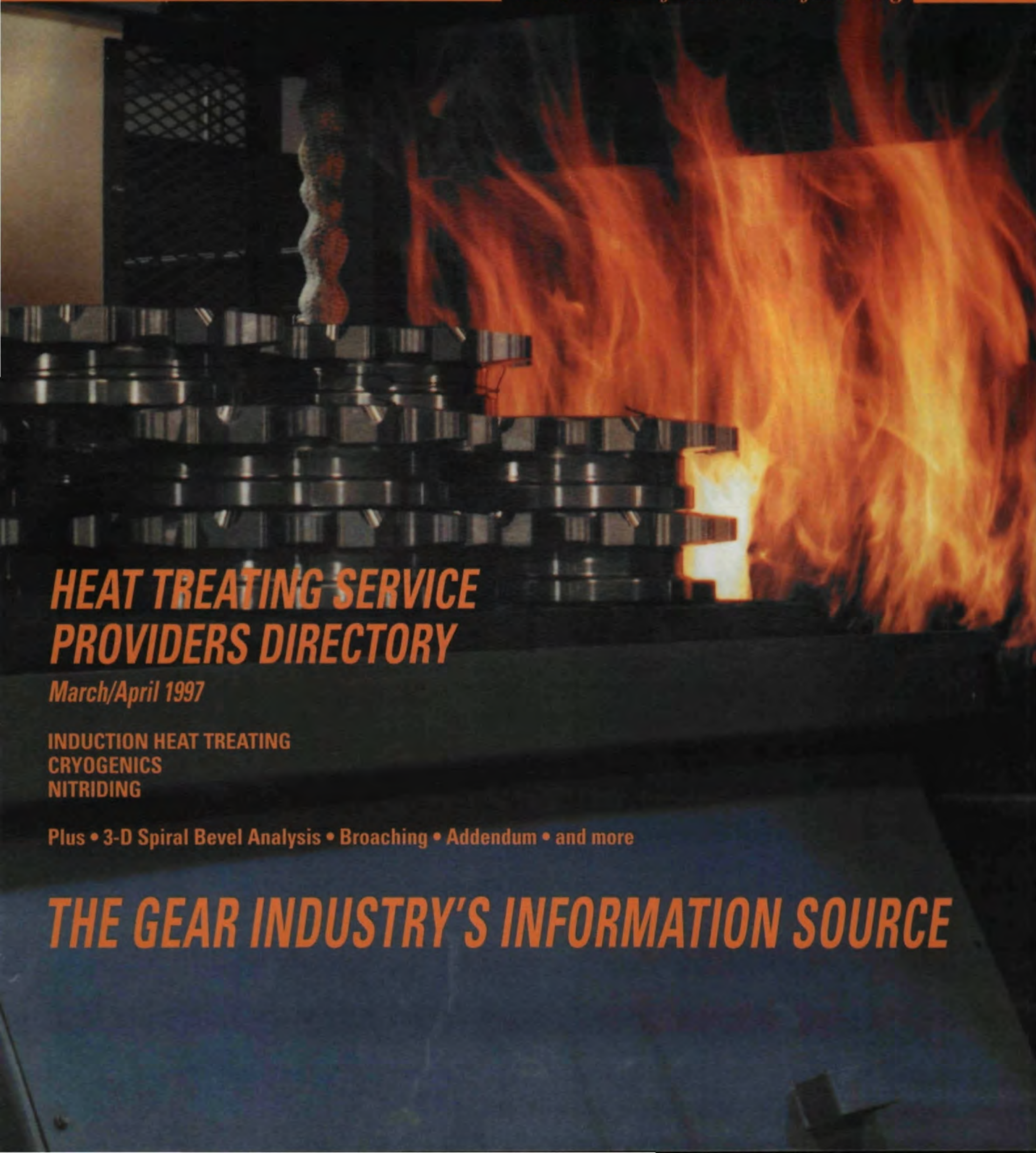
GEAR TECHNOLOGY

The Journal of Gear Manufacturing



HEAT TREATING SERVICE PROVIDERS DIRECTORY

March/April 1997

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GEAR TECHNOLOGY

MARCH/APRIL 1997

The Journal of Gear Manufacturing

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Maumee, OH

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GEAR TECHNOLOGY

The Journal of Gear Manufacturing

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SPREADING The Word

Long-time readers of these pages will know that I have always felt strongly about the subject of professional education. There's nothing more important for an individual's career development than keeping up with current technology. Likewise, there's nothing more important that a company can do for itself and its employees than seeing to it they have the professional education they need. Giving people the educational tools they need to do their jobs is a necessary ingredient for success.

But one of the problems with this worthy goal is finding out who's offering good, reliable training in gear-related subjects, and where it's being offered. Now, thanks to the AGMA Foundation, there is a solution. It has compiled a booklet containing lists of gear manufacturing and related training courses, detailed descriptions of the various curricula, dates of classes, costs—in short, everything you need to know to find out about particular courses.

This booklet, "Education & Training for the Gear Industry," is available from AGMA headquarters (703-684-0211). The 1997 version should be available by the time this editorial goes to print. This book is a "must have" for anyone interested in keeping up with the latest and best gear training available in the U.S.

The book is well-organized, broken down by subject, type of training (courses or seminars) and level of difficulty. It also includes instructor credentials and detailed contact information about each organization offering training. The AGMA Foundation deserves full marks for pulling all this material together and organizing it in usable form.

Having said all that, I do have one quibble, not with the book, but with the Foundation. The 1996 edition of the book was priced at $12.95, with free copies going to "principal members" of AGMA. As of this writing, pricing information was unavailable for the 1997 edition.

Now no one knows better than I do what paper and print cost. Trust me—they're not cheap. Still, this charge seems counterproductive. I assume the Foundation's goal is to support these educational efforts and encourage participation in them. There's not a school in the country that charges for its catalog of courses. This seems to me to be the equivalent of a company saying, "We make a really good product, and if you send us $12.95, we'll tell you all about it."

If the Foundation feels it has to recoup its printing costs, it would make more sense to charge a modest fee to the organizations whose courses appear in the book. Or, since the Foundation (and AGMA itself) are non-profits, maybe the book should be looked on as a service they provide for the industry. A charge for shipping and handling seems reasonable enough, as does a charge for companies that might want dozens of copies to distribute to customers. But $12.95 a pop to individuals just for information that, arguably, AGMA should have been providing for its members anyway seems a bit much.

A highly trained work force is absolutely essential to the continuing success of the gear industry, and the AGMA Foundation has done us all a service by gathering together this training information in convenient and usable form. Now I'd like to see the Foundation take the next step, and make it available and affordable to everyone in the industry who could benefit from it.

Michael Goldstein

Michael Goldstein
Publisher & Editor-in-Chief

Induction Heat Treating: Things Remembered, Things Forgotten

Fred Specht

Many potential problems are not apparent when using new induction heat treating systems. The operator has been trained properly, and setup parameters are already developed. Everything is fresh in one's mind. But as the equipment ages, personnel changes or new parts are required to be processed on the old equipment, important information can get lost in the shuffle.

Now it's time to develop a new and updated checklist for the heat treating operation. In this article, we will discuss items to be included in a guideline for setups and a checklist for installation and operation of the induction system. We will also discuss the importance of the coil design, quenching, part rotation and induction temper, as well as what can be done about distortion of parts and shortcuts for nondestructive testing.

Ten Steps to Easy System Maintenance

Successful moneymaking induction systems should require few, if any, tools to change from one part to another. Great success can be achieved if you follow a few simple rules.

1. Read your OEM supplier manual.

2. Every day check the tightness of the bolts on the coil, bus work and quick disconnects.

3. Wear rubber gloves and a rubber apron when operating the equipment; wear hearing protection if needed.

4. Clean the inductor weekly or when a coil changeover is made to remove quench polymer and scale before it dries hard as a rock.

5. Before installing the coil, use a plastic scouring pad on the bus mating surface to remove foreign material from the electrical surface. Do not use sandpaper!

6. Do not use your induction system as a parts washer. Heavy oil will contaminate the quench. Chips will cause arcing and damage the coil. They will also clog the quench holes.

7. When installing the plumbing for a power supply, use only nonferrous material. Do not use aluminum, iron or steel. One single piece of iron in the cooling system will cause rust in the water recirculating system. Use copper, brass, 300-series stainless or Schedule 80 PVC pipe.

8. Clean the water cooling system at least once a year or as instructed in your OEM manual. Check the conductivity of the water system used to cool the power supply every three months. If you ignore rules seven and eight, your induction system will not last ten years and will give you problems constantly.

9. Never disconnect or jumper the ground detector circuit. Never operate the power supply or heat station with the doors open; replace door gaskets as needed. Keep the dirt out!

10. If you see sparks, overheating or smell anything funny, shut off the equipment immediately and find the problem before further damage is done.

The Setup

Change the coil via quick disconnects. Quench hoses should use "Hansen" quick couplings as shown in Fig. 1. Use one size coupling for quenching and another for coil cooling water. This eliminates the possibility of getting the hoses confused. Avoid using "O" rings. They are high-maintenance.

Tooling cups and centers for part support should not require any tools, yet they should be rugged enough to support the part without wobbling. The machine operator should use a setup sheet with all data pertinent to the job. Don't rely solely on his or her memory to adjust the machine to get a good pattern. The setup sheet or control memory should yield a good part. Only qualified personnel should be allowed access to change the program.

Fig. 1 — Machined integral quench coil with quick disconnect for power, water and quench.

A minimum of 5–10kW per square inch of coil face is required to get good results.

The Coil

The distance between the coil turn or winding and the part (coupling) should be kept to a minimum to reduce power consumption and time cycles.

If the part wobbles during rotation and touches the coil, do not make the coil coupling larger. Fix the rotation bearings!

If the copper coil is discolored, especially down the center leg, it is from overheating. More water cooling or less kW per square inch is required. By adding a booster pump in the coil water circuit, more heat can be removed from the coil. Remember, heat in the coil or tooling is your enemy. You want the heat in the part.

Every six months, flush the inside water cooling path of the coil with a "Lime-Away" type solution. This prevents buildup of salts that precipitate out of the water at 135°F. These salts look like a white powder adhering to the inside of the coil tube. This powder insulates the copper from the water, and the coil fails prematurely.

This happens often on high kW density applications, especially on pancake-type coils, when heating the inside of a hole (I.D.), and on tooth-by-tooth coils. On I.D. heat treating applications, the failure of the coil occurs on the inside (down the center) leg. This is where the water temperature is the greatest. Make sure that on I.D. coils, the coolant water enters down the center leg first.

Machined coils shown in Fig. 1 are the most expensive type, yet they last the longest. Tubing type is the least expensive, but it can be bent with the bare hand. Precision work should always use machined coils, or setup time will increase and slight variations in the pattern from one setup to the next will develop.

Never change the wall thickness of a coil. The original OEM designed the coil wall thickness for a maximum kW density, current density, heat dissipation and frequency. The result of too thin or too thick of a wall is coil meltdown.

Quench is Everything!

Check polymer percentage every morning with a refractometer after the quench has been on and recirculating for a few minutes, but before any heat treating takes place. Recirculating will stir up the quench and give an accurate reading. It will also remove any air trapped in the quench lines. Use a timed quench temperature heater set up like a house thermostat. This turns on the heater for an hour or so before production starts, ensuring that every part sees the same quench temperature.

Quench temperature should be automatically controlled with a heat exchanger and solenoid valve. More than a 10°F window of operation can result in more distortion or a better chance of cracking the workpiece.

The volume or flow rate of quench can never be too great in most cases. The more quench, the faster the part can be processed. Spray shields, doors and enclosures should prevent the operator and floor from getting wet. Never place rag-type shields in the quench. As the polymer attacks them, they dissolve into the quench and plug the small holes in the quench barrel.

Quench barrels and integral quench coils should have at least four quench water inputs for even distribution. If in doubt, with the power supply turned off, the workpiece removed and the quench on manual, stick your hand into the quench and "feel" if one side has more force than the other. Uneven quench will result in more distortion. Use a standard ball valve to adjust for even flow around the quench.

The quench impingement point, the angle at which the quench strikes the part, is important. It needs to be a perfect cooling circle. If a single hole in the quench head is not at the correct angle, it can cause the barber pole effect as shown in Fig. 2. Sometimes foreign matter can become lodged in the hole and cause the same barber pole effect. The smaller the diameter of the workpiece, the more important the impingement point is!

If the quench has a bad smell, it is growing fungi. Agitation or operation will induce oxygen into the quench, but this is only a quick fix to cover the smell. Disposal and cleaning should be done every six months to a year. Check with your quench sales representative.

Distortion

On scan heating applications, if you cannot heat a part and keep it straight, you surely cannot heat and quench it and expect it to be straight. If you are having distortion problems, run the normal cycle without quench applied. Let the part air cool and check the distortion. If it is not straight, you will never keep it straight with quench on. This distortion is usually caused by prestresses in the part. If the quench head is made of PVC material, you must remove it for this test because the radiant heat will melt it without quench running through it.

Special attention should be given to parts that require hardening over keyways or holes. To avoid overheating, melting or cracking, keep the kW density down by adjusting the power level and the scan speed. Look closely as the part is heating. Only experience teaches what 1550°F looks like. Once you have "the eye," you can see the difference between 1550° and 1900°F.

For those just learning, temperature sensitive sticks or paints work well as indicators. Paint small stripes of different temperature values (1500°, 1550° and 1600°F, for example) in the area to be heated. Leave the quench off and pay close attention to the part as it heats. You will see the paint melt and change colors. If the paint does not change color, the temperature was never achieved.

Never attempt to induction-harden frozen workpieces. Your part recipe is based on material at 70°F heating to 1550°F. If frozen material is processed, the same kW will yield 1470°F, resulting in low hardness.

Part Rotation

If the workpiece is rotating slowly enough to count the rpms visually, then rotation is too slow. Scanners with slow rotation can yield a barber pole effect. The barber pole's soft rings can sometimes be seen by the naked eye as shown in Fig. 2. Speeding up the rotation will narrow the rings to less than .125", which should result in a good part.

Rotation has less effect on single shot heat treating. However, short heat cycles can result in uneven heating. If in doubt, speed up the rpms.

Make sure the part rotates evenly and smoothly. There should be little, if any, noticeable wobble in a machine part as it is rotated. The exceptions to this rule are castings and some raw forgings. They will have a wobble equal to the casting tolerance. Make sure that there is a machine surface of reference for location of the part. Raw castings usually do not have the dimensional tolerances needed for induction. Without at least a rough location (within .005"), a good consistent hardness pattern is hardly achievable.

Induction Temper

Induction tempering on a scanner is usually only done with high-volume parts because of the time it takes to develop a part recipe, as well as the tying up of machine time. Small lots of parts with similar steel grades can be set in a basket and placed in the same oven at the same temperature and at a lower cost than induction.

In the cell approach to manufacturing, induction temper is a valuable tool, provided that the material can be cooled completely at the end of the temper cycle. Some alloy materials can not be quenched during the temper cycle. They must be allowed to cool slowly before any other operations can be performed.

Between the induction hardening cycle and the start of the temper cycle, make sure that the quench delay is long enough to cool down the part to at least 150°F. Rescan the part for temper using no more than one-third of the power that was used for hardening, usually at one-third to one-half of the scan speed. The temper cycle start position should go beyond the original start point of the hardening cycle. Do not attempt to develop a temper cycle until a good hardness pattern and hardness are achieved.

The merits of "slack quenching," or leaving residual heat from the hardening cycle in the workpiece, have long been reported, but it is next to impossible on a vertical scanner. Manufacturers use slack quenching on SAE 1045 steel for cylinder rods. These are processed on horizontal scanners. The smaller the diameter, the less merit slack quenching has. In order to even have a chance of controlling this process, a top-of-the-line

Fig. 2 — Barber pole type rings.

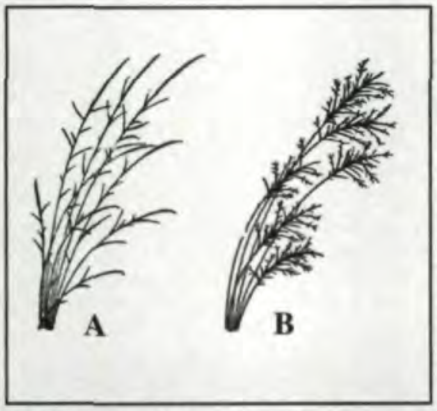

Fig. 3 — a) Sparks from SAE 1015 steel showing simple "forking effect." b) Sparks from SAE 1045 steel showing "secondary burst."

PLC-type controller and a kW second monitor are needed. Tight control of quench temperature, polymer percentage, pressure and flow is an absolute must.

Nondestructive Testing

Sandblasting or shot peening will both yield identifiable hardness patterns: sand within seconds, and shot within minutes.

Never cut the sample unless the length of the pattern is correct. Reuse the same setup pieces or save them for next time. Full anneal before reuse. This may not work on long parts due to distortion from repeated processing.

Know how to use your Rockwell hardness tester. Get it calibrated as required. Do not let inexperienced personnel operate the tester. Use the correct load in relationship to depth of hardness. Do not be fooled by decarburization at the surface that results in soft, erratic readings. On rough-ground workpieces, check the hardness at the final grind depth, not at the surface.

After heat treatment, look for suspicious rings that are more than .125" wide. Check across and between the rings for soft barber pole. Look for uneven colors, such as silver (hard) and blue (soft) in the hardness area.

The File Check. One quick way to get a feel for part hardness is to use a file. Most files are 65 RC. Temper one file at 1100°F, one at 1000°F, etc. After slow cooling, check with a Rockwell hardness tester and inscribe the handles with the corresponding hardness. This will result in a set of files of known hardness. A file that is 45 RC will skate across a surface that is 55 RC, yet it will dig into a part that is 40 RC. Files must be replaced, depending on usage and as teeth wear off. These are to be used as a quick check only, and it does take some practice to get "the feel." They are especially useful in checking hardness in corners and between gear teeth.

The Spark Test. Much has been written over the years identifying various materials using the spark test. It is a great investigative tool when heat treating metals.

The spark test is a method for the classification of steels according to their chemical composition by visual examination of the sparks that are thrown off when the steels are held against a high speed grinding wheel. It is not a substitute for chemical analysis and is not intended for the identification of "unknown" samples. The character of spark streams is examined from a number of specimens supposedly of the same hardness. The spark burst, that is, the "carbon spark," is the most useful characteristic of the spark picture, since the variations in the number and intensity of the bursts indicate the changes in the carbon content. (See Fig. 3 for examples.)

As a commercial heat treater, I learned early that just because someone said the material was 1045 did not make it so. Many times a part is set up on the induction machine and processed with a normally good recipe. The part would show low hardness when checked on a Rockwell hardness tester. Even though the material should have gotten hard due to its carbon level, a repeated process with a little more heat would not yield the hardness required. This is the time to use the spark test.

Conclusion

Induction heat treating is a complex process that involves many intangibles. Just because the machine is producing parts does not make them right. The heat treater of today must use every advantage possible in his bag of tricks.

References:

1. Hildorf, W. G. and C. H. McCollam. "The Spark Testing of Steel," *ASM International Metals Handbook*, 1948.

Acknowledgement: *This article is taken from* Heat Treating, Proceedings of the 16th conference (1996), *ASM International, Materials Park, OH, p. 141–144. Reprinted with permission.*

Fred Specht *is with the Midwest Sales Office of Ajax Magnethermic of Warren, OH, manufacturers of induction heating equipment and supplies. He presented a version of this material at the 1996 ASM Heat Treating Conference.*

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If you found this article of interest and/or useful, please circle **201.**

For more information about **Ajax Magnethermic**, circle **202.**

Dry Hobbing: Another Point of View

If you have a viewpoint you would like to share with us, please send it to Gear Technology, *1401 Lunt Ave., Elk Grove Village, IL 60007, fax us at 847-437-6618 or e-mail* people@geartechnology.com.

I would like to comment on David Arnesen's article, "Dry Hobbing Saves Automaker Money, Improves Gear Quality," in the Nov/Dec, 1996 issue.

An article like this could irritate engineers because of its commercial emphasis. It states that Ford's goals were "to improve gear quality, surface finish and pitch diameter runout and meet increased production demands." Though these are very legitimate expectations, only two can be attributed to the dry carbide hobbing operation: potential improvement of surface finish and higher surface speed of the hob. The other two goals, improving gear quality and pitch diameter runout, have nothing to do with dry carbide hobbing, since they can easily be achieved by improving the machine accuracy, the hob accuracy and the workholding fixture, which is exactly what Liebherr did in the dry carbide application.

The helicoid surface of a parallel axis gear tooth generated by a hobbing operation has two errors: the involute error and the lead error. The involute error is a function of the number of gashes of the hob. By going from 15 to 12 gashes, this error was increased, and since I am assuming these gears are finish-cut, the involute error overall worsened. The lead error is generated mainly by the hobbing machine, while the surface finish (of finish-cut gears) is mainly attributed to the scallops' depth. The scallops are a function of the hob diameter and the feed rate per revolution of the workpiece. The major contribution to improving the surface finish of the helicoid in the hobbing operation is the reduction of the feed rate that can be achieved at the expense of increasing the machine cycle time. Using carbide hobs that can run at about 3 times the surface speed of the actual HSS hob, it is easier to compromise both parameters.

Therefore, I conclude that a carbide hobbing operation has the potential to improve the surface finish of the gears just hobbed with additional finish operations just while the cycle time is still lower than that achieved by a HSS hob. The capital investment to produce a certain amount of gears per year could therefore be lower using carbide instead of HSS hobs.

The article also states that "tool life improved to 252,000 pinions per hob (14 regrinds) using dry carbide from 39,000 pinions per HSS hob (12 regrinds) on existing wet grinding machines. Machining cost fell by 44%." Here we are far from comparing the HSS hob to the carbide hob.

I can manufacture a hob with 8-9" length and one with 4-5" length and claim that one cuts more parts than the other. The author should have compared the number of pieces produced by the carbide hob by giving the number of pieces cut per hob unit length of the total shiftable length and the measured wear. The same figures should have been given for the HSS hob . . .

Next, considering the resharpening cost and the cost of recoating after each resharpening, the author should have given the cost per piece produced by each hob. Finally, the author should have mentioned whether the existing hobs at Ford Indianapolis plant were optimized. It would also have been interesting to know what results would have been obtained if the hobs were optimized and used on new generation machines.

It appears to me that Ford's continuing efforts to improve to dry carbide hobbing was forced by initial poor life of the carbide application and better results have now been accomplished. Could it have been done with the existing HSS hobs? The author does not say.

I refuse to accept articles such as this one strictly devised to promote brand name dry carbide hobbing sales.

To conclude, I urge the author [and the editors] to distinguish among strictly commercial articles and technical ones.

Dr. Sante Basili
Global Carbide Tools Inc.
Ann Arbor, MI

We welcome letters from our readers. Please send yours to the address shown above. All letters become the property of Gear Technology. *Names will be withheld by request, but no anonymous letters will be published. Letters may be edited for space. Opinions expressed by contributors are not necessarily those of the editor or publishing staff.*

Tell Us What You Think . . .
If you found this article of interest and/or useful, please circle **203.**

March 6–8. AGMA Annual Meeting. Loews Ventana Canyon Resort, Tucson, AZ. This year's theme is "Strategic Positioning for Solutions, Success, Growth and the Future." Featured speakers include Charles B Dygert, Ph.D., president of Motivational Enterprises International, Inc., Dr. Michael Bradley of George Washington University and Dick Kleine, Vice President for Quality at Deere & Company. For registration information, contact AGMA Headquarters at 703-684-0211 or fax 703-684-0242.

AGMA GEAR SCHOOL & HOB SHARPENING CLINICS

The AGMA Training School for Gear Manufacturing is held at Daley College, Chicago, IL. This one-week course is designed for employees with a least six months' experience in setup or machine operation, and it covers setup, gear inspection, gear calculations and basic gearing principles. The curriculum includes both classroom and hands-on training in hobbing, shaping and inspection. Sessions for 1997 are scheduled for **April 7–11, June 16–20, Sept. 22–26 and Nov. 17–21**.

The Hob Sharpening Workshop is also held at Daley College. It is a two-day course with both classroom and hands-on training in hob sharpening basics, grinding and wheel dressing, setup, inspection and sharpening helical flute hobs. Classes for 1997 are scheduled for **April 24–25, June 26–27 and Aug. 7–8**. For more information, contact Susan Fentress at AGMA. Phone 703-684-0211 or fax 703-684-0242.

