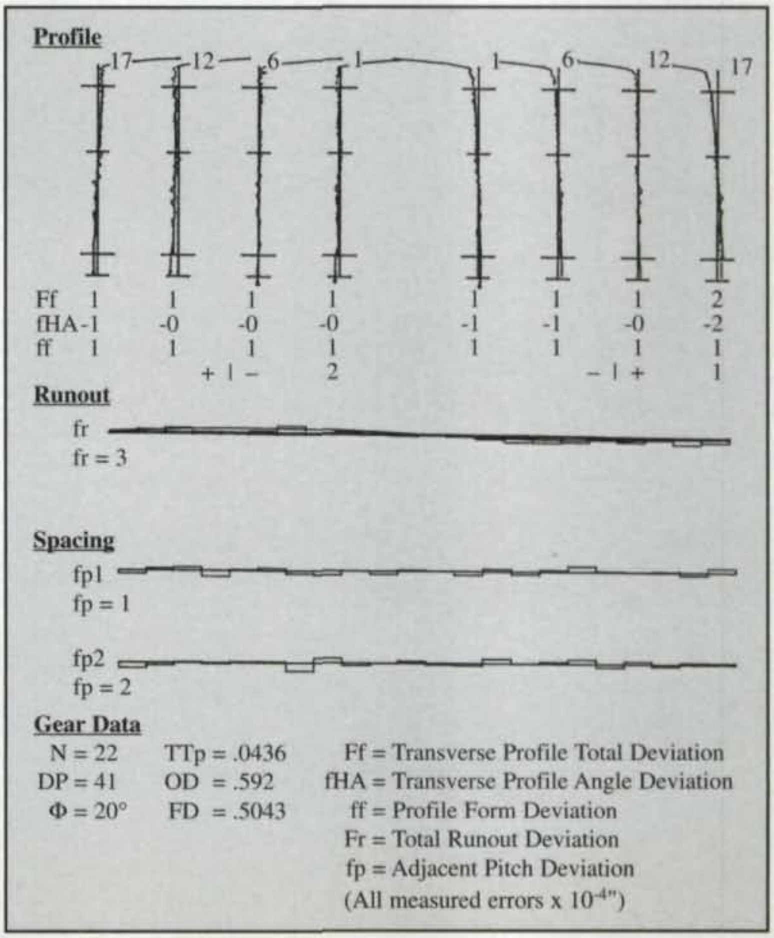

Fig. 9 — 41 DP wire EDM gear data.

This 5 DP gear satisfies the criteria for a Class 2 master gear, with similar cost and production advantages over form-ground gears.

The involute shape is not particularly difficult for the wire EDM. Any mathematical path that can be described in arcs and/or lines can be generated with similar accuracy. Tip relief, root relief and noninvolute tooth forms can be generated with very little added complexity or cost. The ability to cut two separate shapes at the same time with the upper and lower cutting arms opens other possibilities as well. We have already produced bevel gears using Tregold's approximation of the equivalent spur gear form. Low helix angle gears can be accurately cut with only slight overcut on the root area at one end of the gear. Even crowning can be approximated. In many ways, the use of this process is only limited by the user's cleverness.

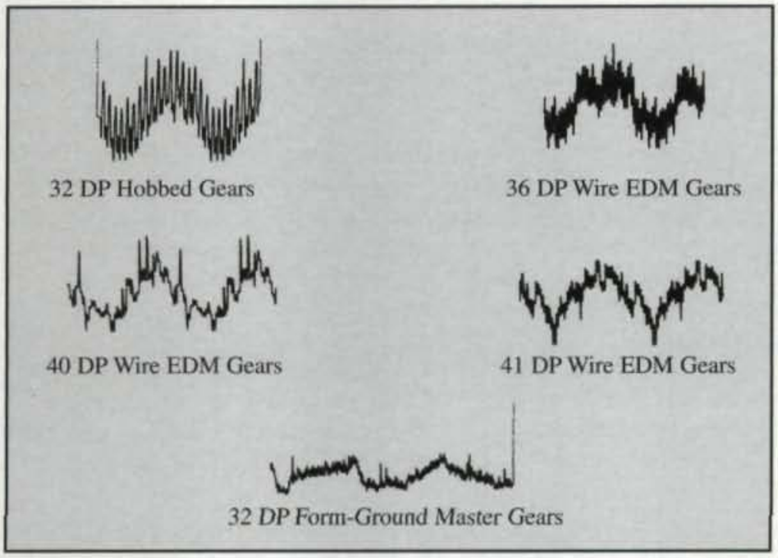

Fig. 10 — Roll tests.

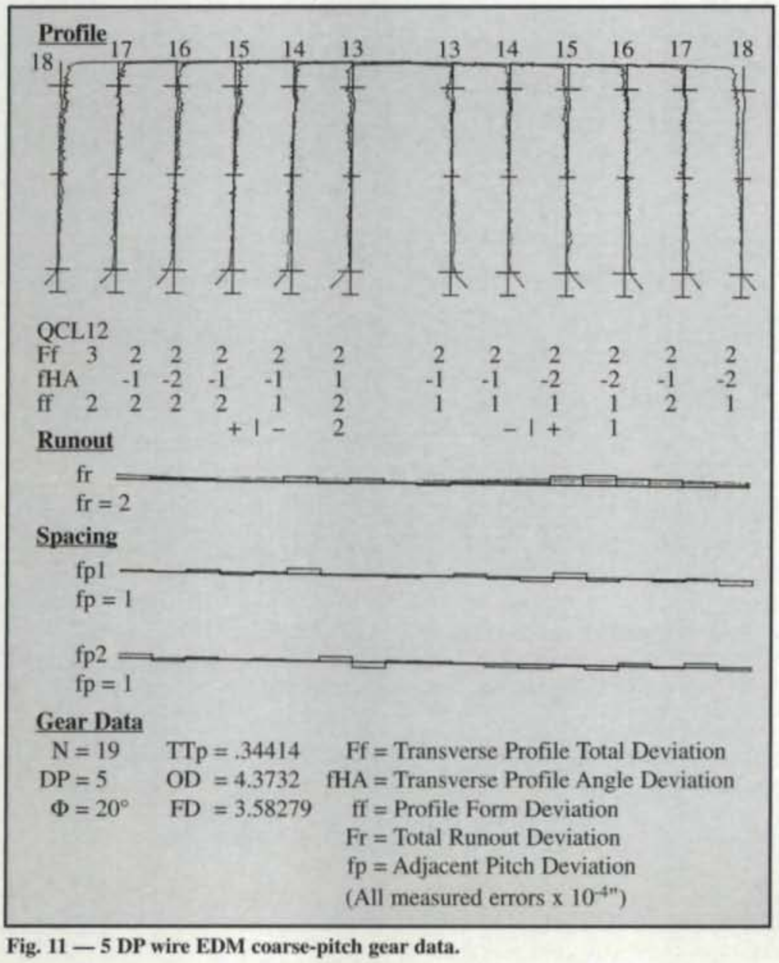

Fig. 11 — 5 DP wire EDM coarse-pitch gear data.

Further investigation needs to be done on the production and effect of the EDM process. Since the generating method is new, current standard inspection criteria may not adequately cover all possible production errors. Simply specifying maximum tooth-to-tooth and total composite error may not be sufficient. It would also be interesting to investigate the effect of EDM metallurgy on life, wear, pitting, etc. For instance, hardening with EDM is achieved with through-hardened steels, but the cutting process under water can produce an additional hard thin surface layer exceeding 70 Rockwell C. Whether this effect can be significant for gears is unknown.

Mathematically describing the total gear shape can be extended to other generation methods as well. The latest CNC equipment can follow the same type of path as the wire EDM. NC dressers can directly form grind spur and helical forms. This type of generation is bound to become more available as the gearing community continues to seek a continually improved and cost-effective product. Computer generation of the necessary forms and numerically controlled inspection of the resultant shapes will ultimately yield an accurate and verifiable product. ○

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3. Khiralla, T. W. *On the Geometry of External Involute Spur Gears*. C/I Learning Publications, 1976.
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Acknowledgement:
Our sincere gratitude to Jim Gamble and the Rainbird Corporation for supporting and encouraging this development effort. We are also grateful to the Kurt Gear Company in Minneapolis, MN, for performing all the profilometry measurements presented herein.

First presented at the 1993 AGMA Fall Technical Meeting as AGMA Paper 93FTM12. Reprinted with permission.