HANNOVER FAIR

April 14–19. 50th Anniversary Hannover Fair. Hannover, Germany. Featured technologies this year will be Power Transmission and Control, Electric Automation Technology, Tools, Factory Equipment and Compressed Air, Lighting Technology, Subcontracting & Industrial Materials, Research & Technology and Plant Engineering.

For more information, call Hannover Fairs USA at 609-987-1202, fax 609-987-0092 or the Fair's Web site, *www.messe.de*.

April 22-25. 7th International Induction Heating Seminar, sponsored by The Inductoheat Group, at the Adams' Mark Hotel, St. Louis MO. Experts from around the world will discuss such topics as basic induction heating, tempering/annealing, power supplies, gear hardening, process monitoring, cellular manufacturing and more. A discount is available if you register before **March 23**. Contact Laurie Moorhouse at 800-624-6297, by fax at 810-585-0429 or by e-mail at *moorhous@inductoheat.com*. Information about this seminar is also available at *www.inductoheat.com*.

SME GEAR CLINICS

May 12, Preliminary Gear Design Development Course: Where Do You Begin? Taught by Ray Drago; **May 13–14** Advanced Gear Processing and Manufacturing Conference. Indianapolis, IN. These popular seminars on a variety of gear manufacturing and design subjects fill up early, so register now. Phone SME at 313-271-1500 or fax 313-240-8254.

WORLD'S FIRST DOUBLE-DIE AUSFORM FINISHING MACHINE INSTALLED AT PENN STATE

The world's first production-capable, double-die ausform finishing machine has been installed at the National Center for Advanced Drivetrain Technologies at Penn State University. The installation process and the systems integration is complete, and prototype production and specimen evaluation will begin shortly.

The end-of-project demonstration of the installation is scheduled for early this spring.

Ausform finishing is a low-temperature, thermomechanical process that was developed at Penn State to precision finish spur and helical gears. It integrates gear heat treatment and hard finishing processes into a single, in-line automated manufacturing operation which, according to the NCADT, will improve performance and reliability and reduce manufacturing costs.

The machine is capable of processing spur and helical gears from 1.5" to 8.0" in diameter (face widths of up to 2") and tooth sizes from 6 to 26 DP. It can handle carburized steels, through-hardening steels and powder metal gears.

Companies involved in the construction of the machine include National Broach & Machine, Contour Hardening Inc., and MTS Inc.

AMERICAN WERA TO REPRESENT HOBBING MACHINE MANUFACTURER

American Wera Inc., the North American source for the Profilator®, and other synchronized dry cutting machinery, will also represent Hurth Modul GmbH, a German manufacturer of gear hobbing machines. Hurth Modul is not to be confused with Hurth Maschinen und Werkzeug GmbH, which was recently acquired by Gleason Corp.

Hurth Modul makes gear hobbing and bevel gear cutting machines with CNC controls, compact design, and automatic work-changing systems for hob arbors and workpiece fixtures.

KLINGELNBERG PURCHASES HÖFLER

As of January 1, Sigma Pool of Saline, MI, will integrate the Höfler gear measuring machines into its North American sales and service program. The Höfler inspection machine division in Ettlingen, Germany, was purchased in May, 1996, from Carl Zeiss by Klingelnberg Sohne. Klingelnberg, Liebherr, Lorenz and Oerlikon make up the Sigma Pool. Höfler will market its range of 3-D CNC gear inspection centers through the group's Sigma Pool location at Liebherr-America in Saline.

PETER KOVAR, U.S. TECH PARTNER, *GEAR TECHNOLOGY* AUTHOR, DIES

E. Peter Kovar of U. S. Tech Corporation, Wheaton, IL, passed away on December 9 after a long bout with cancer. Prior to joining U. S. Tech, Peter worked for some years for American Pfauter. He also wrote a number of articles on computer software and machine controls for *Gear Technology.*

An American Success Story

Joe Garfien came to America in 1928 to play soccer. He also learned to cut gears and build a business.

Nancy Bartels

"When I came here [to America] I came in on a Friday, and I had to go work on Monday, so I found a job at Perfection Gear . . . and that's how I got started in gears."

Thus begins the story of Joseph M. Garfien, founder of United States Gear Corporation of Chicago. It is a story of real personal success, but it is also an almost mythic tale of an immigrant Horatio Alger making good and a piece of gear history unlikely to be repeated. Both the America and the gear industry that Joe Garfien entered in 1928 are long gone. Nobody could make it the way Joe did in this business anymore. But it's a good story, one worth telling.

In 1928, Joe was just 16 and playing soccer for the Austrian national team. After several matches in England, Joe refused to go back home. Instead his uncle in the U.S. agreed to sponsor both Joe and his mother to come here.

When he arrived in Chicago with his mother, he had no job, no money and no English, but he did have two skills that would get him established here—although he only knew about one of them. He knew he could play soccer. What he didn't know until he went to work at Perfection Gear was that he had an intuitive grasp of gear geometry and manufacturing that would not only be the foundation of a successful business, but also would make him something of a legend in the industry.

1928 was perhaps not the best year to start a new job in America, but Joe persevered. Perfection managed to keep its doors open during the Depression, and Joe stayed on. "1929–1931, that was a very bad time," he says. "You couldn't buy a job. I worked for 35 cents an hour. The first job I had was I put a pinion on a machine and pushed a button. That's all I did."

Joe Garfien at work.

He supplemented his income with his other marketable skill: He played soccer (using borrowed shoes in the beginning because he couldn't afford his own) for a team called The Maccabees. "I played on Sundays," he recalls. "I got $25.00 a week for playing soccer, and I got $15.00 a week from Perfection. That made $40.00 a week."

This tidy arrangement came to an end in 1936. Then his wife of three years made him give up soccer. "She was afraid I'd get hurt, and I couldn't afford that," Joe explains.

But by then he had begun to develop the skills that would serve him throughout his career. Without any formal education in the U.S. besides three years of night school, he was turning into a hands-on gear engineer.

Joe describes his approach to gear design this way: "I used a logarithm book to get some of the figures, and then I would think, if I move the ratio gears, then I can top off an undercut, and so on, and that's how I learned to do some of the gear changes."

This deceptively simple, seat-of-the-pants approach got Joe the attention of some serious players in the gear industry. He still tells with fondness the story of his encounter with the engineering staff at The Gleason Works many years ago.

In 1934, the method for cutting automobile axle gears underwent a change to hypoid to accommodate the 1 3/4" drop in the drive shaft that allowed cars to ride much closer to the ground. Joe was sent to Rochester by Perfection to learn the new techniques.

"I brought 50 gears with me so they could show me how to cut them," Joe recalls. "We worked on them for two weeks, and we couldn't cut them the way we needed to. So I said, 'Let me do it my way.' They asked, 'What are you going to do?' and I said, 'I'm going to move the vertical this much, and I'm going to move the cone that much and the face angle this much, and let's see what I come up with.'"

When asked where he came up with his figures, he explained: "The only thing I know is when I move this, I figure the cutter is the gear, and the pinion is like a set, and I move it accordingly—10 for 3, and 5 for 7 and so on—and that's how I got the figures."

Joe shrugs at this point in the story and says with a twinkle in his eye, "It worked. I went home, and we still cut the gears that way."

By 1941, this intuitive approach to gear engineering brought Joe into consultation with the U.S. Army and with Colonel Rockwell of Rockwell Industries. Concerned with the poor performance of 2 1/2- and 5-ton trucks used in the desert war, the army called for a meeting with the major manufacturers in Detroit. Since Perfection was supplying gears for the trucks, Joe was made part of the consulting team.

When asked for his view on what was wrong, Joe, never a man to pull his punches, said, "Everything. The pressure angle's wrong, the ratio's wrong, everything is wrong on the gear."

From Joe's point of view, the problem was not the difficulty in changing the design, but in overcoming the time lag caused by the war-time shortage of materials. He explained that it would take weeks, perhaps more, to get the necessary blanks and cutters. But there are advantages to working for the army in wartime: Colonel Rockwell had what Joe needed within the week.

"We got the cutters and the blanks," Joe explains. "We tested them in Detroit, and they worked even better than we expected. So then everybody changed to my design, and we made the gears that way all through the war years."

A quarter century later, Joe was again taking apart desert vehicles, but this time for a different army in a different war. In the 1967 Six-Day War between Israel and Egypt, the Israelis captured thousands of Russian-made tanks and trucks. It was a vein of intelligence gold that Joe was asked to mine. The Israeli government asked him to supervise the reverse engineering that would give it clues as to the state of gear manufacturing (and, by implication, the rest of heavy industry) in Russia. Joe made copies of the gears and helped to set up the largest gear plant in Israel, Ashot Ashkelon. He still carries in his wallet a snapshot of him and Golda Meir as a souvenir.

FOR ALL JOE HAS SEEN IN SIX EVENTFUL DECADES, HE STILL SEES SOME EXCITEMENT IN THE FUTURE. HIS FIRST PREDICTION: ELECTRIC CARS.

But between jobs for various armies, Joe was building a business of his own. He left Perfection Gear in 1952 to start his own company, U.S. Gear Corporation. Although the company has had its ups and downs over the years, it still operates out of a plant on the far south side of Chicago, employing over 300 people, many of whom joined Joe in 1952, as well as some of their sons, brothers and cousins. U.S. Gear is a major supplier of gears to Ford, GM and other major OEMs. The company has earned the Ford Q1 quality certification award and will be ISO 9000-certified this year.

Joe is still very much a hands-on gear manufacturer. Although his son, Mark, and son-in-law, Don Garfield, handle the day-to-day administration of U.S. Gear, Joe is still on-site every day. At a time in his life when most men would have retired to warmer climates years ago, he's still out on the shop floor before 7:00 a.m., watching, supervising, offering advice in any one of the several languages spoken at the plant.

While his personal history has been exciting enough, the changes he's seen in the industry are of note as well.

When we asked him what changes he had seen over the nearly 70 years he's been cutting gears, he zeroed in on three.

"There's accuracy," he says. "When I first started at Perfection, nobody cared whether a gear was noisy or not. All we cared about was whether or not it could turn. Now the industry has changed in terms of tolerances and quietness. People used to take a part and hold it up to the next one, and if they matched, that was it. Now we work in ten thousandths of an inch. Today when you buy a car, you hear a little noise, you say, 'Take it back. I don't want it.'"

And speed. "When I was at Perfection, it took us a long time to cut gears. Pinions would take three or four hours. Now we get one tooth in 35 seconds. On a nine-toothed gear, that's 35 times 9 or 5 1/4 minutes."

The globalization of the industry and the resulting competitiveness is another change Joe has seen over the years. "Years ago, the U.S. was number one," he says. "We made automobiles. England made Rolls-Royce. Italy made a car. Nobody else made them. Today everybody's making cars.

"In 1952, the government sent me to Japan to teach the Japanese how to shave gears. Now they make cars all over the world. The whole world is making cars now."

And if everyone is making cars, they're also cutting gears. "India's making gears," says Joe. "Korea, Brazil. They're all making gears, and some of them can pay a dollar a day in labor. It's very, very competitive."

But Joe also sees the U.S. as having a key competitive advantage: quality. "The reputation of U.S. products is still very good. That's why we get more money for our gears and stamp a flag and 'made in the U.S.A.' on our products.

"Now the automobile industry comes to you and says, 'I want QS-9000.' They don't give you the work unless you meet their standards. If you've got Q1, they'll talk to you, but if you don't, they don't want you."

All of this adds up to a major cost pressure on gear manufacturers, another change Joe has seen in the industry.

"There are all these new machines out there," he observes. "Gleason has this new Phoenix that does everything . . . but they're a million dollars a piece. A person who starts up a gear plant and buys four, five machines, cutters, testers and stuff, it runs to millions. How can anybody afford that?

"When I started U.S. Gear, the machines were cheap. I had three or four and that was enough. It's not like that anymore."

For all Joe has seen in six eventful decades, he still sees some excitment in the future. His first prediction: electric cars.

"I think there'll come a time when we're all riding on batteries. Oh, you'll still need gears, but far fewer of them. This is long-term, of course. Right now they [electric cars] can't ride too long without charging the battery, but the engineers will find a way around that. They [the cars] won't need much gasoline anymore. Maybe for trucks, but that's all.

"In the short term, the industry's not shrinking. The reason is, how many automobiles in your family? Three? Four? Years ago, you had one and thought you were lucky to have it. Now everybody's making automobiles.

"The long-term picture is a different story, but for now, everybody's building cars, and they all need gears."

Manufacturing techniques will be different too. "I think some time in the future, the gear industry won't cut gears.

We'll forge them. We're doing it now on some items.

"Why? Because it's cheaper. What costs in forging is the die. If you have the volume, you can afford to do it. Then the cutting will be a thing of the past.

"And you can get better quality from a forged gear. You press the metal; you don't weaken it by cutting it, and you can cut out all the post-processing like grinding. The only problem still is that the die costs so much that when you're doing a short run, it doesn't pay."

As we wrapped up our interview with Joe, we asked him the one question that is perhaps inevitable when talking to a man who can bring nearly seventy years of perspective to an industry: What advice do you have for young people starting out in gearing?

His answer is both predictable and surprising. "Get an education," he says. "But when you get this education, know what you want. Don't come to me and say, 'I got a college education.' So what? What do you know? I don't need anybody with a college education. I need somebody who specializes in something. If a kid has a high school or a college education, it's the same thing. It doesn't mean anything. I would advise young people to go for a trade. Learn to be a metallurgist or an engineer or something."

When asked about what accomplishment he was proudest of, Joe surprised us again. He talked about his work with Gleason, his ideas that were turned into workable designs, his jobs with and for various governments. Then he grew thoughtful and related the haunting experience of returning to his home in Austria, knowing that much of his family and many of his friends and neighbors had disappeared into the maelstrom of the Holocaust.

"Sometimes I wonder why I got out and they didn't," he says softly.

Then he returns to the pictures in his wallet. This time, he shows us those of his nine grandchildren and tells us about their careers as doctors, sportscasters, businesswomen.

He smiles and says, "This is what I can brag on. My grandchildren. This here. Yeah, I got money. A lot of people got money, but very few people have what I got." ○

Increasing Hardness Through Cryogenics

Dr. John Cesarone

INFAC experiments examine how carburizing process variables and types of cryogenic treatments affect the microstructure of 9310 alloy steel.

Introduction

The Instrumented Factory for Gears (INFAC) conducted a metallurgical experiment that examined the effects of carburizing process variables and types of cryogenic treatments in modifying the microstructure of the material. The initial experiment was designed so that, following the carburizing cycles, the same test coupons could be used in a future experiment.

Background

The aerospace industry, specifically in the manufacturing of helicopters, has always used cryogenic treatments to stabilize both the geometry and microstructure of the precision gears used in the transmissions. The loading and noise requirements for these gears call for dimensional stability because of its effect on the center spacing of the gear set in operation. Research has shown that material containing levels of approximately 20% retained austenite yields parts with a higher fatigue life than that observed in parts containing lesser amounts. An increase in gear life endurance of 166% has been observed when the retained austenite level was increased from 17% to 40% (Ref. 1). However, accompanying the increase in fatigue life is a loss of geometric shape and an increase in drivetrain noise during gear set "run-in." Though these phenomena are usually not a significant problem in automotive and agricultural applications, a reduction in the amount of retained austenite in these materials may also be necessary as the need for quieter, higher performing transmissions in cars and trucks increases. The mechanism that increases a gear's performance is the mechanical shearing of the austenite, resulting in a finer martensitic structure than thermomechanically (deep frozen to -110° F) formed martensite (Ref. 2).

New helicopter designs and modifications to existing weapons systems are always taxing a material's useful life. New alloys are being adopted or modified for use. Although some of these "new" alloys have existed for as long as 25 years, most have not been used in production transmissions. SAE AMS 6265H (SAE 9310), Pyrowear 53 and Vasco X2 are the three most commonly used alloys in today's helicopter transmissions. This initial investigation focuses exclusively on SAE AMS 6265H.

Aerospace manufacturers currently specify cryogenic treatment of -110°F and generally utilize carburizing cycles that result in microstructures effectively treated at this temperature. Cryogenic processing of materials has been performed for a wide range of materials with varying levels of success based on the material chemistry. Specifications for carburized parts in current aerospace gearing materials include cryogenic treatments that improve dimensional stability, minimize retained austenite levels, increase surface hardness and improve wear properties. Efforts to shorten carburizing cycles continue despite the negative consequences that often accompany shorter carburizing cycles. Although increases in either the carbon potential or the carburizing temperature can shorten a carburizing cycle, both methods have drawbacks. For example, an increase in temperature may lead to an improper grain size or increased intergranular oxidations (IGO), and an increase in carbon potential may lead to high levels of retained austenite and a greater tendency to form carbides.

Most previous research in cryogenics has been done on tool and die materials. One reason that research has not focused on gears is that a temperature of -60°F allows complete martensitic transformation. The bulk of current research in deep cryogenics is conducted on alloy tool steels that have higher carbon contents than gear steels, which may be another reason gears have not been candidates for deep cryogenic research. However, in the carburization of a gear, the carbon level in the carburized region becomes either equal to or higher than the carbon level in the tool steels. Therefore, this series of experiments focuses on improving the properties of the gear teeth without affecting the tough, low-carbon core.

In this presentation, *deep cryogenics* refers to treatment at temperatures lower than -110°F. Deep cryogenics does not add a step to a manufacturing process that already includes freezing parts at -110°F. The present commercial availability of liquid nitrogen and the sophistication of the process control systems make -300°F treatment readily

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applicable. A relatively new proprietary process developed by Nu-Bit, Inc., call the Nu-Bit Process (NBP), involves the immersion of room temperature parts into liquid nitrogen (-320°F) for the length of time required for the temperature of the part to equilibrate with the liquid nitrogen. The part temperature equilibration is achieved when the liquid nitrogen stops boiling. A criticism of liquid nitrogen processes is that they may impart thermal shock to the parts and/or that microcracking may result (Ref. 3).

Treatment at -110°F is adequate when decreasing levels of retained austenite is the main goal, but if treating at -300°F or lower results in consistently superior performance, specification for treatment at -300°F may be appropriate. The cryogenic temperature of -110°F corresponds to the use of dry ice as a method for low temperature treating, which is still being used, as is treatment in mechanical freezers, which can freeze as low as -140°F.

Several recent research projects and various successful manufacturing processes provide valuable information regarding deep cryogenics on gear materials. One research project reports dramatic wear resistance with 10% improvement on low carbon steels and cast iron as a result of deep cryogenics treatment, although problems arise with thermal stresses when using liquid nitrogen as a quenching (cryogenic) medium (Ref. 4). According to James Smith, vice president and co-founder of 3X Kryogenics, the only sure way to use ultra-low temperatures is in carefully controlled environments with tight control over the entire cycle and in cycles that take time—days as opposed to hours. Tight control over long cycles also provides a built-in safety against thermal shock (Ref. 5).

Cryogenic treatment has been more successful on alloyed steels than on plain carbon steels (Ref. 6). It has been suggested that when martensite constitutes more than 70% of the microstructure, 10–15% retained austenite can help reduce cracking (Ref. 7). Lower percentages of retained austenite transform under work-hardening to a very fine crystalline martensite that has a tendency to resist surface cracking rather than contribute to it. As a result, 10–20%, and in some instances, up to 25% retained austenite in the case surface of carburized gears is acceptable and may be beneficial for most applications.

Debate among engineers continues about the best level of retained austenite in the case surface or carburized and hardened parts. Some argue that the retained austenite may transform to untempered martensite, either by work-hardening or by exposure to extremely cold climates, and cause tensile cracking of the surface. Others object to the presence of retained austenite in the case of a carburized part that is to be subsequently ground. Under certain grinding conditions, even small amounts of retained austenite can cause severe grinding burns and cracking. Research published by the International Nickel Company (INCO) indicates that levels of less than 50% retained austenite enhance contact fatigue and compressive stresses (Ref. 8). Other research indicates that 15–30% retained austenite is desirable in carburized direct quenched gears as long as hardness is HRC 57 or more (Ref. 9).

The purpose of this experiment is to examine the effects of the carburizing atmosphere and the cryogenic treatment on the microstructure of the material to determine how to modify effectively the material. Input variables for the experiment include the carburizing atmosphere and the cryogenic treatment. Output variables include measurements of retained austenite, surface hardness, case depth and carbon and nitrogen gradients. Because this experiment is the first phase of another experiment in which the same samples will be used, the carburizing cycles were designed to be nondestructive to the test coupons. The information contained in this report will also provide data for the next experiment. The future experiment will include more cryogenic data for determining what cryogenic treatment is necessary to yield a desired microstructure as well as performance data for further differentiating between the cryogenic treatments.

Experimental Procedure

Eleven different carburizing cycles, designed to yield eleven different carbon gradients and eleven different retained austenite levels, were performed on test coupons. Table I lists the carburizing cycle conditions. The coupons were machined from 0.40" thick AMS 6265 (AISI 9310) steel. The

Table I Matrix for the Carburizing of the Cryogenic Coupons

Process	Temperature (°F)	% Carbon	Time (hours)	NH_3
A	1600	0.6	12	Yes
B	1600	0.8	12	Yes
C	1600	0.8	12	No
D	1600	1.0	8.5	No
E	1700	0.8	6	No
F	1700	1.0	4.5	No
G	1700	1.2	3.5	No
H	1800	0.8	3	No
I	1800	1.0	2.5	No
J	1800	1.2	2	No
K	1800	1.4	1.5	No

coupons consisted of discs with teeth hobbed into them, as shown in Fig. 1, and stamped with an identification on each test area, as designated in Table II. Sections of each test coupon were removed for analysis at the appropriate step of the process, leaving the remaining part of the coupon to continue through the cycle.

The coupons were reheated and integrally quenched in a gas-fired, vertical, radiant-tube, integral quench furnace (GVRT-IQ) before deep-freeze treatment. The -110°F deep freeze consisted of one hour exposure in a chamber lined with dry ice; the -310°F deep-freeze treatment consisted of immersion for 15 minutes in liquid nitrogen. The transfer time from quench to deep freeze was less than two minutes. Samples were tempered at 300°F for one hour.

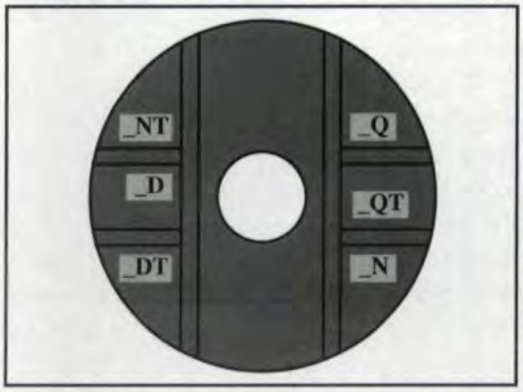

Fig. 1 — Test coupon showing identification location, position and labelling.

Table II Coupon Identification Assignments		
Designation	Treatment	Time
D	Dry ice deep freeze (-110°F)	120
DT	Dry ice deep freeze (-110°F) followed by 300°F temper	90
N	Liquid nitrogen immersion	15
NT	Liquid nitrogen immersion followed by 300°F temper	90
Q	None (as-quenched)	–
QT	300°F temper	90

Note: Identification is as follows: Each coupon is identified for the cycle and treatment, e.g., A-D, A-DT, A-N, A-NT, A-Q, A-QT; B-D, B-DT, etc. for the remaining carburizing cycles.

Measurements of retained austenite, Rockwell "C" hardness (HRC) at the surface and case depth Knoop hardness (KHN) were conducted at each step of the process. Six measurement points were chosen to observe the material behavior at each step in the process. The retained austenite measurements were conducted on a Windows-based TEC x-ray analyzer using a standard setup. The Rockwell hardness tests were conducted according to ASTM Specification Designation E 18-89a. The case depth measurements were conducted in accordance with ASTM Specification Designation E 384-89. Carbon and nitrogen gradient bars of material identical to the coupons were machined into 4" long bars, approximately 1" in diameter. The carbon and nitrogen gradients were conducted by collecting the turnings that were generated from the lathe without lubricant, but with deliberate care to prevent burning. The turnings were collected and bagged according to the depth turned, based on micrometer measurements. These turnings were broken into smaller pieces, and a 1-gram sample was analyzed in a Leco Carbon Determinator; nitrogen gradients were generated on a Leco Nitrogen Determinator. The carbon and nitrogen gradients were determined after the quench step, since they are not affected by further processing as long as no further high temperature processing occurs. Carbon and nitrogen gradient results appear in Table III.