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For more information about Accu-Prompt EDM **circle 224.**

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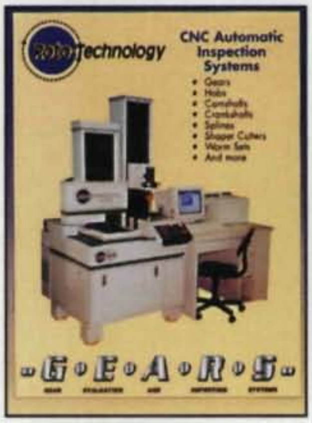

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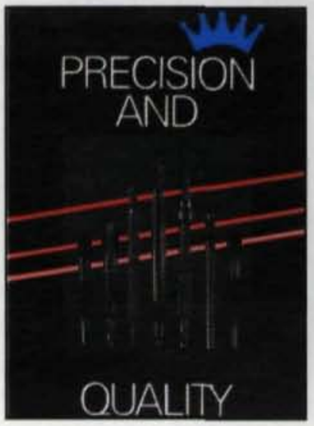

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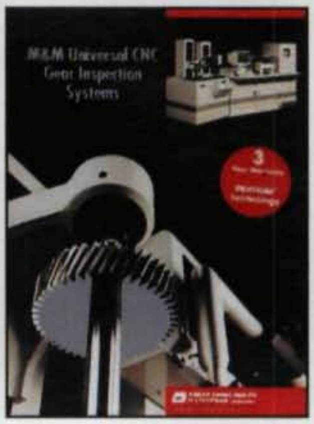

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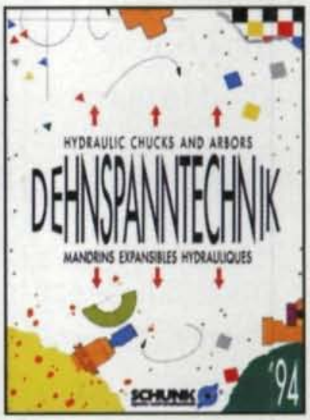

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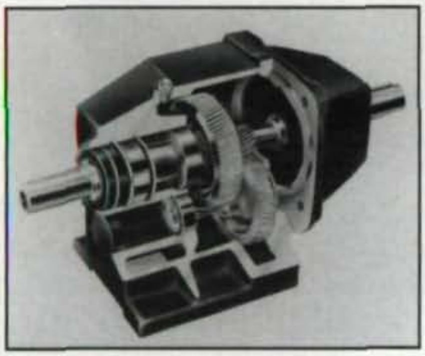
CIRCLE 188

PRODUCT NEWS

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



Severe Shock Speed Reducers

Nord Gear presents a new line of speed reducers developed for heavy duty applications in industries such as mining, paper, wood technology and steel. The Nord **ECLIPSE™** incorporates a simple helical gear design for single through quadruple reductions. The reducers are designed for long-life performance, with oil changes required after 10,000 to 20,000 hours of service.

Circle 226

Heavy Grade Grease

Designed for heavy equipment with components that operate under extreme pressure and temperature, **Dylon GR-F13 Grease**, from **Dylon Technologies Co.**, is environmentally safe. Solid film additives cling to metals to provide a protective barrier for maximum metal-to-metal separation. The grease provides high temperature protection up to 450° Fahrenheit. GR-F13 is available in tubes, 5-gallon drums, 55-gallon drums and custom-sized pails and kegs.

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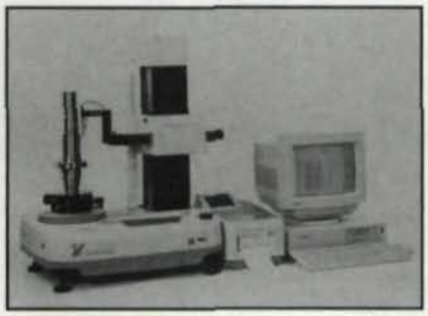


Roundness Measurement System

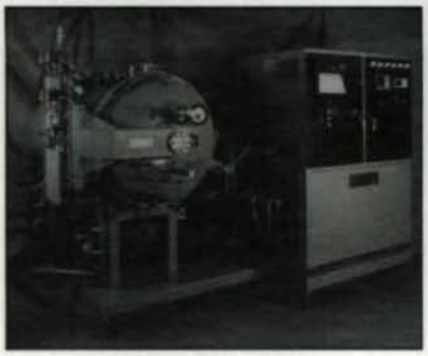
For the precise analysis of roundness and cylindricity profiles, **Carl Zeiss'** Industrial Measuring Technology division presents the **TSK Rondcom 45A**. This Windows®-based system features a static air bearing for long-term rotational accuracy, an RS-232 interface to download measurements to a PC for data analysis, and an assist function that displays X and Y alignment error using an LCD bar graph display. Tolerance zones can be set to display and analyze data simultaneously.