Table III Carbon and Nitrogen Gradient Results (weight percent by depth in inches)													
Run	A	B	C	D	E	F2	G	H	I	J	K	A	B
Depth	Carbon	Carbon	Carbon	Carbon	Carbon	Carbon	Carbon	Carbon	Carbon	Carbon	Carbon	Nitrogen	Nitrogen
0.000	Bar 26	Bar 28	Bar 15	Bar 16	Bar 17	Bar 30	Bar 19	Bar 20	Bar 21	Bar 24	Bar 25	Bar 27	Bar 29
0.005	0.519	0.703	0.687	0.816	0.715	0.832	0.884	0.926	0.725	0.797	0.853	0.250	0.370
0.010	0.487	0.653	0.674	0.756	0.624	0.742	0.774	0.845	0.602	0.685	0.741	0.260	0.280
0.015	0.429	0.566	0.609	0.670	0.547	0.644	0.658	0.697	0.509	0.572	0.617	0.210	0.250
0.020	0.418	0.555	0.556	0.572	0.488	0.564	0.578	0.601	0.461	0.508	0.522	0.180	0.200
0.025	0.398	0.529	0.466	0.463	0.412	0.478	0.482	0.495	0.400	0.422	0.425	0.110	0.130
0.030	0.342	0.452	0.392	0.356	0.357	0.392	0.372	0.398	0.327	0.348	0.342	0.069	0.087
0.035	0.280	0.384	0.328	0.282	0.296	0.314	0.295	0.302	0.279	0.288	0.274	0.054	0.041
0.040	0.243	0.329	0.278	0.219	0.250	0.256	0.231	0.243	0.243	0.246	0.230	0.030	0.028
0.045	0.211	0.248	0.232	0.180	0.212	0.208	0.192	0.193	0.204	0.206	0.194	0.013	0.016
0.050	0.182	0.197	0.193	0.159	0.180	0.170	0.163	0.165	0.182	0.168	0.150	0.022	0.012
0.060	0.143	0.153	0.157	0.124	0.144	0.153	0.136	0.133	0.143	0.138	0.130	0.016	0.017
0.070	0.128	0.129	0.130	0.122	0.126	0.128	0.118	0.127	0.128	0.122	0.117	0.013	0.012
0.080	0.123	0.121	0.118	0.115	0.118	0.116	0.116	0.122	0.122	0.115	0.121	0.010	0.011
0.090		0.116	0.120	0.109	0.118	0.113	0.112	0.124	0.120	0.106	0.114	0.018	0.010
0.100		0.119	0.126	0.115	0.117	0.114	0.112	0.115	0.117	0.112	0.113	0.012	0.013

Data Analysis

A desired case depth of 0.030–0.040" was achieved and verified by microhardness examination. Table IV lists the retained austenite measurement results for the various steps of processing. The highest levels of retained austenite were observed in the high carbon potential carburized samples (G, J and K) and in the ammonia-addition carburized samples (B). The ammonia additions had no effect on the oxygen probe response, as verified by shim stock test results included in Table VI. It is possible that the addition level was too low to dramatically affect the atmosphere. The two ammoniated cycles had identical levels of added ammonia; the cycle with the higher carbon level (B) had the largest amount of retained austenite.

In general, higher carbon levels for carburizing result in larger amounts of retained austenite. This expected phenomenon was observed for the as-quenched condition; however, it did not prove to be the general convention with atmospheres of high carburizing potentials. The 1600°F runs (A, B, C and D) showed varying amounts of retained austenite after deep freezing, attributable to the ammonia addition. The 1700°F runs (E, F and G) followed the convention of increased carburizing carbon levels resulting in increased levels of retained austenite. The 1800°F runs (H, I, J and K) did not follow the convention and contained varying amounts of retained austenite not attributable to ammonia addition, since none was added during these cycles.

The differences in retained austenite between cryogenics and deep cryogenics are illustrated in Figs. 2–4. In general, NBP treatment decreased retained austenite levels more than the dry ice treatment. When the parts were tempered, the dry ice treated parts transformed more retained austenite than the NBP treated parts; therefore, the levels of total percent change in retained austenite for either cryogenic treatment were approximately equal.

Recent research by the Iron and Steel Institute of Japan (ISIJ) indicates that performance properties may be improved without evidence of further retained austenite reduction. This is explained by martensitic decomposition, formation of beneficial η-carbides, reduction of detrimental commonly formed ε-carbides and a finer martensitic structure. The formation of η-carbides was observed by electron microscopy only when the parts were treated to deep cryogenics. Conventional cryogenic treating to -110°F does not form η-carbides (Ref. 10).

Previous research (Ref. 11) indicates that increased carbon levels assist nitrogen diffusion

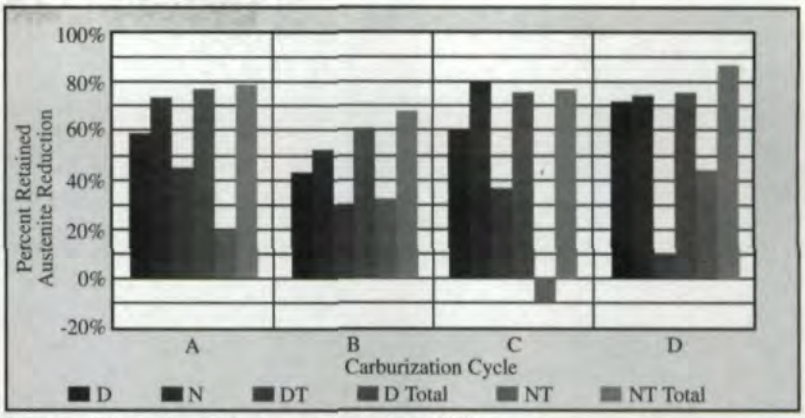

Fig. 2 — Change in retained austenite in the 1600°F runs.

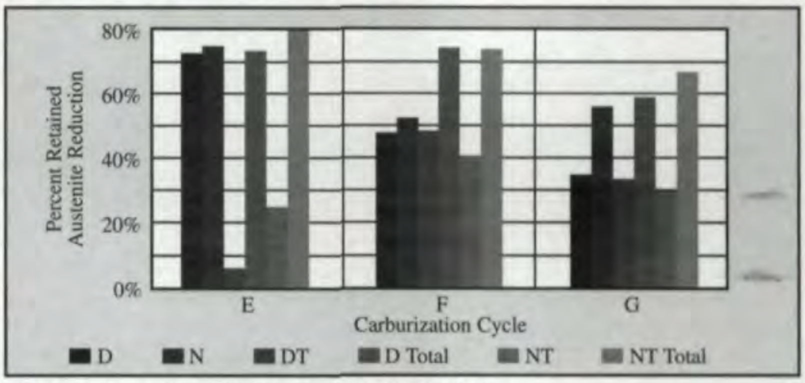

Fig. 3 — Change in retained austenite in the 1700°F runs.

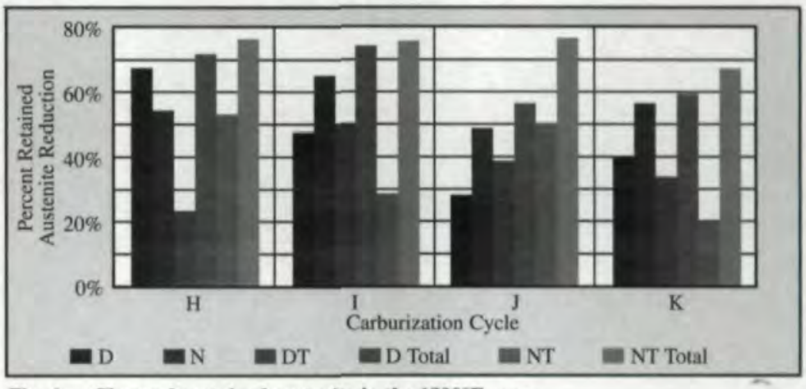

Fig. 4 — Change in retained austenite in the 1800°F runs.

because the carbon atoms open up the crystal lattice to allow easier nitrogen atom diffusion. The observed nitrogen gradient results for this experiment do not indicate this to be true for 9310. The nitrogen gradients appeared similar between runs A (0.6% C) and B (0.8% C); however, this may not be enough of a difference in carbon level to observe an effect of the nitrogen diffusion. Other research (Ref. 12) indicated much higher amounts of nitrogen in a carburized case than that achieved in the investigation presented in this report. The higher nitrogen case levels involve Raw Town Gas (RTG), which contained a different CO/CO_2 ratio than an endothermic based atmosphere. This research suggests that the amount of nitrogen diffusion into the case is not only dependent on temperature, but also on the CO/CO_2 ratio. The different CO/CO_2 ratio also resulted in lower levels of carbon diffusion into the case.

Table IV Retained Austenite Levels Before and After Cryogenic Treatments of -110°F and -320°F						
Run	Q	QT	D	N	DT	NT
A	41.4	35.9	17.0	11.2	9.4	8.9
B	83.2	72.2	48.9	40.9	33.8	27.4
C	38.3	35.6	15.3	8.0	9.5	8.8
D	29.5	25.4	7.9	7.7	7.1	4.3
E	41.2	37.2	1.5	10.5	10.8	8.0
F	55.1	45.5	29.2	25.8	15.0	15.4
G	66.2	57.0	41.5	31.5	27.1	21.9
H	42.7	34.4	15.1	20.6	11.7	9.9
I	51.6	46.4	26.2	17.6	13.0	12.5
J	63.0	57.3	44.7	31.8	27.3	15.9
K	68.5	64.7	40.9	29.0	27.8	23.2

Table V Rockwell "C" Surface Hardness Test Results						
Run	Q	QT	D	N	DT	NT
A	62.4	59.3	62.8	63.2	62.3	62.7
B	61.0	58.7	62.4	65.6	63.6	64.3
C	60.0	58.4	64.2	65.1	61.4	61.2
D	58.0	56.5	63.7	63.8	62.5	63.0
E	60.9	58.8	64.8	68.0	62.5	65.5
F	59.5	56.4	63.9	62.8	62.1	62.2
G	55.6	58.3	63.1	65.3	64.8	62.8
H	61.6	57.7	64.4	64.4	60.5	61.3
I	59.8	56.6	64.6	63.4	61.1	61.1
J	57.6	53.8	61.9	63.5	61.2	61.8
K	55.0	48.9	62.3	62.4	60.6	61.8

The HRC results are listed in Table V, and a project data summary in Table VI. The results indicate that hardness is not necessarily a function of retained austenite. Using 30% retained austenite as a reference point, hardness values varied from a high of 68.0 HRC to a low of 56.5 HRC for amounts less than 30%, and from a high of 65.6 HRC to a low of 48.9 HRC for amounts greater than 30%. The maximum hardness resulted from the NBP treatment.

Conclusions

• Only the runs at 1700°F showed increased levels of retained austenite as a result of increased carbon levels.

• Increasing the carburizing temperature shortened the cycle times and did not increase the amount of retained austenite. Providing the furnace does not leak, increasing the carburizing temperature does not contribute to increased intergranular oxidation (IGP).

• The 1800°F carburizing cycles resulted in an increased grain size of the core material for the as-quenched samples; however, this may be controlled by a proper reheat and quench cycle.

• The effect of the NBP process is not apparent by hardness, retained austenite, residual stress or metallographic structure.

• Treatment at -110°F or NBP both reduced the retained austenite levels significantly and increased hardness from a range of HRC 49–59 to a range of HRC 60–65.

• NBP treated samples exhibited no signs of thermal shock or cracking.

Future Work

The effect of the NBP process on the performance properties of wear and single tooth bending will be studied in the next experiment. Gear teeth were cut on every sample coupon to simulate real-world material applications. The test coupons were tempered after deep freeze treatment to lock in the properties until performance testing could proceed. This will determine if the deep cryogenics impart similar benefits to gears as those observed in the tool and die materials in which they have been used successfully.

Future experiments may include expanding to other "new" gear materials such as Vasco, which was developed by Boeing Vertol and Teledyne Vasco for high hot hardness and the ability to be carburized.

Further studies on atmosphere addition will be investigated using higher ammonia additions, higher temperatures and higher carbon levels.

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Table VI Data Summary Sheet

		Ret. Aus.						Avg. HRc	Effective Case	Averages			
Run	Sample	Q	QT	D	DT	N	NT		HRc 50	0.40% C	P.V.	Shim	F. Factor
A	64	41.40						62.4	0.031	0.025	0.601	0.599	-0.006
1600°F	65		35.87					59.3	0.029				
0.6% C	66			17.01				62.8	0.037				
12.0 hrs	67				9.41			62.3	0.033				
+NH_3	68					11.18		63.2	0.034				
	69						8.90	62.7	0.033				
B	70	83.15						61.0	0.037	0.033	0.798	0.785	0.013
1600°F	71		72.17					58.7	0.038				
0.8% C	72			48.85				62.4	0.039				
12.0 hrs	73				33.76			63.6	0.040				
+NH_3	74					40.90		65.6	0.037				
	75						27.44	64.3	0.037				
C	10	38.32						60.0	0.030	0.029	0.801	0.834	0.061
1600°F	11		35.57					58.4	0.032				
0.8% C	12			15.26				64.2	0.034				
12.0 hrs	13				9.54			61.4	0.033				
	14					7.98		65.1	0.033				
	15						8.77	61.2	0.035				
D	16	29.47						58.0	0.032	0.028	1.003	1.017	0.025
1600°F	17		25.38					56.5	0.030				
1.0% C	18			7.87				63.7	0.033				
8.5 hrs	19				7.12			62.5	0.033				
	20					7.74		63.8	0.033				
	21						4.33	63.0	0.030				
E	22	41.15						60.9	0.031	0.026	0.802	0.801	0.036
1700°F	23		37.18					58.8	0.031				
0.8% C	24			11.49				64.8	0.035				
6.0 hrs	25				10.82			62.5	0.034				
	26					10.49		68.0	0.035				
	27						7.99	65.5	0.034				
F1*	28	51.98						64.8	0.039	0.030	1.001	0.925	-0.054
1700°F	29		46.94					63.5	0.037				
1.0% C	30			23.96				62.6	0.041				
4.5 hrs	31				12.75			62.4	0.037				
	32					16.33		65.7	0.039				
	33						11.46	62.0	0.038				
F2*	76	55.07						59.5	0.034	0.029	0.999	0.981	-0.008
1700°F	77		45.51					56.4	0.034				
1.0% C	78			29.15				63.9	0.037				
4.5 hrs	79				14.96			62.1	0.033				
	80					25.76		62.8	0.033				
	81						15.40	62.2	0.033				
G	34	66.20						55.6	0.037	0.030	1.175	1.169	-0.049
1700°F	35		57.03					58.3	0.033				
1.2% C	36			41.50				63.1	0.037				
3.5 hrs	37				27.06			64.8	0.035				
	38					31.54		65.3	0.040				
	39						21.88	62.8	0.036				
H	40	42.67						61.6	0.034	0.025	0.806	0.792	-0.012
1800°F	41		34.43					57.7	0.030				
0.8% C	42			15.13				64.4	0.032				
3.0 hrs	43				11.68	0.00		60.5	0.033				
	44					20.60		64.4	0.038				
	45						9.85	61.3	0.031				
I	46	51.60						59.8	0.032	0.026	0.991	0.970	-0.018
1800°F	47		46.39					56.6	0.034				
1.0% C	48			26.18				64.6	0.035				
2.5 hrs	49				13.03			61.1	0.028				
	50					17.59		63.4	0.028				
	51						12.52	61.1	0.029				
J	52	62.97						57.6	0.032	0.027	1.143	1.129	-0.025
1800°F	53		57.34					53.8	0.034				
1.2% C	54			44.71				61.9	0.034				
2.0 hrs	55				27.29			61.2	0.032				
	56					31.82		63.5	0.029				
	57						15.85	61.8	0.034				
K	58	68.50						55.0	0.030	0.028	1.287	1.178	-0.067
1800°F	59		64.65					48.9	0.029				
1.4% C	60			40.89				62.3	0.028				
1.5 hrs	61				27.80			60.6	0.029				
	62					29.00		62.4	0.030				
	63						23.23	61.8	0.029				

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Lake County Steel Treating
Lawrence Industries Inc.
Lexington Heat Treat Inc.
Lindberg Heat Treating Co. —Berlin
Lindberg Heat Treating Co. —Houston
Lindberg Heat Treating Co. —Melrose Park
Lindberg Heat Treating Co. —New Berlin
Lindberg Heat Treating Co. —Racine
Lindberg Heat Treating Co. —Rochester
Lindberg Heat Treating Co. —St. Louis
Magnum Metal Treating Inc.
Master Heat Treating Inc.
Merit Gear Corp.
Metal Improvement Co.—Columbus
Metal Improvement Co.—Lafayette
Metal Improvement Co.—McLean/Wichita
Metal Treaters Inc.
Metal Treating & Research
Metallurgical Inc.
Metallurgical Processing Inc.
Metals Engineering Inc.
Metals Technology
Metlab Co.
Metro Steel Treating
Met-Tek Inc.—Racine
Midland Metal Treating Inc.
Midwestern Machinery Co.
Modern Industries Inc.
Mountain Metallurgical
National Broach
National Metal Processing
Oakland Metal Treating Co.
Ohio Metallurgical Service
P & L Heat Treating & Grinding
Partek Laboratories Inc.
Paulo Products Co.—Birmingham
Paulo Products Co.—Kansas City
Paulo Products Co.—Memphis
Paulo Products Co.—Murfreesboro
Paulo Products Co.—Nashville
Paulo Products Co.—St. Louis
Pennsylvania Metallurgical
Peters Heat Treating Inc.
Phoenix Heat Treating Inc.
Pitt-Tex Inc.
Precision Heat Treating
Progressive Steel Treating
Racine Heat Treating Co.
Rochester Steel Treating
Rotation Products Corp.
Shore Metal Technology
Sonee Heat Treating Corp.
Southeastern Heat Treating
Specialty Heat Treating Inc.—Athens
Specialty Heat Treating Inc.—Elkhart
Specialty Heat Treating Inc.—Grand Rapids
Specialty Heat Treating Inc.—Holland
Specialty Steel Treating—Farmington Hills
Specialty Steel Treating—Fraser
State Heat Treat Inc.
Steel Treaters, Inc.
Steel Treating
Suncoast Heat Treating—Orlando
Suncoast Heat Treating—Pompano Beach
Suncoast Heat Treating—Tampa
Superior Metal Treating
Syracuse Heat Treating
T. N. Woodworth Inc.
Therm Tech of Waukesha
Thermal Metal Treating Inc.
Thermal Treatment Center
Thermo Electron Metal Treating Div.
Thermo Treaters Ltd.
TracTech
Treat All Metals Inc.
Trutec Industries
Universal Heat Treating
Washington Metallurgical Services
Weiss Industries Inc.
Westside Flame Hardening

CRYOGENICS

ABS Metallurgical Processors Inc.
Accurate Steel Treating
Advanced Thermal Technologies Inc.
Alco Heat Treating Corp.
Alliance Metal Treating
American Brazing
American Heat Treating
American Met. Treating Inc.
Applied Cryogenics Inc.
Beehive Heat Treating Inc.
Benedict-Miller Inc.
Bennett Heat Treating & Brazing Co.
Bodycote/Hinderliter

Thermal Processing
Braddock Metallurgical
Braddock Metallurgical Alabama
Burbank Steel Treating Inc.
Cal-Doran Division
Carolina Commercial Heat Treating
Century Sun Metal Treating
Certified Heat Treating Inc.
Cincinnati Flame Hardening Co.
Cincinnati Gear Co.
Cincinnati Steel Treating
City Steel Treating Inc.
Detroit Flame Hardening
Detroit Steel Treating Co.
Drever Heat Treating
East Carolina Metal Treating Inc.
East-Lind Heat Treat
Edwards Heat Treating
Elmira Heat Treating
Engineered Heat Treat Inc.
Erie Steel Treating Inc.
Fairfield Mfg. Co.
Fenton Heat Treating
Flame Metals Processing
Fox Steel Treating Co.
FPM Heat Treating—Elk Grove
FPM Ipsen Heat Treating
FPM Milwaukee
General Heat Treating Corp.
General Metal Heat Treating Inc.
Geo. H. Porter Steel Treating Co.
Gibson Heat Treat Inc.
Hauni Richmond Inc.
Heat-Treating Inc.
Heat Treat Corp. of America
Hi-Tech Steel Treating Inc.
HI TecMetal Group—Cleveland
Hinderliter Heat Treating Inc.—Anaheim
Hinderliter Heat Treating Inc.—Dallas
Hinderliter Heat Treating Inc.—Tarzana
Hinderliter Heat Treating Inc.—Tulsa
HiTech Aero
Hy-Vac Technologies Inc.
Hydro-Vac
Illiana Heat Treating Inc.
Impact Strategies Inc.
Induction Metal Treating
Industrial Steel Treating Co.
Industrial Steel Treating Inc.
Irwin Automation Inc.
Jasco Heat Treating Inc.
Kowalski Heat Treating Co.
Lexington Heat Treat Inc.
Lindberg Heat Treating Co.—Berlin
Lindberg Heat Treating Co.—Houston
Lindberg Heat Treating Co.—Melrose Park
Lindberg Heat Treating Co.—Racine
Magnum Metal Treating
Master Heat Treating Inc.
Metal Improvement Co.—Columbus
Metal Improvement Co.—McLean/Wichita
Metal Treaters Inc.
Metallurgical Inc.
Metals Engineering Inc.
Metals Technology
Metro Steel Treating
Met-Tek Inc.—Clackamas
Midland Metal Treating Inc.
Modern Industries Inc.
Mountain Metallurgical
National Metal Processing
Nitro-Vac Heat Treating
Ohio Metallurgical Service
Paulo Products Co.—Birmingham
Paulo Products Co.—Kansas City
Paulo Products Co.—Memphis
Paulo Products Co.—Nashville
Paulo Products Co.—St. Louis
Penna Flame Industries Inc.
Peters Heat Treating Inc.
Phoenix Heat Treating Inc.
Pitt-Tex Inc.
Progressive Steel Treating
Racine Heat Treating Co.
Rochester Steel Treating
Rotation Products Corp.
S.K.S. Heat Treating Inc.
Shore Metal Technology
Solar Atmospheres Inc.
Sonee Heat Treating Corp.
Southeastern Heat Treating
Specialty Heat Treating Inc.—Athens
Specialty Heat Treating Inc.—Elkhart
Specialty Heat Treating Inc. *—Grand Rapids*
Specialty Heat Treating Inc.—Holland
Specialty Steel Treating—Fraser
Steel Treaters, Inc.
Steel Treating
Sun Steel Treating
Suncoast Heat Treating—Orlando
Suncoast Heat Treating—Pompano Beach
Suncoast Heat Treating—Tampa
Superior Metal Treating
Syracuse Heat Treating
T. N. Woodworth Inc.
Therm Tech of Waukesha
Thermal Treatment Center
Thermo Electron Metal Treating Div.
Treat All Metals Inc.
Trutec Industries
Universal Heat Treating
Walker Heat Treating
Washington Metallurgical Services
Westside Flame Hardening

DIE QUENCHING

American Brazing
Benedict-Miller Inc.
Bennett Heat Treating & Brazing Co.
Burbank Steel Treating Inc.
Caterpillar Industrial Products Inc.
Certified Metal Craft Inc.
Cincinnati Gear Co.
Cincinnati Steel Treating
Dynamic Metal Treating
Engineered Heat Treat Inc.
Euclid Heat Treating Co.
Fairfield Mfg. Co.
Fox Steel Treating Co.
Franklin Steel Treating Co.
General Metal Heat Treating Inc.
The Gleason Works
Grand Rapids Heat Treating Co.
Heat Treat Corp. of America
Hy-Vac Technologies Inc.
Illiana Heat Treating Inc.
Impact Strategies Inc.
Industrial Steel Treating Inc.
Jasco Heat Treating Inc.
John V. Potero Co.
Kowalski Heat Treating Co.
Lindberg Heat Treating Co.—Racine
Metallurgical Inc.
Metals Technology
Ohio Metallurgical Service
Paulo Products Co.—Birmingham
Paulo Products Co.—Kansas City
Paulo Products Co.—Memphis
Paulo Products Co.—Nashville
Paulo Products Co.—St. Louis
Phoenix Heat Treating Inc.
Roboduction Thermal Processing
Solar Atmospheres Inc.
Specialty Steel Treating—Fraser
Sun Steel Treating
Therm Tech of Waukesha
Thermal Metal Treating Inc.
Treat All Metals Inc.

FLAME HARDENING

Alco Heat Treating Corp.
American Heat Treating
Beehive Heat Treating Inc.
Benedict-Miller Inc.
Bennett Heat Treating & Brazing Co.
Bodycote/Hinderliter Thermal Processing
The Bowdil Co.
Bucyrus International Inc.
California Surface Hardening Inc.
Calumet Surface Hardening
Certified Heat Treating Inc.
Chicago Flame Hardening
Chicago Induction
Cincinnati Flame Hardening Co.
Cincinnati Gear Co.
Cincinnati Steel Treating
Cleveland Flame Hardening Co.
Coleman Commercial Heat Treating
Detroit Steel Treating Co.
Detroit Flame Hardening
Drever Heat Treating
East-Lind Heat Treat
Edwards Heat Treating
Erie Steel Treating Inc.
Flame Hardening Co. of California
Fox Steel Treating Co.
Franklin Steel Treating Co.
Gibson Heat Treat Inc.
Hansen-Balk Steel Treating
Heat-Treating Inc.
Hi-Tech Steel Treating Inc.
Hinderliter Heat Treating Inc.—Tulsa
Horizon Steel Treating Inc.
Houston Flame Hardening
Illiana Heat Treating Inc.
Induction Metal Treating Co.
John V. Potero Co.
Kowalski Heat Treating Co.
M & M Heat Treat
Metal Improvement Co.—McLean/Wichita
Metallurgical Inc.
Met-Tek Inc.—Racine
Michigan Flame Hardening
Mid-West Flame Hardening
Midwestern Machinery Co.
National Induction Heating
Ohio Metallurgical Service
Penna Flame Industries Inc.
Pennsylvania Metallurgical
Revas Engineering Co.
Specialty Heat Treating Inc.—Athens
Steel Treaters, Inc.
Suncoast Heat Treating—*Orlando*
Suncoast Heat Treating—Pompano Beach
Suncoast Heat Treating—Tampa
Superior Metal Treating
Syracuse Heat Treating
Therm Tech of Waukesha
Thermo Electron Metal Treating Div.
Thermo Treaters Ltd.
Washington Metallurgical Services
Westside Flame Hardening
Wohlert Corp.

FREE QUENCHING

ABS Metallurgical Processors Inc.
Advanced Thermal Technologies Inc.
Alliance Metal Treating
AP Westshore
Benedict-Miller Inc.
Bennett Heat Treating & Brazing Co.
Bodycote/Hinderliter Thermal Processing
Braddock Metallurgical
Burbank Steel Treating Inc.
Cal-Doran Division
Carolina Commercial Heat Treating
Caterpillar Industrial Products Inc.
Certified Metal Craft Inc.
Certified Heat Treating Inc.
Cincinnati Gear Co.
Cincinnati Steel Treating
City Steel Treating Inc.
Commercial Induction
Commercial Steel Treating
Diamond Heat Treating Co.
Dixie Heat Treating Co. Inc.
Drever Heat Treating
East Carolina Metal Treating Inc.
Elmira Heat Treating
Engineered Heat Treat Inc.
Erie Steel Treating Inc.
Euclid Heat Treating Co.
Fenton Heat Treating
FPM Heat Treating—Elk Grove
FPM Milwaukee
Franklin Steel Treating Co.
General Metal Heat Treating Inc.
Heat Treat Corp. of America
Heat-Treating Inc.
Hinderliter Heat Treating Inc.—Anaheim
Hinderliter Heat Treating Inc.—Tarzana
Horizon Steel Treating Inc.
Illiana Heat Treating Inc.
Induction Metal Treating Co.
Industrial Metal Treating
Industrial Steel Treating Inc.
Jasco Heat Treating Inc.
Kowalski Heat Treating Co.
Lake County Steel Treating
Lawrence Industries Inc.
Lindberg Heat Treating Co.—Berlin
Lindberg Heat Treating Co.—Houston
Lindberg Heat Treating Co.—Melrose Park
Lindberg Heat Treating Co.—Racine
Metal Improvement Co.—Lafayette
Metal Improvement Co.—McLean/Wichita
Metallurgical Inc.
Metals Technology
Metlab Co.
Met-Tek Inc.—Racine
Midland Metal Treating Inc.
Mid-West Flame Hardening
National Broach
National Induction Heating
Nettleson Steel Treating
Ohio Metallurgical Service
P & L Heat Treating & Grinding
Pfauter-Maag Cutting Tools
Phoenix Heat Treating Inc.
Progressive Steel Treating
Racine Heat Treating Co.
Rotation Products Corp.
S.K.S. Heat Treating Inc.
Scot Forge
Sonee Heat Treating Corp.
Specialty Steel Treating—Fraser
State Heat Treat Inc.
Sun Steel Treating
Suncoast Heat Treating—Orlando
Suncoast Heat Treating—Pompano Beach
Superior Metal Treating
Syracuse Heat Treating
T. N. Woodworth Inc.
Thermal Treatment Center
Thermo Electron Metal Treating Div.
Treat All Metals Inc.
Walker Heat Treating
Washington Metallurgical Services
Westside Flame Hardening
Wohlert Corp.

HOT OIL QUENCHING

ABS Metallurgical Processors Inc.
Alco Heat Treating Corp.
Alpha Heat Treaters Div.
American Heat Treating
Atmosphere Annealing Inc.
Beehive Heat Treating Inc.
Benedict-Miller Inc.
Bennett Heat Treating & Brazing Co.
Bodycote/Hinderliter Thermal Processing
Bomak Corp.
Burbank Steel Treating Inc.
Carolina Commercial Heat Treating
Century Sun Metal Treating
Certified Heat Treating Inc.
Certified Metal Craft Inc.
Cincinnati Gear Co.
Cincinnati Steel Treating
City Steel Treating Inc.
Cleveland Flame Hardening Co.
Commercial Steel Treating
Custom Heat Treating Co.
Detroit Steel Treating Co.
Disston Precision Inc.
Dixie Heat Treating Co.
Dixie Machine & Heat Treating Inc.
Drever Heat Treating
East Carolina Metal Treating Inc.
Eckel Heat Treat
Edwards Heat Treating
Elmira Heat Treating
Engineered Heat Treat Inc.
Erie Steel Treating Inc.
Euclid Heat Treating Co.
Feinblanking Ltd.
Fenton Heat Treating
Fox Steel Treating Co.
FPM Heat Treating—Elk Grove
FPM Ipsen Heat Treating
FPM Milwaukee
Franklin Steel Treating Co.
General Heat Treating
General Metal Heat Treating Inc.
Gibson Heat Treat Inc.
Hansen-Balk Steel Treating
Hauni Richmond Inc.
Heat Treat Corp. of America
Heat-Treating Inc.
Hi-Tech Steel Treating Inc.
HI TecMetal Group—Cleveland
Hinderliter Heat Treating Inc. —Tulsa
Horizon Steel Treating Inc.
Huron Metallurgical Inc.
Illiana Heat Treating Inc.
Induction Metal Treating Co.
Industrial Metal Treating
Industrial Steel Treating Co.
Industrial Steel Treating Inc.
Irwin Automation Inc.
Jasco Heat Treating Inc.
John V. Potero Co.
Kowalski Heat Treating Co.
Lexington Heat Treat Inc.
Lindberg Heat Treating Co.—New Berlin
Lindberg Heat Treating Co.—Racine
M & M Heat Treat
Magnum Metal Treating
Merit Gear Corp.
Metal Treating & Research
Metal Improvement Co.—Columbus
Metal Improvement Co.—McLean/Wichita
Metallurgical Inc.
Metallurgical Processing
Metals Engineering Inc.
Metals Technology
Metlab Co.
Metro Steel Treating
Met-Tek Inc.—Clackamas
Met-Tek Inc.—Racine
Mid-West Flame Hardening
Midwestern Machinery Co.
Modern Industries Inc.
Ohio Metallurgical Service
Paulo Products Co.—Birmingham
Paulo Products Co.—Nashville
Paulo Products Co.—St. Louis
Pennsylvania Metallurgical
Pitt-Tex Inc.
Progressive Steel Treating
Racine Heat Treating Co.
Rochester Steel Treating
S.K.S. Heat Treating Inc.
Sonee Heat Treating Corp.
Southeastern Heat Treating
Specialty Steel Treating—Farmington Hills
Specialty Steel Treating—Fraser
Sun Steel Treating
Suncoast Heat Treating—Orlando
Suncoast Heat Treating—Pompano Beach
Therm Tech of Waukesha
Thermal Treatment Center
Thermo Treaters Ltd.
Treat All Metals Inc.
Washington Metallurgical Services
Westside Flame Hardening

INDUCTION HARDENING

Advanced Heat Treating
Advanced Heat Treat Corp. —Monroe
Advanced Heat Treat Corp. —Waterloo
Ajax Magnethermic Corp.
Alco Heat Treating Corp.
Alpha Heat Treaters Div.
American Met. Treating Co.
American Met. Treating Inc.
Beehive Heat Treating Inc.
Benedict-Miller Inc.
Bennett Heat Treating & Brazing Co.
Bodycote/Hinderliter Thermal Processing
Braddock Metallurgical
Bucyrus International Inc.
Carolina Commercial Heat Treating
Caterpillar Industrial Products Inc.
Certified Heat Treating Inc.
Chicago Induction
Cincinnati Gear Co.
Cincinnati Steel Treating
Coleman Commercial Heat Treating
Commercial Induction
Contour Hardening Inc.
Dixie Machine & Heat Treating Inc.
Drever Heat Treating
East Carolina Metal Treating Inc.
Edwards Heat Treating
Elmira Heat Treating
Euclid Heat Treating Co.
Fairfield Mfg. Co.
Flame Metals Processing
Fluxtrol Manufacturing Inc.
Franklin Steel Treating Co.
Gear Company of America
General Heat Treating
Gibson Heat Treat Inc.
Good Earth Tools, Inc.
Hauni Richmond Inc.
Heat Treat Corp. of America
Heat-Treating Inc.
Hi-Tech Steel Treating Inc.
HI TecMetal Group—Cleveland
Hinderliter Heat Treating Inc.—Anaheim,
Hinderliter Heat Treating Inc.—Tulsa
Horizon Steel Treating Inc.
Illiana Heat Treating Inc.
Impact Strategies Inc.
Induction Services Inc.
Induction Metal Treating Co.
Induction Heat Treating
Inductoheat Inc.
Industrial Metal Treating
Industrial Steel Treating Co.
International Induction Inc.
Jasco Heat Treating Inc.
John V. Potero Co.
Lawrence Industries Inc.
Lexington Heat Treat Inc.
Lindberg Heat Treating Co. —Houston
Lindberg Heat Treating Co. —Melrose Park
Lindberg Heat Treating Co. —Racine
Lindberg Heat Treating Co. —St. Louis
Mannings U.S.A.
Master Heat Treating Inc.
Merit Gear Corp.
Metal Improvement Co.—McLean/Wichita
Metal Processing Co.
Metal Treaters Inc.
Metallurgical Inc.
Metals Engineering Inc.
Met-Tek Inc.—Clackamas
Met-Tek Inc.—Racine
Michigan Induction Inc.
Midland Metal Treating Inc.
Modern Industries Inc.
Molon Gear & Shaft
National Induction Heating
National Metal Processing
O & W Heat Treat Inc.
Ohio Metallurgical Service
Paulo Products Co. —Kansas City
Paulo Products Co. —Memphis
Paulo Products Co. —Nashville
Paulo Products Co. —St. Louis
Pennsylvania Metallurgical
Pitt-Tex Inc.
Precision Heat Treating
Racine Heat Treating Co.
Revas Engineering Co.
Roboduction Thermal Processing
S.K.S. Heat Treating Inc.
Southeastern Heat Treating
Specialty Heat Treating Inc. —Elkhart
Specialty Heat Treating Inc. —Grand Rapids
Specialty Heat Treating Inc. —Holland
State Heat Treat Inc.
Steel Treaters, Inc.
Steel Treating
Suncoast Heat Treating—Pompano Beach
Suncoast Heat Treating—Tampa
Superior Metal Treating
Syracuse Heat Treating
Thermal Braze Inc.
Thermal Treatment Center
Thermet Inc.
Thermo Electron Metal Treating Div.
Tocco, Inc.
Treat All Metals Inc.
Washington Metallurgical Services
Westside Flame Hardening
Wohlert Corp.
Zion Industries

ION NITRIDING

Advanced Metallurgical Technology
Advanced Heat Treat Corp. —Monroe
Advanced Heat Treat Corp. —Waterloo
AMT Monroe Inc.
Century Sun Metal Treating
Cincinnati Gear Co.
Fox Steel Treating Co.
FPM Heat Treating—Elk Grove
FPM Ipsen Heat Treating
Hansen-Balk Steel Treating
Hauni Richmond Inc.
HI TecMetal Group—Cleveland
Impact Strategies Inc.
Magnum Metal Treating Inc.
Progressive Engineering Co.
Solar Atmospheres Inc.
Sonee Heat Treating Corp.
Sun Steel Treating
Thermal Treatment Center

LASER HARDENING

Cincinnati Gear Co.
National Metal Processing
Weiss Industries Inc.

NITRIDING

Accurate Steel Treating
Albany Metal Treating
Alco Heat Treating Corp.
American Met. Treating Inc.
Benedict-Miller Inc.
Bennett Heat Treating & Brazing Co.
Bodycote/Hinderliter Thermal Processing
Braddock Metallurgical
Burbank Steel Treating Inc.
Cal-Doran Division
Caterpillar Industrial Products Inc.
Cincinnati Gear Co.
Cincinnati Steel Treating
City Steel Treating Inc.
Commercial Steel Treating
Custom Heat Treating Co.
Drever Heat Treating
Dynamic Metal Treating
East Carolina Metal Treating Inc.
Elmira Heat Treating
Engineered Heat Treat Inc.
Erie Steel Treating Inc.
Euclid Heat Treating Co.
Fairfield Mfg. Co.
Fox Steel Treating Co.
FPM Heat Treating—Elk Grove
FPM Ipsen Heat Treating
FPM Milwaukee
General Metal Heat Treating Inc.
Grand Rapids Heat Treating Co.
H & M Metal Processing
Hansen-Balk Steel Treating
HI TecMetal Group—Cleveland
Hinderliter Heat Treating Inc.—Anaheim
Hinderliter Heat Treating Inc.—Dallas
Hinderliter Heat Treating Inc.—Tarzana
Hinderliter Heat Treating Inc.—Tulsa
Horizon Steel Treating Inc.
Hydro-Vac
Illiana Heat Treating Inc.
Impact Strategies Inc.
Induction Metal Treating Co.
Industrial Metal Treating
Industrial Steel Treating
Jasco Heat Treating Inc.
Lake County Steel Treating
Lindberg Heat Treating Co. —Houston
Lindberg Heat Treating Co. —Melrose Park
Lindberg Heat Treating Co. —Racine
Lindberg Heat Treating Co. —St. Louis
Merit Gear Corp.
Metal Improvement Co.
Metal-Tec Heat Treating Inc.
Metallurgical Inc.
Metals Technology
Metlab Co.
Metro Steel Treating
Met-Tek Inc.—Clackamas
Modern Industries Inc.
Modern Steel Treating
Nitrex Metal Inc.
Nitro-Vac Heat Treating
Nitron Inc.
O & W Heat Treat Inc.
P & L Heat Treating & Grinding
Peters Heat Treating Inc.
Phoenix Heat Treating Inc.
Precision Heat Treating
Rochester Steel Treating
Rotation Products Corp.
Shore Metal Technology Inc.
Specialty Heat Treating Inc. —Elkhart
Specialty Heat Treating Inc. —Grand Rapids
Specialty Heat Treating Inc. —Holland
Specialty Steel Treating—Fraser
Steel Treaters, Inc.
Sun Steel Treating
Suncoast Heat Treating—Orlando
Suncoast Heat Treating—Pompano Beach
Suncoast Heat Treating—Tampa
Syracuse Heat Treating
T. N. Woodworth Inc.
Therm Tech of Waukesha
Thermal Treatment Center
Treat All Metals Inc.
Trutec Industries
Universal Heat Treating
Walker Heat Treating

NITROCARBURIZING

Alco Heat Treating Corp.
American Met. Treating Inc.
Benedict-Miller Inc.
Bennett Heat Treating & Brazing Co.
Bodycote/Hinderliter Thermal Processing
Carolina Commercial Heat Treating
Cincinnati Gear Co.
Cincinnati Steel Treating
City Steel Treating Inc.
Commercial Steel Treating
Dynamic Metal Treating
Erie Steel Treating Inc.
Euclid Heat Treating Co.
Fairfield Mfg. Co.
Flame Metals Processing
Fox Steel Treating Co.
FPM Heat Treating—Elk Grove
FPM Ipsen Heat Treating
FPM Milwaukee
Gear Company of America
Hansen-Balk Steel Treating
Hauni Richmond Inc.
Hinderliter Heat Treating Inc.—Anaheim
Hinderliter Heat Treating Inc.—Tarzana
Hinderliter Heat Treating Inc.—Tulsa
Illiana Heat Treating Inc.
Impact Strategies Inc.
Induction Metal Treating Co.
Industrial Steel Treating
Jasco Heat Treating Inc.
Lindberg Heat Treating Co. —Houston
Lindberg Heat Treating Co. —Melrose Park
Lindberg Heat Treating Co. —New Berlin
Lindberg Heat Treating Co. —Racine
Lindberg Heat Treating Co. —Rochester
Lindberg Heat Treating Co. —St. Louis
Merit Gear Corp.
Metallurgical Inc.
Metals Technology
Metlab Co.
Metro Steel Treating
Met-Tek Inc.—Clackamas
Metal-Tec Heat Treating
Modern Industries Inc.
Nitrex Metal Inc.
Paulo Products Co.—Birmingham
Paulo Products Co.—Kansas City
Paulo Products Co.—Memphis
Paulo Products Co.—Murfreesboro
Paulo Products Co.—Nashville
Paulo Products Co.—St. Louis
Pennsylvania Metallurgical
Peters Heat Treating Inc.
Phoenix Heat Treating Inc.
Rochester Steel Treating
Shore Metal Technology
Specialty Heat Treating Inc. —Athens
Specialty Heat Treating Inc. —Elkhart
Specialty Heat Treating Inc. —Grand Rapids
Specialty Heat Treating Inc. —Holland
Suncoast Heat Treating—Pompano Beach
Syracuse Heat Treating
Therm Tech of Waukesha
Thermal Treatment Center
Trutec Industries

NORMALIZING

ABS Metallurgical Processors Inc.
Accurate Steel Treating
Advanced Heat Treating Inc.

Advanced Metallurgical Technology
Advanced Thermal Technologies
Albany Metal Treating
Alco Heat Treating Corp.
Alliance Metal Treating
Alpha Heat Treaters Div.
American Brazing
American Heat Treating
American Met. Treating Inc.
Atmosphere Annealing Inc.
Beehive Heat Treating Inc.
Benedict-Miller Inc.
Bennett Heat Treating & Brazing Co.
Bodycote/Hinderliter Thermal Processing
Bomak Corp.
The Bowdil Co.
Braddock Metallurgical
Braddock Metallurgical Alabama
Brazing & Metal Treating —Cleveland
Brazing & Metal Treating of KY
Brazing & Metal Treating of MN
Brite Brazing
Burbank Steel Treating Inc.
Cal-Doran Division
Carolina Commercial Heat Treating
Caterpillar Industrial Products
Certified Metal Craft Inc.
Certified Heat Treating Inc.
Cincinnati Flame Hardening
Cincinnati Gear Co.
Cincinnati Steel Treating
City Steel Treating Inc.
Coleman Commercial Heat Treating
Commercial Induction
Commercial Steel Treating
Custom Heat Treating Co.
Detroit Steel Treating Co.
Diamond Heat Treating Co.
Disston Precision Inc.
Dixie Heat Treating Co.
Dixie Machine & Heat Treating Inc.
Drever Heat Treating
East Carolina Metal Treating Inc.
East-Lind Heat Treat
Eckel Heat Treat
Edwards Heat Treating
Elmira Heat Treating
Engineered Heat Treat Inc.
Erie Steel Treating Inc.
Euclid Heat Treating Co.
Fairfield Mfg. Co.
Feinblanking Ltd.
Fenton Heat Treating
Flame Metals Processing
Fox Steel Treating Co.
FPM Heat Treating— Elk Grove
FPM Ipsen Heat Treating
FPM Milwaukee
Franklin Steel Treating Co.
Gear Company of America
General Heat Treating Corp.
General Metal Heat Treating Inc.
Geo. H. Porter Steel Treating Co.
Gibson Heat Treat Inc.
Grand Rapids Heat Treating Co.
Hansen-Balk Steel Treating
Hauni Richmond Inc.
Heat Treat Corp. of America
Heat Treating Services
Heat-Treating Inc.
Hi-Tech Steel Treating Inc.
HI TecMetal Group— Cleveland
Hinderliter Heat Treating Inc.—Anaheim
Hinderliter Heat Treating Inc.—Dallas
Hinderliter Heat Treating Inc.—Tarzana
Hinderliter Heat Treating Inc.—Tulsa
Hitech Metallurgical Co.
Horizon Steel Treating Inc.
Horsburgh & Scott Co.
Hy-Vac Technologies Inc.
Hydro-Vac
Illiana Heat Treating Inc.
Impact Strategies Inc.
Induction Metal Treating Co.
Industrial Metal Treating
Industrial Steel Treating Co.
Industrial Steel Treating Inc.
Irwin Automation Inc.
Jasco Heat Treating Inc.
John V. Potero Co.
Kowalski Heat Treating Co.
Lake County Steel Treating
Lawrence Industries Inc.
Lexington Heat Treat Inc.
Lindberg Heat Treating Co. —Berlin
Lindberg Heat Treating Co. —Houston
Lindberg Heat Treating Co. —Melrose Park
Lindberg Heat Treating Co. —Racine
Lindberg Heat Treating Co. —St. Louis
M & M Heat Treat
Magnum Metal Treating
Master Heat Treating Inc.
Merit Gear Corp.
Metal Improvement Co. —Columbus
Metal Improvement Co. —Lafayette
Metal Improvement Co.— McLean/Wichita
Metal Methods
Metal Treating & Research
Metallurgical Inc.
Metals Engineering Inc.
Metals Technology
Metlab Co.
Metro Steel Treating
Met-Tek Inc.—Clackamas
Met-Tek Inc.—Racine
Midland Metal Treating Inc.
Midwestern Machinery Co.
Modern Industries Inc.
Modern Metal Processing
Mountain Metallurgical
National Broach
National Metal Processing
Nettleson Steel Treating
Nitro-Vac Heat Treating
O & W Heat Treat Inc.
Oakland Metal Treating Co.
Ohio Metallurgical Service
P & L Heat Treating & Grinding
Partek Laboratories Inc.
Paulo Products Co.— Birmingham
Paulo Products Co.— Kansas City
Paulo Products Co.— Memphis
Paulo Products Co.— Nashville
Paulo Products Co.— St. Louis
Pennsylvania Metallurgical
Peters Heat Treating Inc.
Phoenix Heat Treating Inc.
Pitt-Tex Inc.
Precision Heat Treating
Progressive Steel Treating
Racine Heat Treating Co.
Rochester Steel Treating
Rotation Products Corp.
S.K.S. Heat Treating Inc.
Scot Forge
Shore Metal Technology
Solar Atmospheres Inc.
Sonee Heat Treating Corp.
Southeastern Heat Treating
Specialty Heat Treating Inc. —Athens
Specialty Heat Treating Inc. —Elkhart
Specialty Heat Treating Inc. —Grand Rapids
Specialty Heat Treating Inc. —Holland
Specialty Steel Treating— Fraser
State Heat Treat Inc.
Steel Treaters, Inc.
Sun Steel Treating
Suncoast Heat Treating— Orlando
Suncoast Heat Treating— Pompano Beach
Suncoast Heat Treating— Tampa
Superior Metal Treating
Syracuse Heat Treating
T. N. Woodworth Inc.
Therm Tech of Waukesha
Thermal Metal Treating
Thermal Treatment Center
Thermo Electron Metal Treating Div.
Thermo Treaters Ltd.
TracTech
Treat All Metals Inc.
Trojan Heat Treat Inc.
Universal Heat Treating
Vacu Braze
Walker Heat Treating
Wall Colmonoy Corp.
Washington Metallurgical Services
Weiss Industries Inc.
Wohlert Corp.