Circle 228

Shaft Loader/Unloader

A new product from **Maxim International** is designed to automatically load and unload long shafts into CNC turning centers. The machine, manufactured by **Pietro Cucchi USA**, comes in two shaft capacity sizes, 8–40 inches or 12–60 inches. Load/unload cycle times range from 12–15 seconds, and changeover times for small sizes are about 15 minutes.

Circle 229



Small Batch Vacuum Furnace

Designed specifically for tool room applications, the **ToolQuencher** vacuum furnace from **Abar Ipsen** features 2, 4 or 6-bar quenching capability. Features a rapid gas quench capability for small batch heat treating of cold work die steels, conventional high speed steels and advanced powder metal tooling materials. The furnace has a 12" x 12" x 24" work zone with a 200 lb. load capacity and a maximum operating temperature of 2,400° Fahrenheit.

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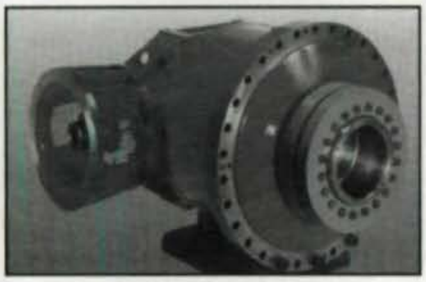

High Power Planetary Drives

Santasalo North America Inc. introduces a new series of planetary gear units designed to deliver 30–50% higher power ratings. The planetary gear series offers 15 sizes with power ratings from 27,000 Nm to 1,000,000 Nm. The new series features wider face widths, four planets, and Kymmenite ADI for the annulus. Applications include agitators, mixers, presses, mills, cranes, windmills and antenna drives.

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NEXT ISSUE: LOOK FOR
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[1]gear (gēr), *n*. 1. a toothed wheel

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

Gear Terms You Didn't Know About

The word *gear*, in various forms, has been in use since around A.D. 1200, according to the *Oxford English Dictionary*. Last issue we brought you Shakespearean gears. Now we'd like to show you some of the uses Americans have given our favorite word (from the *Random House Dictionary of American Slang*).

pack the gear. To have the necessary ability or authority; to meet standards or requirements. Originating in the U.S. Marine Corps. As in, "That new recruit can't handle it. He doesn't pack the gear."

slip (one's) gears. To lose one's sanity. As in, "You must have slipped your gears in order to have become the Addendum Editor."

gear-dropper. An aviation term referring to an airplane copilot.

gear jockey. A driver of trucks or other large motor vehicles. Also **gear jammer**.

There were also a considerable number of gear terms listed with various vulgar, naughty and objectionable meanings. Considering the refined, cultured character of the Addendum Page, we regret to say that we're unable to print them here. (We're above that sort of thing). Besides, we already told you where to look them up.

Obscure Gear Biographies — Part III

With baseball season underway, we thought it appropriate to introduce the Addendum Page's baseball hall of fame, which consists of just one player: **Dale Dudley Gear**.

Gear was a 5'11" right-hander from Lone Elm, KS, who played three seasons in the big leagues, with the National League Cleveland Spiders (1896–7) and the American League Washington Nationals (1901).

Gear played both outfield and pitcher in a total of 69 games over the three seasons. His lifetime batting average was .239. He never hit a home run, but managed to come up with 25 RBIs. As a pitcher, his best season was 1901 with the Washington Nationals, when he was 4–11 with a 4.03 ERA. Guess he just didn't *pack the gear.*

While he will never make it into the real hall of fame, we are proud to add **Dale Dudley Gear** to our list of semi-famous gears.

"Bad News – our consultant says living outside our means is no longer tax-deductible."

Who's Got The Biggest Gears?

The *Guinness Book of World Records* (1995 edition) has many listings for the world's largest and smallest items, but (alas!) there are no gears. For example, the world's largest nuts (outside of the Addendum office, of course) are the so-called "Pilgrim nuts" manufactured by Pilgrim Moorside Ltd. of Oldham, Great Britain. They weigh 5 tons each and have an outside diameter of 52".

We already have a candidate for the world's smallest gear. Recently, the researchers at Sandia National Laboratories in Albuquerque, NM, announced that they had created a gear that's 50 microns in diameter. It's part of a silicon micromotor that is only a square millimeter in size. Engineers hope to use this tiny motor to power micromedical pumps or high-performance gyroscopes for automotive or military use.

We're looking for the world's *largest* gears. If you have them, or if you know where they are, please contact the Addendum office at once. The reader who contributes the biggest gear story will have his or her name in a future edition of Addendum. Verifiable gear stories only will be considered.

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


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