PLASMA CARBURIZING

Cincinnati Gear Co.
HI TecMetal Group— Cleveland

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Burbank Steel Treating Inc.
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Kowalski Heat Treating Co.
Lindberg Heat Treating Co. —Racine
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Metallurgical Inc.
Metals Technology
Metlab Co.
Mountain Metallurgical
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Roboduction Thermal Processing
Specialty Steel Treating— Farmington Hills
Specialty Steel Treating— Fraser
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Engineered Heat Treat Inc.
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H & M Metal Processing
HI TecMetal Group— Cleveland
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Induction Metal Treating Co.
Jasco Heat Treating Inc.
Lake County Steel Treating
Lexington Heat Treat Inc.
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Lindberg Heat Treating Co —Racine
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Nitro-Vac Heat Treating
O & W Heat Treat Inc.
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Trutec Industries
Walker Heat Treating
Wear-Ever Surface Treating
Weiss Industries Inc.

SINTERING

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American Brazing
Benedict-Miller Inc.
Bennett Heat Treating & Brazing Co.
Certified Metal Craft Inc.
Cincinnati Gear Co.
Fluxtrol Manufacturing Inc.
Hinderliter Heat Treating Inc.—Tarzana
Hitech Metallurgical Co.
HiTech Aero
HTG Aerobraze
Hy-Vac Technologies Inc.
Hydro-Vac
Illiana Heat Treating Inc.
Induction Metal Treating Co.
Metal Improvement Co.— McLean/Wichita
Metals Technology
Modern Metal Processing
Pennsylvania Metallurgical
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Specialty Heat Treating Inc. —Athens
Specialty Heat Treating Inc. —Elkhart
Specialty Heat Treating Inc. —Grand Rapids
Specialty Heat Treating Inc. —Holland
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Suncoast Heat Treating— Pompano Beach
Syracuse Heat Treating
Walker Heat Treating

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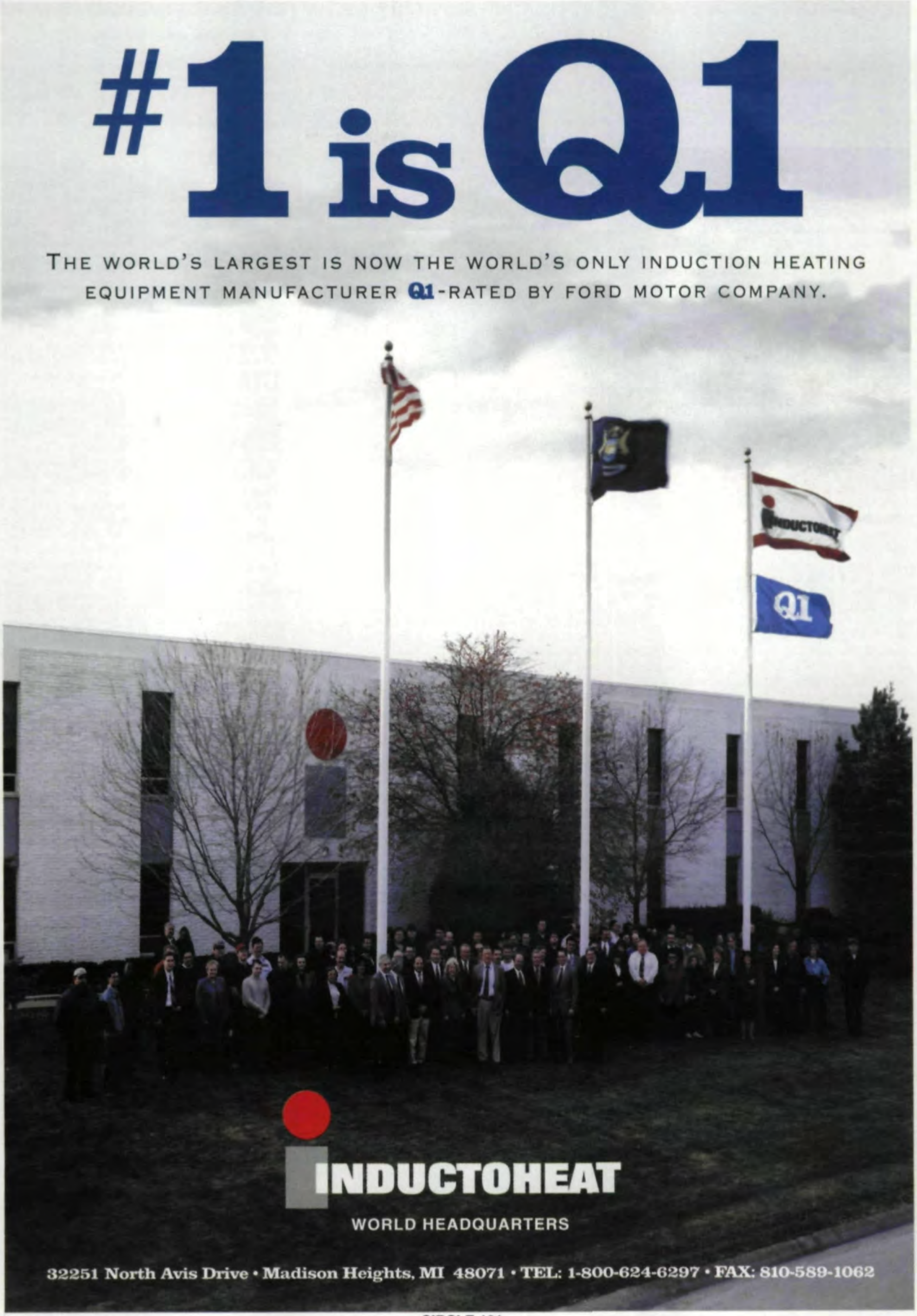

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Specialty Heat Treating Inc.—Athens
Specialty Heat Treating Inc.—Elkhart
Specialty Heat Treating Inc.—Grand Rapids
Specialty Heat Treating Inc.—Holland
Specialty Steel Treating—Farmington Hills
Specialty Steel Treating—Fraser
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Steel Treaters, Inc.
Steel Treating
Sun Steel Treating
Suncoast Heat Treating—Orlando
Suncoast Heat Treating—Pompano Beach
Suncoast Heat Treating—Tampa
Superior Metal Treating
Syracuse Heat Treating
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Therm Tech of Waukesha
Thermal Metal Treating
Thermal Treatment Center
Thermet Inc.
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Tocco, Inc.
TracTech
Treat All Metals Inc.
Trutec Industries
Vacu Braze
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Advanced Heat Treating Inc.—*Steam treating*
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Alpha Heat Treaters—*Black oxiding*
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American Metal Treating Inc.—6-bar vacuum processing
AP Westshore—*Carbo austempering*
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Flame Hardening Co. of California—*On-site*
Fox Steel Treating Co.—*Select hole quenching*
FPM Ipsen Heat Treating—*Blast cleaning*
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Hinderliter Heat Treating Inc.—Anaheim—*Age hardening, Kool kase "FNC"*
Hinderliter Heat Treating Inc.—Dallas—*Vacuum processes*
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Lindberg Heat Treating Co.—Rochester—*Boronizing*
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- ❑ Plain Bearings
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  - ❑ Personal Computers
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  - ❑ Displays
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- ❑ Gear Reducers
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While we have made every effort to ensure that company names and addresses are correct, we cannot be held responsible for errors of fact or omission. If your company was not listed in this directory, and you would like to be included in 1998, please call 847-437-6604.

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Fax: 817-921-5372

Advanced Thermal Technologies, Inc.
P.O. Box 875
Kendallville, IN 46755
219-347-1203
Fax: 219-347-3568

Ajax Magnethermic Corp.
1745 Overland Ave.
Warren, OH 44483
216-372-8511
Fax: 216-372-8608

Albany Metal Treating
400 S. Dowden Ave.
Albany, IN 47320
317-789-6470
Fax: 317-789-6839

Alco Heat Treating Corp.
130 Verdi St.
Farmingdale, NY 11735
516-249-1660
Fax: 516-249-7889

Alliance Metal Treating
P.O. Box 68
Eola, IL 60519
630-851-5880
Fax: 630-851-0733

Allread Products
22 S. Main St.
Terryville, CT 06786
860-589-3566
Fax: 860-589-3566

Alpha Heat Treaters
P.O. Box 23
York County Industrial Park
Emigsville, PA 17318
717-767-6757
Fax: 717-764-0129

American Brazing
Div. of Paulo Products Co.
4428 Haman Pkwy.
Cleveland, OH 44094
216-946-5900
Fax: 216-946-3091

American Heat Treating
1346 Morris Ave.
Dayton, OH 45408
937-461-1121
Fax: 937-461-1166
E-mail: wilcher@ibm.net

American Metal Processing Co.
22720 Nagel
Warren, MI 48089
810-757-7337
Fax: 810-757-8232

American Metal Treating Co.
1043 E. 62nd St.
Cleveland, OH 44103
216-431-4492
Fax: 216-431-1508

American Metal Treating Inc.
500 Manley St.
High Point, NC 27260
910-889-3277
Fax: 910-889-7950

AMT Monroe Inc.
615 Harbor Ave.
Monroe, MI 48162-5601
313-242-1733
Fax: 313-242-0993
E-mail: TraCombs@aol.com

AP Westshore
4000 State Hwy. 91
Oshkosh, WI 54904
414-235-2001
Fax: 414-235-2701

Applied Cryogenics Inc.
1191 Chestnut St.
Newton, MA 02164
617-969-6490
Fax: 617-969-6266
E-mail: nsengine@aol.com

Applied Process Inc.
12238 Newburgh Rd.
Livonia, MI 48150
313-464-2030
Fax: 313-464-6314

Atmosphere Annealing Inc.
1300 Industrial Dr.
N. Vernon, IN 47265
812-346-1275
Fax: 812-346-4534

B

Beehive Heat Treating Inc.
132 Water St.
S. Norwalk, CT 06854
203-866-1635
Fax: 203-855-9327

Benedict-Miller Inc.
P.O. Box 912
Lyndhurst, NJ 07071-0912
201-438-3000
Fax: 201-438-3137
E-mail: info@benedict-miller.com

Bennett Heat Treating & Brazing Co.
690 Ferry St.
Newark, NJ 07105
201-589-0590
Fax: 201-589-6518

Bodycote/Hinderliter Thermal Processing
2005 Montgomery St.
Fort Worth, TX 76107
817-737-6651
Fax: 817-377-9601

Bomak Corp.
Six Jefferson Ave.
Woburn, MA 01801
617-935-4100
Fax: 617-932-0542
E-mail: bomak@industry.net

Bonal Technologies Inc.
21178 Bridge St.
Southfield, MI 48034
810-353-2041
Fax: 810-353-2028

The Bowdil Co.
2030 Industrial Place S.E.
Canton, OH 44707
216-456-7176
Fax: 216-456-4625

Braddock Metallurgical
14600 Duval Place West
Jacksonville, FL 32218
904-741-4777
Fax: 904-741-4813

Braddock Metallurgical Alabama
3008 Red Morris Pkwy.
Anniston, AL 36207
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Brazing & Metal Treating
Div. of HI TecMetal Group
1101 E. 55th St.
Cleveland, OH 44103
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Fax: 216-881-6811

Brazing & Metal Treating of KY
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1379 Jamike Ln.
Erlanger, KY 41018
606-647-1115
Fax: 606-647-1165

Brazing & Metal Treating of MN
2501 Hi Tec Avenue
Albert Lea, MN 56007
(507) 373-9630
Fax: 507) 373-3771

Brite Brazing
5476 Lake Ct.
Cleveland, OH 44114
216-881-8100
Fax: 216-881-6811

Brite Metal Treating Inc.
8640 Bessemer Ave.
Cleveland, OH 44127
216-341-2266
Fax: 216-341-4273

Bucyrus International, Inc.
1100 Milwaukee Ave.
S. Milwaukee, WI 53172
414-768-4000
Fax: 414-768-5221

Burbank Steel Treating
415 S. Varney St.
Burbank, CA 91502
213-849-7480
Fax: 213-849-3739

C

Cal-Doran Division
1804 Cleveland Ave.
National City, CA 91950
619-477-2121
Fax: 619-477-3219

California Surface Hardening Inc.
P.O. Box 736
Compton, CA 90223
310-608-5576
Fax: 310-608-2072

Calumet Surface Hardening
6805 McCook Ave.
Hammond, IN 46323
219-844-5600
Fax: 219-845-1046

Carolina Commercial Heat Treating
P.O. Drawer 1368
Fountain Inn, SC 29644
803-862-3516
Fax: 803-862-4466

Caterpillar Industrial Products Inc.
100 N.E. Adams St.
Peoria, IL 61629-4375
309-675-5451
Fax: 309-675-6457
E-mail: catgears@cat.e-mail.com

Century Sun Metal Treating
2411 Aero Park Ct. West
Traverse City, MI 49686
616-941-7800
Fax: 616-941-2346

Certified Heat Treating Inc.
1200 E. First St.
Dayton, OH 45403
937-461-2844
Fax: 937-461-4519

Certified Metal Craft Inc.
877 Vernon Way
El Cajon, CA 92020
619-593-3636
Fax: 619-593-3635
E-mail: cmci@certifiedmetalcraft.com

Chicago Flame Hardening Co.
5200 Railroad Ave.
East Chicago, IN 46312
219-397-6475
Fax: 219-397-4029

Chicago Induction
3305 W. Harrison
Chicago, IL 60624
773-826-1213
Fax: 773-826-1178

Cincinnati Flame Hardening Co.
375 Security Dr.
Fairfield, OH 45014
513-942-1400
Fax: 513-942-1414

Cincinnati Gear Co.
5657 Wooster Pike
Cincinnati, OH 45227
513-271-2700
Fax: 513-271-0049

Cincinnati Steel Treating
5701 Mariemont Ave.
Cincinnati, OH 45227
513-271-3173
Fax: 513-271-3510

City Steel Treating Inc.
13007 Los Nietos Rd.
Santa Fe Springs, CA 90670
310-941-1246
Fax: 310-941-1247

Cleveland Flame Hardening Co.
935 West Ave.
Cleveland, OH 44113
216-241-1333
Fax: 216-241-3946

Coleman Commercial Heat Treating
2867 Hangar Rd.
Memphis, TN 38118
901-366-0204
Fax: 901-366-0770

Commercial Induction
11116 Avon Ave.
Cleveland, OH 44105
216-881-8100
Fax: 216-881-6811

Commercial Steel Treating Corp.
31440 Stephenson Hwy.
Madison Heights, MI 48071
248-588-3300
Fax: 248-588-3300

Contour Hardening Inc.
7898 Zionsville Rd.
Indianapolis, IN 46268
317-876-1530
Fax: 317-879-2484

Cooperheat Inc.
410 Walcot Rd.
Westlake, LA 70669
318-882-1800
Fax: 318-882-1821

Custom Heat Treating Co.
4117 Meadow Lane
Bessier City, LA 71111
318-742-6662
Fax: 318-742-4135

D

Delphi Engineering & Contracting Inc.
131 Blackwood Barnsboro Rd.
Sewell, NJ 08080
609-468-4839
Fax: 609-228-9354

Detroit Flame Hardening
17644 Mt. Elliott
Detroit, MI 48212
313-891-2936
Fax: 313-891-3150

Detroit Steel Treating Co.
1631 Highwood East
Pontiac, MI 48340
810-334-7436
Fax: 810-334-7891

Diamond Heat Treating Co.
5660 W. Jefferson
Detroit, MI 48209
313-843-6570
Fax: 313-842-0280

Disston Precision Inc.
6795 State Rd.
Philadelphia, PA 19135
215-338-1200
Fax: 215-338-7060

Dixie Heat Treating Co.
425 County Road 30
Florence, AL 35630
205-767-1752
Fax: 205-767-1573

Dixie Machine & Heat Treating Inc.
711 E. Franklin
Gastonia, NC 28054
704-864-5454
Fax: 704-864-5456

Drever Heat Treating
6201 Robinwood Rd.
Baltimore, MD 21225
410-789-6160
Fax: 410-789-6659

Dynamic Metal Treating
7784 Ronda Dr.
Canton Township, MI 48187
313-459-8022
Fax: 313-459-7863

E

East Carolina Metal Treating Inc.
1010 S. Saunders St.
Raleigh, NC 27603
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Fax: 810-585-3045

Eckel Heat Treat
8035 W. County Rd.
Odessa, TX 79764
915-362-4336
Fax: 915-362-1827

Edwards Heat Treating
642 McCormick St.
San Leandro, CA 94577
510-638-4140
Fax: 510-638-1438

Elmira Heat Treating Inc.
407 S. Kinyon St.
Elmira, NY 14904
607-734-1577
Fax: 607-732-2572

Engineered Heat Treat Inc.
31271 Stephenson Hwy.
Madison Heights, MI 48071
810-588-5141
Fax: 810-588-6533

Erie Steel Treating Inc.
5540 Jackman Rd.
Toledo, OH 43613
419-478-3743
Fax: 419-478-0109
E-mail: eriesteel@toledolink.com

Euclid Heat Treating Co.
1408 E. 222nd St.
Euclid, OH 44117
216-481-8444
Fax: 216-481-3473

F

Fairfield Mfg. Co.
P.O. Box 7940
Lafayette, IN 47903
317-474-3128
Fax: 317-477-7342

Feinblanking Ltd.
9461 LeSaint Dr.
Fairfield, OH 45014
513-860-2100
Fax: 513-870-5146

Fenton Heat Treating
3605 Homestead Duquesne
West Mifflin, PA 15122
412-466-3960
Fax: 412-466-7931

Flame Hardening Co. of California
6057 State St.
Huntington Park, CA 90255
213-589-5066
Fax: 213-589-5403

Flame Metals Processing Corp.
7317 W. Lake St.
Minneapolis, MN 55426-4396
612-929-7815
Fax: 612-925-0572

Fluxtrol Manufacturing Inc.
1388 Atlantic Blvd.
Auburn Hills, MI 48326
810-393-2000
Fax: 810-393-0277

Fox Steel Treating Co.
2220 Gratiot Ave
Detroit, MI 48207
888-818-0808
Fax: 313-568-0148

FPM Heat Treating
1501 S. Lively Blvd.
Elk Grove, IL 60007
847-228-2525
Fax: 847-228-9887

FPM Ipsen Heat Treating
666 Route 20
Cherry Valley, IL 61016
815-332-4961
Fax: 815-332-3022

FPM Milwaukee
8201 W. Calumet Rd.
Milwaukee, WI 53223
414-355-7900
Fax: 414-355-4719

Franklin Steel Treating Co.
1070 Ridge St.
Columbus, OH 43215-1190
614-488-2556
Fax: 614-486-9489

G

Gear Company of America
14300 Corgin Ave.
Cleveland, OH 44111
216-671-5400
Fax: 216-671-5825

General Heat Treating Corp.
6770 Benedict Rd.
East Syracuse, NY 13057
315-437-1117
Fax: 315-433-1194

General Metal Heat Treating Inc.
941 Addison Rd.
Cleveland, OH 44103
216-391-0886
Fax: 216-391-0890

Geo. H. Porter Steel Treating Co.
1273 E. 55th St.
Cleveland, OH 44103
216-431-6601
Fax: 216-431-0009
E-mail: treating@aol.com

Gibson Heat Treat Inc.
2037 Brookside Ln.
Kingsport, TN 37660
800-359-5542
Fax: 615-246-8629

The Gleason Works
1000 University Ave.
Rochester, NY 14692
716-461-8051
Fax: 716-461-1492

Global Heat Treat Inc.
54 Route 130
Yardville, NJ 08620
609-298-1200
Fax: 609-298-7958

Good Earth Tools, Inc.
Four Industrial Drive
Crystal City, MO 63019
314-937-3330
Fax: 314-937-3386
E-mail: wilkip@aol.com

Grand Rapids Heat Treating Co.
3832 Buchanan S.W.
Wyoming, MI 49548
616-243-0111
Fax: 616-243-4080

H

H & M Metal Processing
1850 Front St.
Cuyahoga Falls, OH 44221
800-304-2636
Fax: 216-928-5472

Hansen-Balk Steel Treating Co.
1230 Monroe N.W.
Grand Rapids, MI 49505
616-458-1414
Fax: 616-458-6868

Hauni Richmond Inc.
2800 Charles City Rd.
Richmond, VA 23231
804-222-5262
Fax: 804-236-5284

Heat Treat Corp. of America
1120 W. 119th St.
Chicago, IL 60643
773-264-1234
Fax: 773-264-4321

Heat-Treating Inc.
1807 W. Pleasant St.
Springfield, OH 45506
513-325-3121
Fax: 513-325-3117

Heat Treating Services Corp.
217 Central Ave.
Pontiac, MI 48341
810-858-2230
Fax: 810-858-2242

HI TecMetal Group
1101 E. 55th St.
Cleveland, OH 44103
216-881-8100
Fax: 216-881-6811

Hi-Tech Steel Treating Inc.
2720 Roberts St.
Saginaw, MI 48601
800-835-8294
Fax: 517-753-2368

Hinderliter Heat Treating Inc.
1025 N. Pauline St.
Anaheim, CA 92801
714-776-8312
Fax: 714-776-8446

Hinderliter Heat Treating Inc.
10530 Doric St.
Dallas, TX 75220
214-357-0394
Fax: 214-357-0195

Hinderliter Heat Treating Inc.
18600 Oxnard St.
Tarzana, CA 91356
818-344-0216
Fax: 818-609-9372

Hinderliter Heat Treating Inc.
1240 N. Harvard
Tulsa, OK 74115
918-834-0855
Fax: 918-836-4162

HiTech Aero
34800 Lakeland Blvd.
Eastlake, OH 44095
216-881-8100
Fax: 216-881-6811

Hitech Metallurgical Co.
7384 Trade St.
San Diego, CA 92121
619-586-7272
Fax: 619-586-7598
E-mail: aajb8@prodigy.com

Horizon Steel Treating Inc.
231 Jandus Rd.
Cary, IL 60013
847-639-4030
Fax: 847-639-1981

Horsburgh & Scott Co.
5114 Hamilton Ave.
Cleveland, OH 44114
216-431-3900
Fax: 216-432-5850

Houston Flame Hardening
215 N. Jenkins St.
Houston, TX 77003
713-926-8017
Fax: 713-926-8316

HTG Aerobraze
940 Redna Terrace
Woodlawn, OH 45215
513-772-1461
Fax: 513-772-0149

Huron Metallurgical Inc.
12611 Haggerty Rd.
Belleville, MI 48111
313-699-6861
Fax: 313-699-6971

Hy-Vac Technologies Inc.
15701 Glendale Ave.
Detroit, MI 48227
313-838-2800
Fax: 313-838-2802

Hydro-Vac
1177 Marquette St.
Cleveland, OH 44114
216-881-8100
Fax: 216-881-6811

I

Illiana Heat Treating Inc.
P.O. Box 1466
Danville, IL 61834-1466
217-443-5418
Fax: 217-443-5419

Impact Strategies Inc.
P.O. Box 5317
Clinton, NJ 08809
908-730-9163
Fax: 908-730-8334

Induction Heat Treating Corp.
775 Tek Drive
Crystal Lake, IL 60014
815-477-7788
Fax: 815-477-7784
E-mail: ihtcorp@mc.net

Induction Metal Treating Co.
P.O. Box 748
York, SC 29745
803-684-2548
Fax: 803-684-9387

Induction Services Inc.
24800 Mound Rd.
Warren, MI 48001
810-754-1640
Fax: 810-754-5402

Inductoheat Inc.
32251 N. Avis Dr.
Madison Heights, MI 48071
810-585-9393
Fax: 810-585-0429
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402 E. Front St.
Wilmington, DE 19801
302-656-1677
Fax: 302-656-4370

Industrial Steel Treating Co.
613 Carroll St.
Jackson, MI 49202
517-787-6312
Fax: 517-787-5441

Industrial Steel Treating Inc.
3370 Benedict Way
Huntington Park, CA 90255
213-583-1231
Fax: 213-589-1255
E-mail: BELL@mail.idt.net

International Induction Inc.
1504 10th Ave.
Port Huron, MI 48060
810-984-3803
Fax: 810-984-3801

Irwin Automation Inc.
715 Cleveland St.
Greensberg, PA 15601
412-834-7160
Fax: 412-834-4670
E-mail: iai@westol.com

J

Jasco Heat Treating Inc.
820 Turk Hill Road
Fairport, NY 14450
716-388-1040
Fax: 716-377-7226

JCS Engineering & Development
211 W. 22nd St.
Hialeah, FL 33010
305-888-7911
Fax: 305-888-9913

John V. Potero Co.
4225-35 Adams Ave.
Philadelphia, PA 19124
215-533-8988
Fax: 215-533-9210

K

Kowalski Heat Treating Co.
3611 Detroit Ave.
Cleveland, OH 44113
888-KHT-HEAT
Fax: 216-631-8921
E-mail: khtheat@aol.com

L

Lake County Steel Treating
960 Anita
Antioch, IL 60002
847-375-8174
Fax: 847-395-7638

Lawrence Industries Inc.
2720 S. Cornhusker Ave.
Hastings, NE 68901
402-463-3158
Fax: 402-463-4128

Lexington Heat Treat Inc.
657 E. 7th St.
Lexington, KY 40505
606-231-0236
Fax: 606-211-9464

Lindberg Heat Treating Co.
675 Christian Lane
Berlin, CT 06037
860-225-7691
Fax: 860-229-3891
E-mail: berlin@lindbergct.com

Lindberg Heat Treating Co.
8316 E. Freeway
Houston, TX 77229
713-672-6601
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Melrose Park, IL 60160
708-344-4080
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16167 W. Rogers Dr.
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Lindberg Heat Treating Co.
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Lindberg Heat Treating Co.
650 E. Taylor Ave.
St. Louis, MO 63147
314-382-6200
Fax: 314-382-3741

M

M & M Heat Treat
1309 Main St.
Essexville, MI 48732
517-893-3677
Fax: 517-893-4423

Magnum Metal Treating
4400 N. Frazier St.
Conroe, TX 77303
713-353-8615
Fax: 409-856-6607

Mannings U.S.A.
53 Abbett Ave.
Morristown, NJ 07960
800-447-4473
Fax: 201-984-5833

Master Heat Treating Inc.
51 Brown Ave.
Springfield, NJ 07081
201-379-7320
Fax: 201-379-3214

Merit Gear Corp.
810 Hudson St.
Antigo, WI 54409
800-756-3748
Fax: 715-627-2558

Metal Improvement Co.
1515 Universal Rd.
Columbus, OH 43207
614-444-1181
Fax: 614-444-0421

Metal Improvement Co.
116 Southpark Rd.
Lafayette, LA 70508
318-837-9273
Fax: 318-837-2505

Metal Improvement Co.
1618 Ida
Wichita, KS 67211
316-267-8201
Fax: 316-267-5735

Metal Improvement Co.
1019 S. McLean Blvd.
Wichita, KS 67213
316-267-8201
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Metal Methods
260 Chenault Rd.
Frankfort, KY 40601
502-695-5700
Fax: 502-695-5702

Metal Processing Co.
3257 N. 32nd St.
Milwaukee, WI 53216
414-871-9010
Fax: 414-871-3910

Metal-Tec Heat Treating Inc.
4723 W. Station St.
Eight Mile, AL 36613
334-456-1133
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Metal Treaters Inc.
859 N. Prior
St. Paul, MN 55104
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Metal Treating & Research
1680 E. 69th Ave.
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Metallurgical Inc.
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Metallurgical Processing Inc.
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Metals Engineering Inc.
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Metals Technology Corp.
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Carol Stream, IL 60188
630-221-2500
Fax: 630-221-0120

Metlab Co.
1000 E. Mermaid Ln.
Glenside, PA 19038
215-233-2600
Fax: 215-233-5653

Metro Steel Treating
9792 Grinnell
Detroit, MI 48213
313-921-5522
Fax: 313-921-0363

Met-Tek Inc.
15651 S.E. 125th St.
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Fax: 503-655-6898

Met-Tek Inc.
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Mid-West Flame Hardening Inc.
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Midwestern Machinery Co.
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Fax: 810-754-5195

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Fax: 810-478-9626

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34501 Commerce Rd.
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E-mail: rharvey@iserv.net

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810-585-6400

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Fax: 206-623-5045

Wear-Ever Surface Treating Corp.
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Fax: 810-778-2393

Weiss Industries Inc.
Metallurgical Services Division
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Mansfield, OH 44901
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Fax: 419-526-1158

Western Stress Inc.
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Richmond, VA 23237
804-271-5447
Fax: 804-271-7692

Westside Flame Hardening Inc.
38200 Executive Dr. North
Westland, MI 48185
313-729-1665
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Wohlert Corp.
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Zion Industries
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Meshing of a Spiral Bevel Gear Set With 3-D Finite Element Analysis

George D. Bibel & Robert Handschuh

Abstract

Recent advances in spiral bevel gear geometry and finite element technology make it practical to conduct a structural analysis and analytically roll the gear set through mesh. With the advent of user-specific programming linked to 3-D solid modelers and mesh generators, model generation has become greatly automated. Contact algorithms available in general purpose finite element codes eliminate the need for the use and alignment of gap elements. Once the gear set is placed in mesh, user subroutines attached to the FE code easily roll it through mesh. The method is described in detail. Preliminary results for a gear set segment showing the progression of the contact line load is given as the gears roll through mesh.

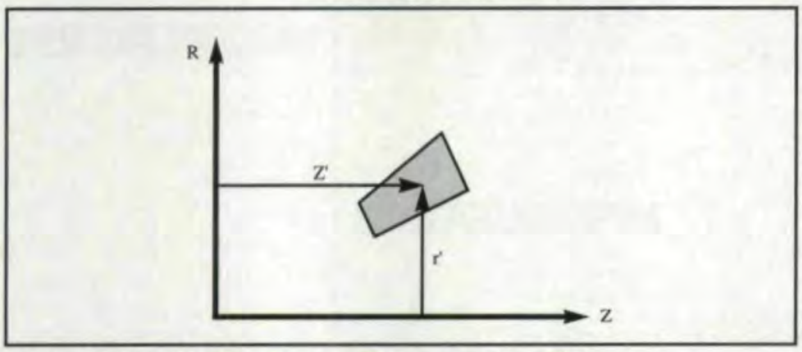

Fig. 1 — Axial and radial projections of gear surface into RZ plane.

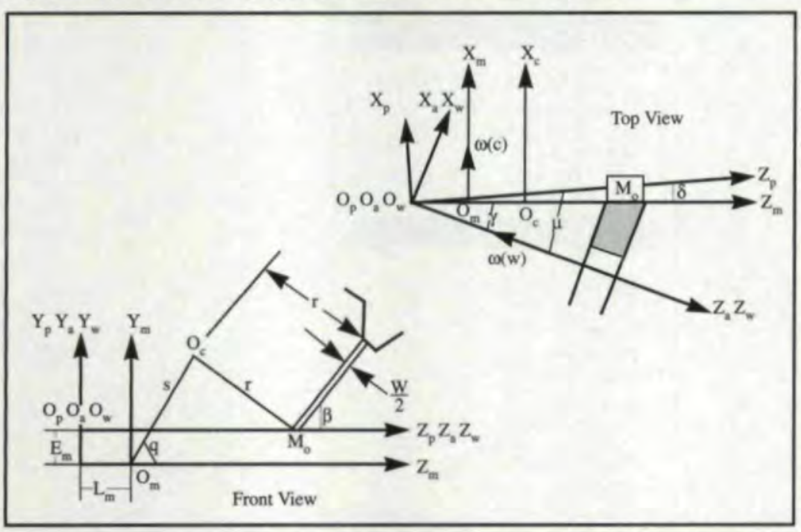

Fig. 2 — Coordinate system orientation to generate a right-hand gear surface (ϕ_c = 0 shown here).

Introduction

One of the most complex and highly loaded components in a helicopter is the main rotor transmission (Cormier, 1979). One of the critical components of the transmission is the spiral bevel gear mesh.

The designer is faced with tradeoffs between weight and reliability. Weight reduction results in increased flexibility and deflection of the teeth and rim. Deflection of the gear creates a departure from the expected contact found by rolling the gears. These deflections cause the contact zone to shift. The shift in contact can dramatically increase contact and tooth bending stresses with a corresponding reduction of component life.

The contact ellipse and localized stress distribution have been historically analyzed with Hertzian theory developed for ball and roller bearing elements (Coy et al., 1985). This theory considers the contact stresses for two general surfaces with direct bearing load. Gear teeth are not loaded directly. The load is transmitted through flexible teeth connected to flexible rims. The tooth and rim flexing of the gear and pinion will greatly affect the location and shape of the contact zone, load sharing between teeth and the contact stress distribution. These factors will in turn affect fatigue life, noise and vibration, thermal degradation and hydrodynamic action of the lubricant. These issues are also important design parameters for spiral bevel gearing in ground vehicles.

Considerable work has been completed to automate 3-D modeling of spiral bevel gears. Fundamental to this work is an understanding of the gear surface geometry. Litvin (1989) and Litvin & Tsung (1989) presented the theory of spiral bevel gear generation and design. Handschuh and Litvin (1991) extended this analysis to the mathematical description of the gear tooth surfaces.

Bibel et al. (1993, 1994) began the automation of the analysis with model development software that creates input for the 3-D solid modeler

(PATRAN) and the finite element code NASTRAN. The finite element modeling done with NASTRAN utilized gap elements. The analysis was greatly simplified by using the contact algorithm in the finite element code MARC (Bibel et al. 1994). A user subroutine compiled with the MARC input file rotates the gear set through mesh.

This work is being extended into a series of programs that receive machine tool settings as input and create 3-D contact analysis of spiral bevel gears rolling through mesh.

Surface Geometry

The most difficult task associated with 3-D modeling of spiral bevel gears in mesh is an accurate description of the gear surface geometry. The surface of a generated gear is an envelope to the family of surfaces of the head cutter. In other words, the points on the generated tooth surface are points of tangency to the cutter surface during manufacture.

The conditions necessary for envelope existence are given kinematically by the equation of meshing. The equation is stated as follows: The normal of the generating surface must be perpendicular to the relative velocity between the cutter and the gear tooth surface. This is given mathematically as

$$\mathbf{n} \bullet \mathbf{V} = 0$$

where **n** is the normal vector and **V** is the relative velocity.

The equation of meshing for straight-sided cutters with a constant ratio of roll between the cutter and workpiece is given in Litvin et al. (1989 and 1991) as

$$\begin{aligned}(u - r\cot\psi\cos\psi)\cos\gamma\sin\tau + \\ s[(m_{cw} - \sin\gamma)\cos\psi\sin\theta \mp \cos\gamma\sin\psi(q - \phi_c)] \\ \mp E_m(\cos\gamma\sin\psi + \sin\gamma\cos\psi\cos\tau) - \\ L_m\sin\gamma\cos\psi\sin\tau = 0 \quad \text{Eq. 1}\end{aligned}$$

where $\tau = (\theta \mp q \pm \phi_c)$

γ = the root angle of the component being manufactured.

u, θ locate a point on the cutting head as given in Handschuh et al., 1991.

ϕ_c = the cradle orientation.

ψ = the blade angle.

r = the radius of the cutter.

L_m = the vector sum, a machine tool setting described in Handschuh et al., 1991.

E_m = machine offset, a machine tool setting described in Handschuh et al., 1991.

s = cradle to cutter distance.

q = cradle angle.

m_c = ratio of angular velocity of the cradle to the workpiece.

All of the above terms, except u, θ and ϕ_c, are known machine tool settings for a given gear set design. These three terms can be numerically solved for if two additional equations are identified.

The points on the gear surfaces found by solving the equation of meshing must also satisfy the axial and radial location of a projection into the RZ plane that identifies the generated workpiece. This is satisfied by the following:

$$Z_w - Z' = 0 \quad \text{Eq. 2}$$

$$r' - (X_w^{\,2} + Y_w^{\,2})0.5 = 0 \quad \text{Eq. 3}$$

where X_w, Y_w and Z_w are coordinates of a point on the workpiece in the workpiece coordinate system, and Z' and r' are the axial and radial projections into the RZ plane of the workpiece as shown in Fig. 1.

Equations 1, 2 and 3 can be solved with a numerical iterative procedure. Equation 1 is given in terms of cutting head coordinates **u**, θ and ϕ_c, whereas Equations 2 and 3 are given in terms of workpiece coordinates X_w, Y_w and Z_w.

A point on the head cutter $\mathbf{r_c}$ (written in terms of u, θ and ϕ_c) must be transformed into a point on the workpiece $\mathbf{r_w}$ (written in terms of X_w, Y_w and Z_w with the following series of homogeneous coordinate transformations.

$$\mathbf{r_w} = [\mathbf{M_{wa}}][\mathbf{M_{ap}}][\mathbf{M_{pm}}][\mathbf{M_{ms}}][\mathbf{M_{sc}}]\mathbf{r_c} \quad \text{Eq. 4}$$

where $[\mathbf{M_{wa}}]$ $[\mathbf{M_{ap}}]$ $[\mathbf{M_{pm}}]$ $[\mathbf{M_{ms}}]$ and $[\mathbf{M_{sc}}]$ are a series of matrix coordinate transformations given in Litvin, 1989, Litvin et al., 1989 and Handschuh et al., 1991.

These coordinate systems are described as follows and shown in Fig. 2 for a right-hand gear surface. The head-cutter coordinate system $\mathbf{S_c}$ is rigidly connected to the cradle coordinate systems $\mathbf{S_s}$. $\mathbf{S_s}$ rotates about fixed coordinate system $\mathbf{S_m}$ attached to the machine frame. Coordinate system $\mathbf{S_p}$ orients the pitch apex of the gear being manufactured. The common origin for coordinate systems $\mathbf{S_p}$ and $\mathbf{S_a}$ locates the apex of the gear under consideration with respect to system $\mathbf{S_m}$. The final transformation is from coordinate system $\mathbf{S_a}$ to $\mathbf{S_w}$, which is fixed to the component being manufactured.

A computer program was written using the above solution technique. This program receives machine tool settings and basic gear geometry as input and creates an output file containing the coordinates of surface points for the gear and pinion. The output from this program is read by a second computer program. This program uses the surface points as input and creates an output file that can be compiled and read into the 3-D solid modeler PATRAN (1991). PATRAN is used to create a NASTRAN or MARC input deck of any mesh density.

A gear set model created in this manner is shown in Fig. 3. The description of these two programs and coding is given in Bibel et al. (1993 and 1994).

Fig. 3 — Spiral bevel gear set modeled as described in text.

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Gap Elements

Previously 3-D contact analysis was accomplished using gap elements. This presented numerous problems related to gap element orientation. After the contact point was located, the surface normal at the contact point was calculated. Lines parallel to the contact point surface normal were constructed from nodes on the pinion.

The intersection of these lines with the gear surface was then calculated. These intersection points on the gear's surface were then incorporated into new, distorted elements on the gear. For every new gear surface node that was added, an existing gear surface node had to be deleted, and the element nodal connectivity had to be redefined. For coarse models, it worked reasonably well to select the new element connectivity by visual inspection. Larger models would require calculation of various permutations of nodal connectivity and distances to determine the most appropriate nodal substitutions and new element connectivity. The resulting remapped elements on the gear surface are shown in Fig. 4.

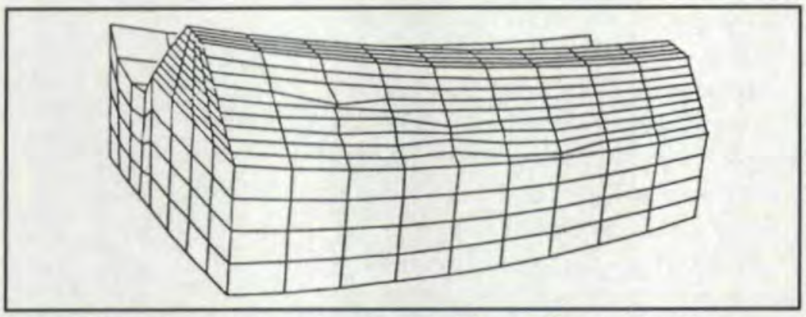

Fig. 4 — Distorted gear surface FE mesh required for gap element orientation.

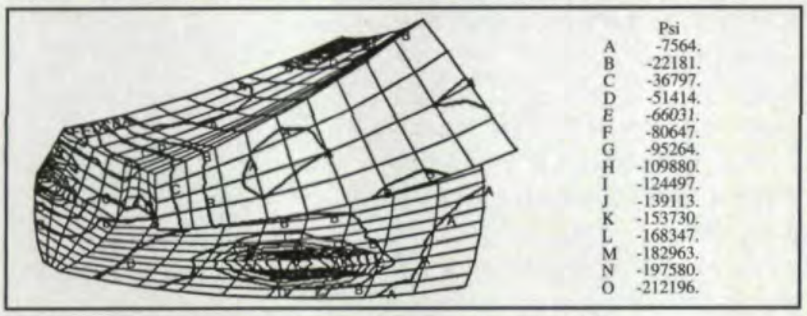

Fig. 5 — Typical contact stress contours from gap element model.

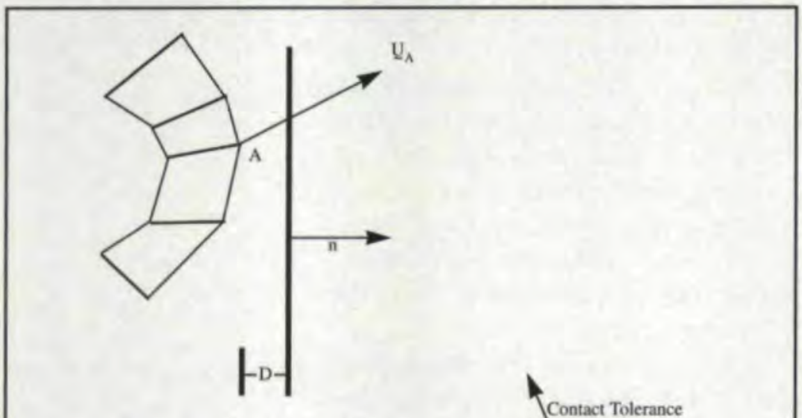

Fig. 6 — Non-penetrating constraints used in contact algorithm.

However, to roll the gear set through mesh, the entire process of contact point and contact point surface normal calculation, intersection of lines from pinion nodal points with a gear surface, definition of new element connectivity on gear surface and calculation of gaps had to be repeated for every incremental rotation. Typical output from a gap element model is shown in Fig. 5. Although the model was relatively coarse, the results compared favorably with Hertzian estimates.

Contact Algorithm

Greatly superior to the method of gap elements is the automated contact algorithm described in MARC K-5.1 (1991). Contact between deformable bodies is handled by imposing non-penetrating constraints as shown in Fig. 6. Automatic in this context means that user interaction is not required in treating multi-body contact. The program has automated the imposition of non-penetration constraints, even while rolling through mesh. The user no longer has to worry about the location, orientation and open/close status checks of "gap elements." Typical output for contact analysis from the contact algorithm is shown in Fig. 7. The results were consistent with previous modeling done with gap elements and with Hertzian estimates.

Automated Meshing With User Subroutine

The model development software mathematically creates the pinion and gear surface coordinates along the same axis of rotation. The gear and pinion must be properly located for meshing action. First the pinion is rotated a small angle about its axis of rotation to accommodate tooth mesh alignment.

The pinion is placed in mesh by a rotation θ corresponding to the shaft angle. The gear set is now properly positioned for 3-D contact analysis with MARC.

After completion of an increment of the finite element contact analysis with MARC, the gear and pinion are rotated by a user subroutine to simulate the gears rolling through mesh. For meshing, the gear is rotated a small increment of "δ" degrees. The pinion would then rotate "δ •

(Number of Gear Teeth)/(Number of Pinion Teeth)" in the opposite sense. The finite element contact analysis is repeated for a new orientation of the gear set. The process is repeated by merely changing the two numbers corresponding to the rotations of the gear set in the user subroutine.

The user subroutine is written in FORTRAN and compiles with the MARC input file.

Preliminary Results

A two-tooth pinion segment and a two-tooth gear segment were rolled through mesh with increments of about one degree of pinion rotation. (There are 19 teeth on the pinion.)

A series of plots is shown in Fig. 8. Shown is a plot of line loading of the forces on the pinion as it rolls through mesh in a counterclockwise direction. The line load is seen to progress from the heel of the back pinion tooth to the toe.

The loading switches from the back pinion tooth to the front after a brief period of load sharing. Also shown is an example of line loading on the gear for a single configuration in Fig. 9.

More work remains to be done concerning mesh refinement, enhanced accuracy of the modeling of the fillet region, better boundary conditions, etc. The work at this point is considered analogous to initial attempts at 2-D FE modeling of spur gears. The models went through a natural progression of increased complexity (i.e., single-tooth models with point contact, multi-tooth models with point contact, multi-tooth models with deformable contact, etc.) As computers became more powerful and the technology became more mature, eventually entire planetary gear sets were rolled through mesh with 2-D models. 3-D modeling needs to go through a similar evolution.

Conclusion

Considerable progress has been made in automating 3-D analysis of spiral bevel gears in mesh. Programs have been written that start with machine tool settings and can create finite element models of any mesh density. This is done by numerically evaluating the kinematic motion of the manufacturing process for generated spiral bevel gears and creating input data for a commercially available 3-D solid modeler.

Deformable gear tooth contact is modeled with the automatic generation of non-penetration constraints. This is done by contact algorithm in a commercially available finite element code. The contact algorithm eliminates the problems of mesh distortion associated with calculating the location and orientation of gap elements.

Although the original finite element analysis was done on a supercomputer, the software used is now available on a desktop PC. ☼

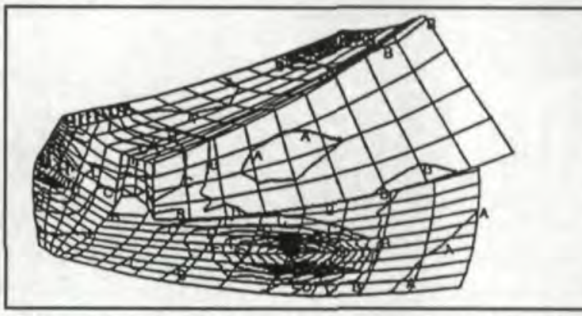

Fig. 7 — Typical contact stress contours from contact algorithm FE model.

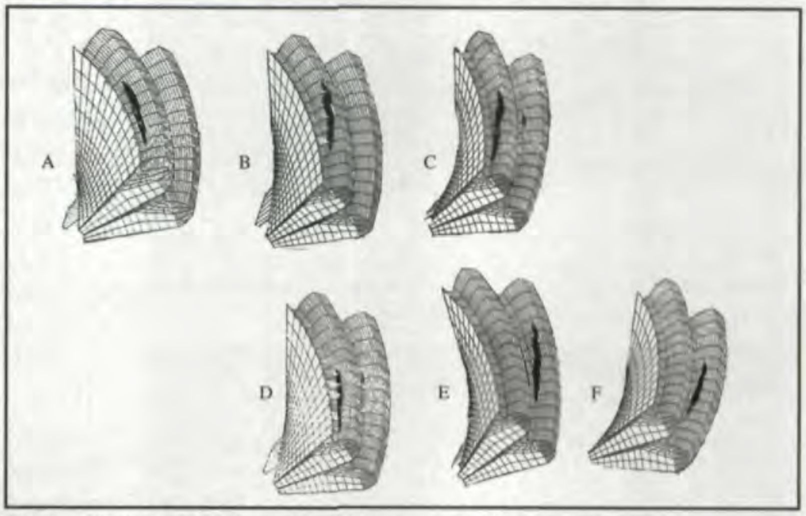

Fig. 8 — Plot of contact forces for pinion segment rolling through mesh.

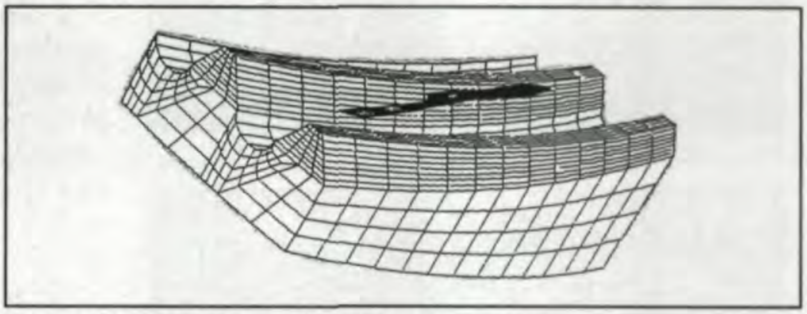

Fig. 9 — Typical plot of contact forces on two-tooth gear segment.

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The Broaching of Gears

Don Kosal

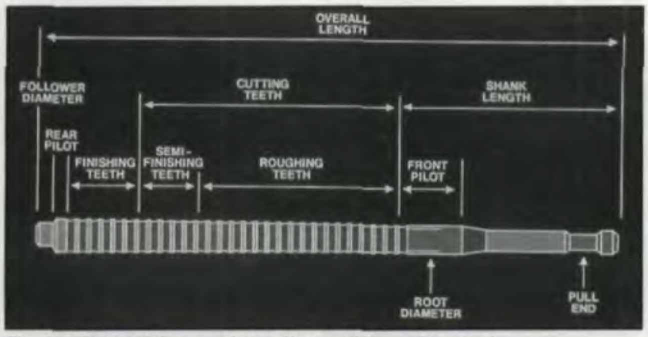


Fig. 1 — Parts of the round or spline tooth broaching tool.

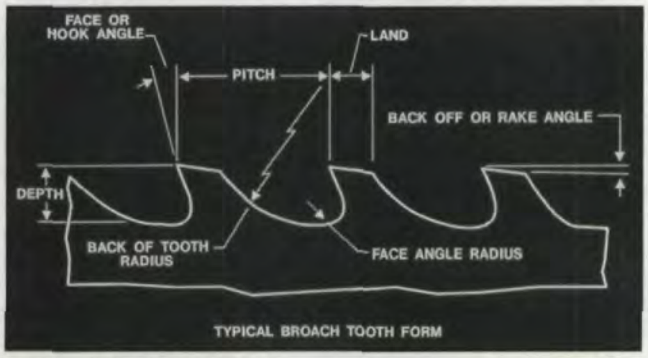
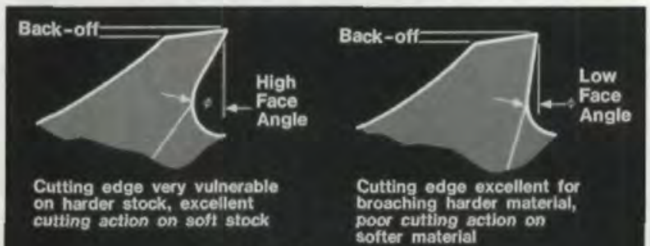


Fig. 2 — Parts of a broach tooth.



HARDNESS ROCKWELL "C"	BRINELL	HOOK ANGLE
40 TO 45	375 TO 429	5°
37 TO 39	352 TO 369	10°
33 TO 36	311 TO 341	12°
22 TO 32	235 TO 302	15°
12 TO 21	192 TO 229	18°
0 TO 11	153 TO 190	20°
UNDER 0	UNDER 153	22°

Fig. 3 — The face angle of a broach tooth is dependent on the type and hardness of the material being cut.

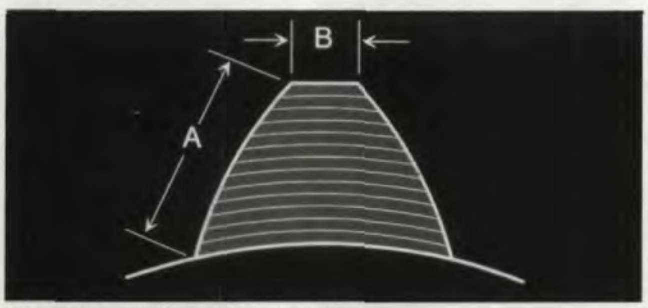


Fig. 4 — Diametral stepping or "nibbling."

Broaching is a process in which a cutting tool passes over or through a part piece to produce a desired form. A broach removes part material with a series of teeth, each one removing a specified amount of stock.

Broached parts come in various shapes and sizes. Diameters under .100" and over 11" can be produced by broaching. Lengths of cut vary from under .125" to over 12". Helical teeth, spur teeth, involutes, gears, straight-sided splines, cam splines and radius lobes can all be cut to tight tolerances using the broaching process. Broaching is often used to generate internal or external gear teeth and splines.

Nomenclature

First, let us discuss some basic nomenclature of the round or spline tooth broaching tool (see Fig. 1). The front end of the broach is called the *pull shank*. This is where the broach machine grabs the tool and pulls it through the part. The *shank length* is the distance from the front end of the broach to the cutting edge of the first tooth. This length is determined from the part face width, the broach puller length and the fixture setup on the machine. The *front pilot* guides the part onto the broach and acts as a gage so as not to accept any parts that may be undersized. The *rough*, *semi-finish* and *finishing* teeth generate the desired tooth form. The *rear pilot* guides the part off the broach, and the *follower* or *retriever* end supports the tail end of the tool during broaching.

The parts of a broach tooth are shown in Fig. 2. The distance between the cutting teeth is the *pitch*. This is determined by the length of cut of the part. Ideally, the designer will try to get one tooth to enter the cut of the part as another one exits. The *land* is the length of any particular cutting tooth. The length of the land reflects the amount of tool life the user can expect. The *depth* determines the amount of area available for the part chip.

The *face angle radius* (the radius just below the cutting edge that blends into the back of the tooth radius) must be kept constant through the life of the tool. The *back radius* (that on the back of the tooth in the chip space) should be polished and must blend smoothly with the face angle radius. Any mismatch between these two radii will increase the chances of the broach chips sticking in the gullet or chip space. This could lead to extensive damage on the tool.

The *face angle* is the angle of the cutting edge of the broach tooth. It is dependent upon the type of material being cut and in steels, the hardness of the material (see Fig. 3). The *backoff angle* (the relief angle behind the cutting edge of the tooth) provides clearance from the cutting edge and prevents the top of the broach from dragging through the part. The degree of backoff is determined by the part configuration and part tolerances.

Broaching Methods

The most common method of broaching is *diametral stepping*, or "nibbling," shown in Fig 4. The broach tooth corners generate the involute profile "A." The finishing teeth of the broach produce the major diameter portion "B." When generating the involute, the starting hole of the part guides the front pilot of the broach. Each successive cutting tooth increases in diameter until the desired form is generated. Since the corners of these teeth develop the profile form, it is crucial that these corners be properly maintained. There could be as many as 20,000 or more cutting corners on a broach. If these corners are not maintained, and one should become deformed, then the quality of the part finish suffers. Also, if one cutting corner is not functioning as designed, the following corner begins to "work" to a higher degree than was intended. This causes premature wear on that tooth, and this pattern will carry on progressively.

Nibbling leaves a poor surface, however. To correct this problem, another method of tooth form generation was developed. This is the *side shaving method* of finishing shown in Fig. 5. This method, used in conjunction with nibbling, increases the tooth thickness and full form shaves the entire involute profile.

Broaching Tools

The most common gear finishing broach tool used today is the *broach assembly*. The assembly consists of both a conventional form generating roughing bar, which performs the nibbling phase, and a full form finishing shell, which does the side shaving. In most applications, the full form shell offers the following advantages:

1. Low production cost when properly maintained. A full form cutting tool can produce a finished part in one simple operation.

2. Quality surface finish. The full form shell has an automatic shearing action and produces finishes as low as 7μ, RMS. Conventional generation broaches usually range between $50–80\mu$/inches.

3. Modified and precise involute profiles. Since the full form is being cut by the shell, it is possible to hold the desired profile form and required tooth thickness to high degrees of accuracy.

4. Extremely accurate tooth spacing and lead. Since the shell is a smaller piece, controlling of the manufacturing is much easier, and this control will be reflected in the quality of the part.

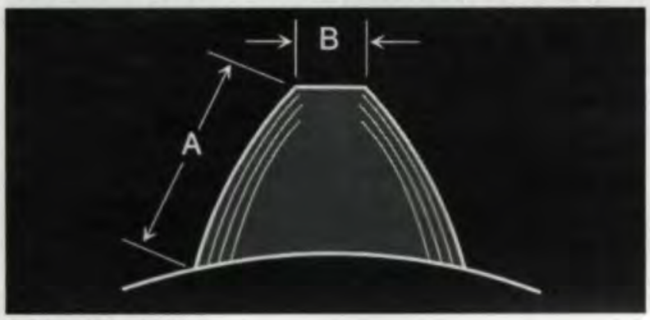


Fig. 5 — Side shaving.

Fig. 6 shows a typical assembly. Part B shows the arbor section of the roughing bar. The side shaving shell shown in Part C will be positioned on this arbor. Part D is the rear pilot locknut, which holds the shell in place.

One major requirement on most part prints and process sheets is a concentricity tolerance. As shown in Fig. 7, good concentricity can be obtained between the outside diameter and inside diameter. This is done with a dwell tooth section or alternating round and spline section. In this case, the spline teeth generate along the O.D. and qualify the major diameter. The full round teeth between the spline teeth remove stock in the spaces of the splines or minor diameter. Since both of the diameters are manufactured in the same operation, the concentricity between the O.D. and I.D. are virtually perfect.

The most requested type of concentricity is between the minor diameter and the pitch diameter, as shown in Fig. 8. The P.D./I.D. concentricity broach looks identical to the O.D./I.D. concentricity broach. However, instead of the spline teeth increasing on diameter, they step out on the spline tooth width. The full round teeth still generate on the diameter. Since the tooth thickness at the pitch diameter is being held with the minor diameter, the two will be concentric.

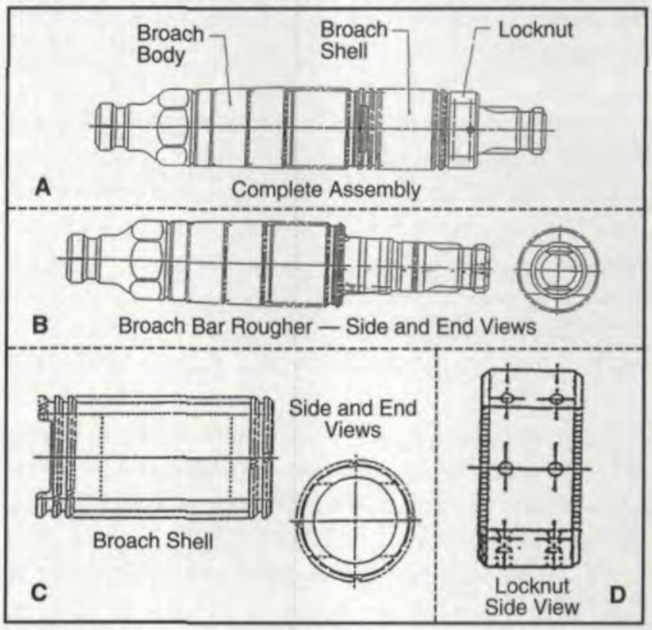


Fig. 6 Typical broach tool assembly.

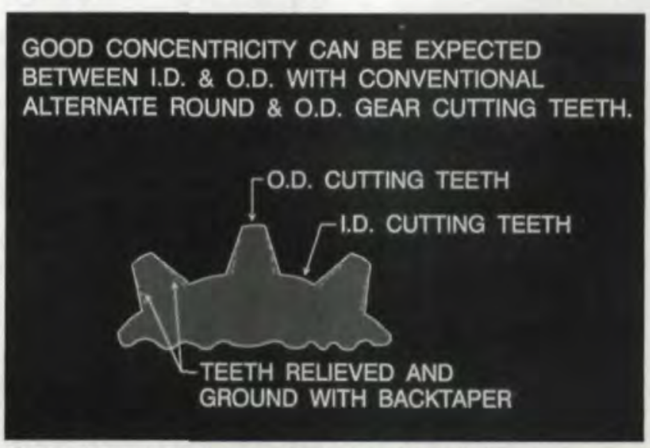


Fig. 7 — Concentricity between the inside and outside diameters.

If the diameter of the tool is large enough, the most effective means of supplying a P.D./I.D. concentricity tool is with the body and shell method. In that case, the rougher body generates a form with a smaller tooth thickness. It also cuts to a full depth and generates a protuberance tip to provide clearance for the shell outside diameter. The shell then qualifies the minor diameter and circular space width in the part simultaneously.

Internal running gears are good candidates for broaching. Because of broaching's suitability in high production applications, the quality demands of customers and the low cost per piece that broaching can offer, most automotive ring gears, both spur and helical, are manufactured by this process.

When broaching these ring gears, the pull broach assembly is recommended. The roughing bar in this assembly generates the basic involute form, leaving stock for the side shaving shell to finish (see Fig. 9).

Right or Left Hand?

The traditional helical broach can be identified for obtuse or acute and right- or left-hand helix by following some basic rules. The helix angles, shown in Figs. 10–11, distinguish the acute side of the broach cutting face. Conversely, the obtuse side produces an obtuse angle with the cutting face. To determine a right- or left-hand helix on the broach tool, simply look from one end of the cutting tool to the other. Whichever direction the spiral of the teeth run in is the hand of the helix angle. You can use the following methods to determine the hand and acute or obtuse side of the part:

1. When holding the part, the side of the broach entry should be facing you. Looking at the lower section of the part, the side of the teeth which can be seen is the obtuse side.

2. When you hold the part and look in the same manner, whichever shoulder the spiral of the splines points to indicates the hand of the helix.

Lead Bar and Drawbar Assemblies

Production of the helical ring gear requires some additional tooling—the lead bar and nut assembly shown in Fig. 12. As the broach passes through the part, the lead bar and nut assembly spin the broach on the identical lead of the teeth. Most helical broaching is performed on a vertical pull down machine; therefore, the driving flats on the broach are placed in the retriever end. The lead bar and broach bar must have identical leads. Otherwise increased torsional forces are applied, and the broach will cut an exaggerated form. For this reason, both bars should be manufactured from the same tooling.

Industry has demanded larger diameter tools to coincide with the increased number of splines in the ring gears. Therefore, new tooling designs, especially for earth moving vehicles, have been developed. Thus, the drawbar assembly was created. The reason a new concept was necessary was the ultimate weight of the tool. What the engineers designed was a long arbor called a drawbar (see Fig. 13). The drawbar can range up to a 6" maximum O.D. and 108" in length. The rougher body section is loaded from the front end of the drawbar. This roughing body has been made up

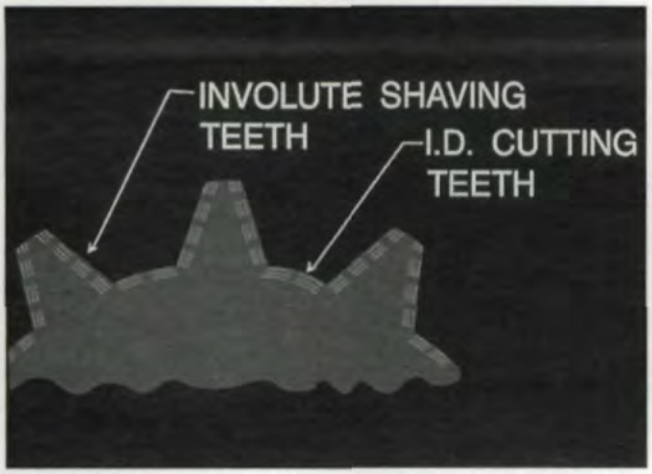


Fig. 8 — Good concentricity can be expected between I.D. & P.D. with special alternate round & involute shaving teeth.

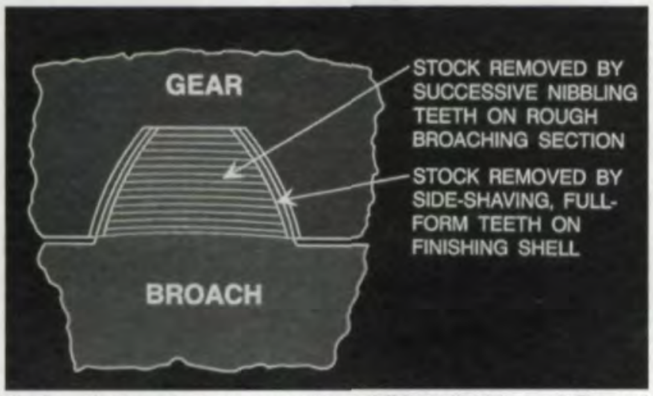


Fig. 9 — Successive stock removal by a full form finishing tool. The tool has both roughing and finishing sections. Nibbling teeth remove most of the material; then special side-shaving teeth remove 0.005" of stock or more from the entire thickness of the teeth. Only one operation is needed.

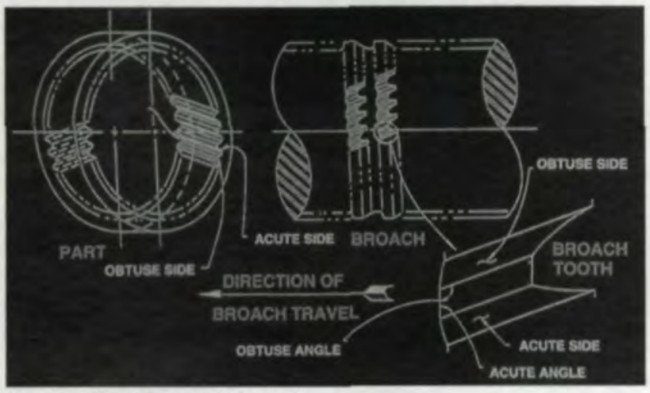


Fig. 10 — The left-hand helix angle.

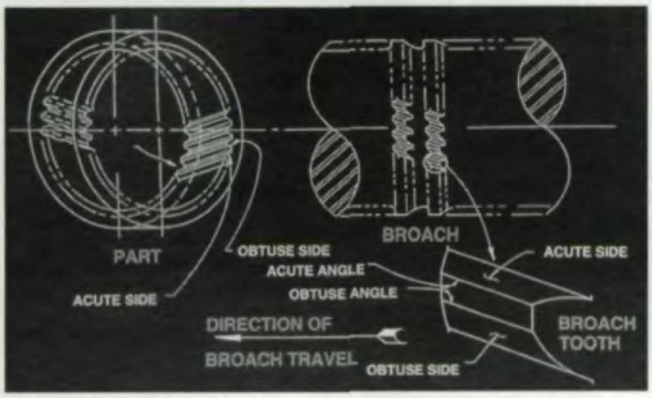


Fig. 11 — The right-hand helix angle.

Fig. 12 — A lead bar and nut assembly.

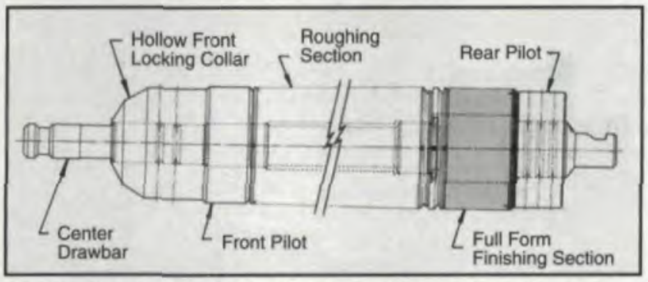


Fig. 13 — Construction details of a tensioned drawbar broaching tool.

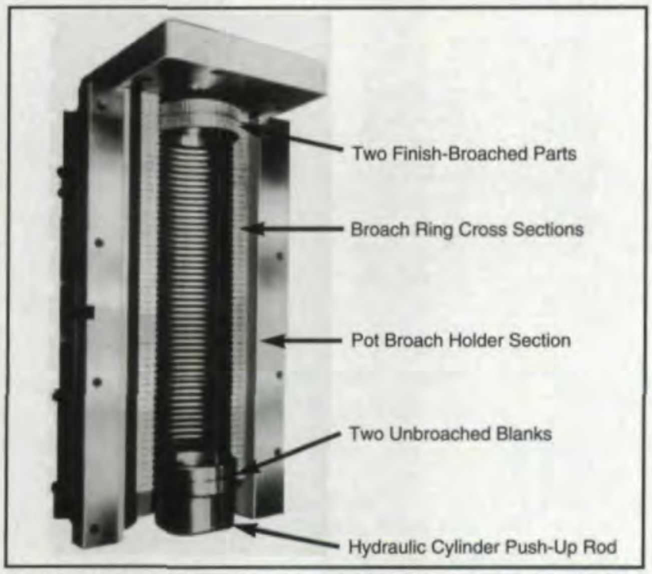


Fig. 14 — Cutaway view of pushup pot broaching process showing how two parts can be produced at a time.

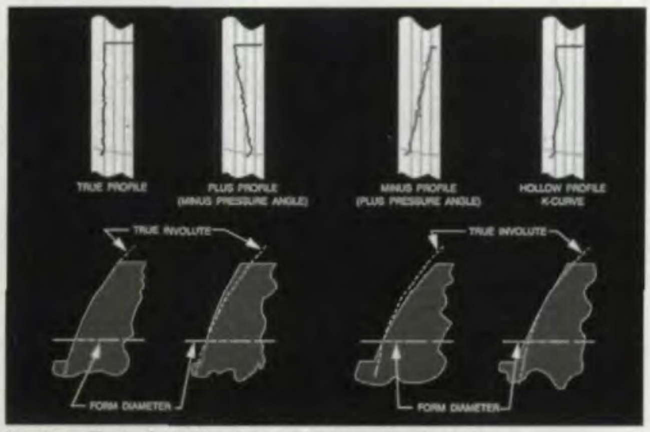


Fig. 15 — Typical profiles that can be ground on broaches.

to 11" in diameter and almost 70" in length with a 3" hole bored through the center. A front pilot and front locknut contain the roughing section against a positive stop designed in the drawbar. The full form finishing shell is mounted from the rear end of the drawbar. Then a rear pilot locknut is mounted and secured.

External Spline or Pot Broaching

The engineer has several options when choosing tools for broaching external splines. First, an all-broach ring or wafer assembly can be used. In this method, a set of rings each cut progressively into the outside diameter of the part. Therefore, the first cutting ring, having the largest minor diameter in the set, begins to break the surface of the part. Then each following ring gets smaller until the desired spline or involute form has been generated. The set of rings is assembled into a pot.

There are different types of pots, but the one shown in Fig. 14 will be the model used. Each ring has a precision cut location slot machined in its outside diameter. This slot provides the proper lineup from ring to ring as the cutting tools are mounted into the pot shell with the locating key. The O.D. of the rings rests on four precision ground rails, two in each pot shell half. A flat surface, ground off-center on the O.D. of the ring, is used as a visual check to make sure the rings were properly assembled. Once all the rings are placed in the half, the assembler can tell whether one ring was mistakenly put in backwards. If all the flats line up, the rings are in the same direction.

Broach rings can also be made to rough-cut a spline first. Then, using a few rings at the end of the assembly, it can be side shaved. This procedure gives a better involute form and better control of the circular tooth thickness.

Another means of generating teeth is the broach insert method. In this method broach inserts are mounted into holder rings, which are set in the pot shell halves in the same manner as in the broach ring method. From the outside of the hold ring, set screws are used to lock down the insert. Broach inserts offer more flexibility, but the spacing is not as accurate as a broach ring.

The third way is a combination of the two. This method offers the best of both worlds. Broach inserts can "hog out" the material and then give it a fine finish with a few side cutting rings. The deep splined sprocket gear is an ideal application. Some pots range in length from 10" of cutting teeth to 60". Part outside diameters of over 6" have been pot broached.

Manufacturing Broach Tools

Manufacturing of spline or gear toothed broaches has become an art with the increasing demand for tighter part tolerances. The broach tool must be processed carefully from the lathe through shipment. Once the certified tool stock is delivered to the manufacturing facility, this tender, loving care begins.

First the broach is turned, leaving a predetermined amount of grind stock, which is dependent on the diameter of the bar. The puller and retriever ends are roughed out. Then the spacing of cutting teeth and taper of the bar are established.

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From the green operations, the broach tool is sent to heat treat, where the cutting section is brought up to an approximate hardness of 64 Rockwell "C." The puller and retriever ends are then drawn down to about a 50 Rockwell "C." This is done to make the ends more durable so they can withstand the constant pounding applied during the broaching process.

After heat treatment, the broach goes to the O.D. grinder where all the diameters are finish ground. Tolerances of .0002" on diameter can be held at this operation. Next is the spline grind operation.

For gear teeth, a master template is used to generate the involute form (true or modified) on the broach tool. The template can reproduce the involute form within .0002" variation. For a sliding spline tooth, the tolerance of the involute profile is usually less critical. For this application, a radius and offset dressing is adequate. The radius approximates the involute and can be held within .0005" variation from a true involute.

Once the method of trimming the form on the grinding wheel has been decided, the operator will grind a "dummy" or a blank on which the profile can actually be inspected. Minor adjustments may be necessary. After the operator is satisfied with the form ground in the "dummy," the broach is ground and inspected.

Should the customer desire, the broach may be coated with one of the various types of surface treatments available. When completed, the broach tool is placed in a wooden box tailor-made for that particular tool. This prevents any unnecessary damage to the crafted broach.

True profiles, plus and minus profiles and hollow profiles all can be ground on broaches (See Fig. 15).

Given current technology, broaching cannot intentionally produce a crown on the flank of a gear tooth or a tapered hole. This is usually a product of the part configuration, such as a hub on one end of the part. From spline grind, the broach tool is face-ground or sharpened. Caution must be taken to apply the correct hook (face) angle, blend the gullet radii smoothly and minimize burrs.

From the beginning, broach manufacturers have steadily progressed to meet the challenges set before them. New and improved techniques for both design and manufacturing are always being developed. The main goal is to keep broaching a viable source for producing parts.

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Don Kosal *is a sales engineer with National Broach & Machine in Macomb, MI. He has many years' experience in broaching and has presented papers at SME and AGMA technical conferences.*

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The Way of the Web

Twelve tips for getting Web site visitors and keeping them coming back for more.

Okay. You've been convinced. You've gritted your teeth and decided to spend the money to launch a company Web site. Everybody from your teenage propeller-head to the girl in the mail room and the salesman in the flashy suit who gave you "such a deal" on Web site services has promised that your site will be the best thing that's happened to your business since the advent of CNC machines.

But you've been around the block a couple of times. Nothing is as simple or easy as the true believers make this sound. Once you're out on the Web, how do you make your considerable investment of time, effort and dollars really pay off?

Just Building It Doesn't Mean They'll Come

There's a lot to building a successful site, but fundamental to making cyberspace work for you are two basic questions you should be asking yourself: How do I get people to visit my site in the first place, and, once they've seen it, how can I get them to come back again?

The answers are not complex.

Promote your site everywhere and often. This first rule may seem obvious, and it is—so obvious that it frequently gets overlooked. Web users may be on the cutting edge of technology, but, generally speaking, they're not psychic. They can't visit your site if they don't know it's there. Be sure your online presence is mentioned in all your corporate literature. Display your URL (Internet address) everywhere you can—your stationery, your business cards, your print advertising. Your URL should be added to any display of your company name, address and phone numbers. Notify your best customers that you've gone online by mail or fax. Send out news releases announcing it to relevant trade publications. Don't forget to add your site address to your listing in professional or business directories and to promote it at your booth at trade shows.

The Lycos search engine opening screen.

Register your site with all the major search engines. Web sites like Lycos, AltaVista and Infoseek make it their business to cruise the Web and index its contents so people looking for information on particular subjects can find it. Take the time to notify these "search engines" of the existence of your site so they can include it in their indexes. The service is free, and you can register right online.

Spend the time to tinker with the wording on your pages so that yours will be among the first to come up under particular topics. Usually search results are listed in groups of ten, and your goal is to get as close to the top of the list as you can. This will take some persistence and considerable vigilance. The rules search engines use to categorize sites seem to change constantly, and every search engine has its own criteria. On the other hand, search engines make frequent repeat visits to sites, so just because your company comes up as number 537 under a category this week doesn't mean it's doomed to stay there forever.

The important thing to keep in mind is that search engines are only a backup to your direct promotion. The easiest and fastest way to get to a particular site on the Internet is to have the URL right in front of you. See to it that anyone you think might be interested in your site knows how to find it directly.

THE NEW KID ON THE BLOCK

Welcome to our newest column, *online@geartek*. Since the Internet seems to be the Next Wave in doing business, even for "mature" industries like gear manufacturing, we want to do what we can to keep you, our readers, up to date on what's happening online. This column will appear from time to time covering various ways in which the Internet can help you promote your gear business. We won't be a substitute for one of the plethora of good computer magazines out there covering the technical aspects of Web site building, e-mail maintenance and other arcana. What we hope to do is help relate this new (and to many of us, intimidating) world of cyberspace to our real lives and real businesses. Let us know how were doing. We welcome your suggestions and comments.

Explore directory sites. Think of these as mega-sites. They play host to the Web sites of other businesses. Examples are Industry.Net or Industrylink or The Gear Industry Home Page™. The virtue of a directory site is that it helps clear away some of the clutter on the Internet. This can be an advantage to people looking for your site, because if it's found on a directory site, they don't have to search through the whole Web to find it. On the other hand, access to these sites is free to users, but not to those with Web sites. Space on a directory site can be quite expensive, and the cost will have to be added to whatever else you've spent to get online.

Some of them also require users to "qualify" to use the site, much in the same way controlled circulation magazines require subscribers to "qualify" before receiving free subscriptions. This restriction cuts both ways for your Web page. The "hits" you get might be from people more seriously interested in your product than the casual surfer, but the requirement puts a wall between you and potential visitors to your site. Many Internet users are reluctant to give out even the most general information online if they're just browsing, so they may not bother to check you out.

Repeat Business

Getting people to your site once is only the beginning. The real measure of Internet success is getting users to come back again and again. The World Wide Web is the essence of an "emerging technology." We're all learning how to best use it as we go along, but some strategies for getting the most out of the Web are becoming clear.

Think paradigm shift. The Web is *not* an advertising medium as we have traditionally understood that term. Don't think of it that way. If all you really want to do is get your company name in front of your customers, there are more effective (and possibly cheaper and easier) ways to do it.

Instead, think of your Internet site as a dynamic, flexible, 24-hour-a-day customer service outpost. Make a list of all the things that you could do from your Web site. For a start, you can provide information for your customers, answer their questions, sell products, keep them informed of important corporate developments and provide technical support. If you can think of a customer-related need, there's a good chance there's a way to address it from your Web page.

Be clear about your goals. Given the flexibility and potential reach of the Web, it's important to be very clear about what you want to accomplish. Just because you can do a great many things on the Web, doesn't mean you should do them all—at least not right away. Prioritize your goals. It's better to do a few things well and add other things later when you're more comfortable with your site and its technologies than to do everything badly. Web users are also becoming more and more sophisticated every day.

They'll drop an amateurish or unfocused site like a bad habit.

Be clear about who your audience is. Think "customer" not "company" when planning material for your site. What do they want? How can your page help them get it? What do you want them to do? How does your page encourage them to do it? People come to Web sites for what they can get out of them. Your ultimate goal in planning a site is to make it so useful and important to its users that they don't want to be without the information and services they can get from it.

Update often. Nothing spells death on the Web faster than stale material. Update your page regularly. If daily or weekly updates are not possible, certainly update monthly. You don't have to redo the entire page, but you should certainly add new items or delete out-of-date ones as often as you can. Once your site is set up, changing the material on it is not that difficult or time-consuming. Set up a schedule and keep to it. Help return users by labelling what's new on your site. Remember that your users are paying for their Internet time. It's only courteous to point them in the direction of the new things on your site so they can get to them quickly.

Make your site truly interactive. Just posting information to be read is not interactivity. Boxes to fill in, e-mail forms, hyperlinks to other sites, games to play, contests to enter, question-and-answer forums, all involve users directly and keep them interested and coming back for more.

Provide information users can't get elsewhere. Remember what we said earlier about making your site a necessity for users. You've got to make it worth their while to call up your site. Timely, interesting, original, useful information, plus graphics that don't take forever to load, will bring your customers back to your site again and again.

Troubleshoot your site on a regular basis. Assign a variety of people to call up your site from their own computers at home. Make sure they're using a variety of browsers. Not all browsers work alike. Your site may load flawlessly on one and be full of glitches on another. You need to identify trouble spots and eliminate them.

Find out how long it takes the average reader to load your site. Have your testers check to make sure all your forms and hyperlinks work the way you want them to on their personal machines. Ask them to notify your webmaster of any glitches in the system *immediately*. It's a real turn-off to repeatedly call up a site only to get an error message of one kind or another.

Pay attention to the graphics. Your site is your company's representative in cyberspace. You want it to look as good as it can. Busy graphics that serve no purpose and take forever to load are a bad idea. So are garish colors that are hard on the eye. (Just because your computer can use 16 million colors doesn't mean they should all appear on your Web site.) On the other hand, a dull boring site implies that your company is also dull and boring—not the message you want to convey.

Use sound and animation sparingly, if at all. Yes, some pretty remarkable technology is out there that can turn your site into an animated video, complete with a sound track if that's what you want to do. It may not be the best use of your resources however. Many Web users don't have state-of-the-art machines that can use this glitzy technology, and all your time, effort and expense will be lost on them. These bells and whistles also consume disk space in huge quantities at an alarming rate and take an age to load. How many visitors to your site will lose patience and leave before they get to your cute video of meshing gears?

Your site should also be easy to use. It should follow some kind of clear visual logic. Users should be able to go to the places on your site they want to be quickly and easily. Buttons and menus should be easy to read and understandable.

Getting the look and feel of your site exactly the way you want it is not easy. Beware of falling into the trap of thinking you can buy a $49.95 "web designer" program and have the receptionist design your site in her spare time. It will be worth it in the long run to pay someone with experience in Web design to provide at least your basic "look" and templates for your pages.

Check out the competition. The World Wide Web is one of the easiest places to do this without having to put on a false moustache and a trench coat or disguising your voice. Spend some time surfing the Net. Take note of the sites you like. See what they do and how they do it. Then adapt the idea to your own business.

Go back to those goals you set for your site. Find other sites with similar goals and see how they achieve them. How do other sites build name recognition? Handle customer service requests? Provide product information? Fill orders? Remember that just because your favorite site is promoting a very different business doesn't mean you can't adopt some of its strategies.

Launching a Web site is in one sense no different from any other new business venture. It requires research, planning ahead, looking out for and avoiding the pitfalls and some hard, concentrated thinking. Do that, and success will follow.

12 WAYS TO MAKE YOUR WEB SITE THE BEST IT CAN BE

- Promote your site everywhere and often. You can't remind people of your URL too often.
- Register with all the major search engines. These are the first place many Internet users go when looking for information.
- Explore directory sites. These mega-sites can help direct interested users to your home page.
- Think paradigm shift. Your Web presence is not the same as an old-fashioned ad. Don't limit your thinking with this comparison.
- Be clear about your goals. Know exactly what you want to accomplish before you start to design your site.
- Be clear about your audience. Know what they want and figure out how your site can help them get it.
- Update often. Stale content is like stale bread—nobody wants it.
- Make your site truly interactive. Use the power of the Web to encourage direct responses from visitors.
- Provide information users can't get elsewhere. Timely, original and exclusive information will keep users coming back for more.
- Troubleshoot your site. Make sure your site is glitch-free. Web users will give up on you if getting into your site is too much hassle.
- Pay attention to the graphics. Make sure they're clear and logical. Don't clutter your site with needless glitz that wastes cyberspace and takes forever to load.
- Check out the competition. Research other sites. See how other sites handle certain problems. Imitate and adapt for your own purposes.

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New Approaches to Nitriding

What you should know about this process now.

Gerald Wolf

The process of nitriding has been used to case harden gears for years, but the science and technology of the process have not remained stagnant. New approaches have been developed which are definitely of interest to the gear designer. These include both new materials and new processing techniques.

A list of the desired properties of a material/heat treat combination desired for high performance gearing should contain the following:

- High load carrying capabilities,
- High resistance to scoring and wear,
- Good low and high cycle endurance,
- Good impact resistance,
- Low distortion during processing,
- Predictable size change,
- Low cost,
- Easy availability.

Nitrided alloy steel can meet many of these requirements. The thin, hard case it forms is highly resistant to both scoring and wear. The base material can be core-treated to high strength levels, and the residual compressive stresses generated in the case produce excellent long-life fatigue properties; however, because the case depths are shallower, nitrided gears cannot be loaded as heavily as carburized gears. Nitrided alloy steel parts also have improved corrosion resistance and are more resistant to softening from heating. And, most important, because the process is performed at relatively low temperatures and doesn't involve quenching, both distortion and size change are very low and predictable. In most applications, gear teeth are used as nitrided. Therefore, when the total manufacturing cost is considered, nitriding can be more economical than carburizing if operations such as press quenching or finish grinding are eliminated.

Table I — Typical Nitriding Materials and Hardnesses Produced by Nitriding

MATERIAL	NOMINAL COMPOSITION							SURFACE HARDNESS
	C	Mn	Ni	Cr	Mo	V	Al	HR15N
SAE 4142	.42	.88	–	.95	.20	–	–	87–90
4140 MOD	.40	.88	–	.95	1.00	–	–	88–91
SAE 4340	.40	.70	1.75	.80	.25	–	–	85–90
Nitralloy 135M	.42	.55	–	1.60	.38	–	1.0	92–94
DIN 31CrMoV9	.33	.60	–	1.50	.23	.20	–	91–93
D6-AC	.47	.75	.55	1.10	1.05	.12	–	87 Min.
EMS 64500	.40	.60	–	3.25	.35	.20	–	92 Min.

Early History

The first patent for nitriding dates back to 1913. About ten years later, the aluminum alloy steel called Nitralloy was developed by Krupp. With these materials, a very hard, wear-resistant case could be produced, but for many applications it was necessary to remove the extremely brittle hard surface layer. Then in the 1940s, Dr. Carl Floe at MIT developed a two-stage nitriding process that significantly reduced this brittle white layer. During this same period, the Germans developed a nitriding process, glow discharge nitriding, which employed an electrically generated plasma. After World War II, both General Electric in the U.S. and Klockner in Germany further refined this process, and by the mid-1970s plasma, or ion nitriding, had become a viable option for many applications.

Contemporary Nitriding

Many different nitriding techniques are available today.

Two 137T, 5 D.P. gears just after nitriding. They will be used in a 13,000 HP marine drive.

Gerald Wolf

is the president of The Cincinnati Steel Treating Company, Cincinnati, OH. Mr. Wolf has been a presenter at Society of Manufacturing Engineers heat treating clinics.

The basic process, however, is relatively simple. The material is heated to 900–1100°F in an active nitrogen-rich atmosphere, held for a sufficient time for the nitrogen to diffuse to the desired depth, then slow-cooled.

The case produced in alloy steel contains two zones. At the surface is a very hard compound zone referred to as the white layer. In conventional gas nitriding, this layer consists of a mixture of gamma prime and epsilon iron nitrides. In ion nitriding, the structure of this zone can be controlled to produce a single phase layer of either gamma prime or epsilon iron nitride. Below the compound zone is the diffusion zone containing precipitated alloy nitrides. Both its depth and properties are greatly dependent on the concentration and type of nitride-forming elements in the steel. Primarily these are aluminum, chromium, vanadium, molybdenum and titanium. In general, the higher the alloy content, the higher the case hardness. However, higher alloy contents retard the nitrogen diffusion rate, which slows the case depth development and, thus, requires longer cycle times to achieve a given case depth.

Most gas nitriding performed on gears has been done using the two-stage Floe process. During the first stage, pure ammonia (NH_3) is used as the furnace atmosphere. This dissociates into hydrogen and nitrogen at the surface of the steel, producing nascent or atomic nitrogen (N), which reacts with and diffuses into the steel. Note that molecular nitrogen (N_2) will not react in this

A load of gears being removed from a gas nitrider.

manner. During the longer second stage, dissociated ammonia (H_2 + N_2) is employed to reduce the nitriding potential of the atmosphere.

Today techniques are available which use pure nitrogen blended with other gases to achieve the desired nitriding potential during different stages of the nitriding process. In this way, the optimum case properties can be obtained for the application involved. For example, with contemporary multi-stage nitriding we can precisely control the white layer thickness to a finite amount or, if desired, completely eliminate it without incorporating post-processing procedures.

Similar results can also be obtained using modern ion nitriding techniques. In ion nitriding, the processing is done in a special vacuum furnace which has been backfilled with nitrogen. An electrical voltage between the work and the surrounding vessel ionizes the gas around the work, supplying the nascent nitrogen needed for nitriding. Although initial work with finer pitched gears often produced nonuniform results, these problems have been largely overcome, and the ion process is being successfully employed in the gear industry. For most work, however, gas nitriding is the popular choice.

Material Selection

Most alloy steels can be nitrided. Since the chrome-containing 4140/4145 grade is widely available and responds very well, it is widely used for gear applications. For higher case hardnesses and core strengths, the special nitriding steels such as the German 31CrMoV9, Nitralloy 135M or a custom grade should be used. Table I lists the composition of several materials used for nitrided gearing and the surface hardnesses that can be obtained with them.

Core treating by quench and tempering to a martensitic structure prior to machining is very important. This creates the desired core properties and also improves the response of the nitriding process, producing higher case hardnesses. Several factors must be considered, however, when determining the desired core hardness. The tempering temperature should be at least 50°F over the nitriding temperature to prevent changes during nitriding. Since as the core hardness increases, machinability decreases and the ability to produce stress-free parts becomes more difficult, the most commonly used range for 4140 steel is 30–34 HRC. However, for heavily loaded parts where the higher alloyed steels are employed, it is not uncommon to use core hardnesses in the 36–40 HRC range. One advantage of ion nitriding is that it can be performed at reduced temperatures, allowing the use of lower tempering temperatures during core treating.

When processing parts to be nitrided, one must ensure that all decarburized material has been removed first. This means that as-forged webs and other such areas should either be fully machined, masked to prevent nitriding or carbon-restored during core treating. Another processing consideration is the removal of machining stresses prior to finish machining and nitriding. It is sometimes necessary to stress relieve complex critical parts in the semi-finished condition to minimize their movement during nitriding.

While most nitrided gears are placed into service as nitrided, finishing operations can be performed after hardening. For example, tooth grinding to remove 0.002–0.005" per flank is used to produce large high-performance gears to AGMA Class 15 specs. For improved endurance life, shot peening can be employed if the white layer is controlled to a 0.0005" maximum during nitriding. O

Acknowledgement: *A version of this article was presented at the SME seminar, "The Heat Treating and Hardening of Gears," Feb. 27, 1996, Livonia, MI. Used with permission of SME.*

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For more information about **Cincinnati Steel Treating Co.,** circle **211.**

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.

Benchtop Grinding/Lapping/Polishing Machines

Struers offers three new benchtop machines for grinding, lapping and polishing. LaboPol™-21 is a two-disc, single-speed (300 rpm) machine, which is a successor to the Struers Knuth-Rotor™. LaboPol-5 features variable speeds from 50–500 rpm, controlled by an electronic servo system that keeps speed constant regardless of load. LaboPol-1 is a single-speed (250 rpm) basic model. All three machines can be automated by mounting a LaboForce™ specimen mover on them.

Circle 300

Double-Flank Gear Roll Tester

Mahr Corp. announces its new DF1 890 series of double-flank gear roll testers. The design uses a leaf spring transmission for precise measuring force adjustments to 0 oz., which the company says is particularly important in the measuring of plastic or powdered metal gears. The proprietary WinGear® software is compatible with Windows 95. Standard tests include total composite, tooth-to-tooth and radial runout. Tests for radial center distance or size variation and calculation of torsional backlash are available as options.

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Non-Lubricated, Cast Gears

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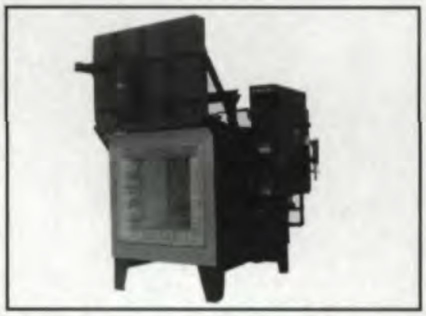

Heavy Duty Box Furnace

The Grieve No. 746 is a heavy duty box furnace with inert atmosphere construction which is currently being used for heat treating carbon parts. Heat input of 63.9 kW provides a maximum operating temperature of 2000°F. The work space dimensions measure 30" wide x 60" deep x 30" high. Insulation of this furnace consists of 6 1/2" thick floors with 4 1/2" thick firebrick and 2" thick block insulation. The heating elements are high-temperature coiled wire supported in lightweight cast ceramic fiber insulation with excellent thermal shock resistance and low heat retention. The vertical lift door is insulated with a 2300°F ceramic fiber blanket. The furnace is equipped with a NEMA 12 dust-tight, oil-tight control panel.

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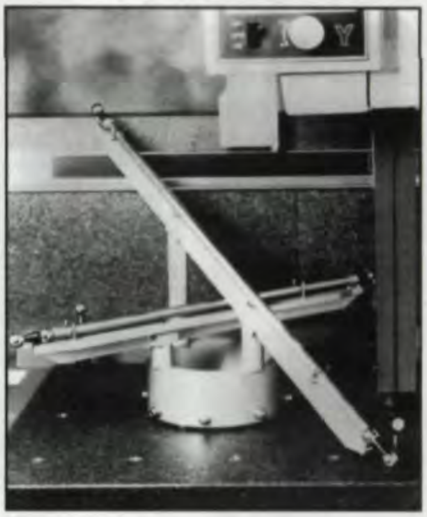

The Ball Bar Thing

Available from Bal-tec Division of Micro Surface Engineering, the Ball Bar Thing is a new approach to interim checking for CMMs. It uses two ball bars for more data points at each index and can be indexed to eight fixed and repeatable positions. Its simple construction—no air lines, valves or cylinders—makes it inexpensive. It also uses standard off-the-shelf ball bars and kinematic hardware. The Ball Bar Thing meets or exceeds all quality requirements as outlined in ANSI B89.1.12M for the "Performance Evaluation of Coordinate Measuring Machines."

Circle 304

Chemical Deburring Process

Surface Technology, Inc. introduces DEBURR 1000, an electroless chemical process for removing burrs on steel parts without distortion. Using short immersion times, the process severs burrs from the workpiece at their bases. The burrs then dissolve in the bath. Longer immersion times polish, shape and round the edges of precision parts. According to the company, the process also leaves parts clean and suitable for immediate use or subsequent surface finishing operations.

Circle 305

TRIM® Straight Oil & Additive

Master Chemical Corp. has added two new products to its TRIM® line of cutting and grinding fluids. TC 212 defoamer is designed not to float out or to be filtered out as part of the typical machining and/or coolant recycling application. This non-silicone defoamer is formulated to become an active component of the coolant working solution. It combats most foaming in chemical emulsions and semi-synthetic products. OM 303 is a heavy duty, chlorine-free straight cutting oil designed for use in conventional and Swiss-style screw machines, high-speed turning centers and high-performance, multi-station machines. Both products are available in 5-gallon pails, 54-gallon drums, bins and tank wagons.

Circle 306

Calibration Instrument

Fred V. Fowler Co. introduces a new Fowler/Trimos calibration instrument combining horizontal and vertical orientation to provide checking of all types of gages. The Fowler/Trimos THV has a maximum measuring range for all internal and external dimensions of 4" (100 mm) and, by virtue of its multiple accessories, can check plug, ring, thread plug gages, dial and lever indicators as well as precision manufactured parts. Its Heidenhain measuring system assures high accuracy and repeatability of .000005" ±2s (.1μm).

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Down By The Old Mill Stream

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

Back in the days when our great, great, great, etc., granddaddies were designing gears, one of the most common materials in use was wood. For fairly obvious reasons, we don't see too many wooden gears around anymore. But there are a few.

Your intrepid Addendum staff has found some—ones that are still in use, operating and not in a museum. Moreover, they're less than thirty years old.

In a small town in southern Maine, Dr. Clement A. Hiebert has built a water wheel to move the water up from a stream some 10 or 11 feet to his 14-acre mill pond. At the heart of the system is a 10.5' wheel driven by a lantern gear. The wheel is made of oak, and its replaceable teeth and the gear are made of rock maple. The drive is connected by a series of pulleys to drive the generator.

The whole system was designed by Dr. Hiebert and built, not by a gear engineer, but by Thos. Moser, a custom cabinet and furniture maker in Auburn, ME. The entire project took months. The wheel had to be constructed in sections, and each tooth was hand-cut individually.

Dr. & Mrs. Clement A. Hiebert and their mill wheel.

Why, we asked Dr. Hiebert, today, when everything not run by fossil fuels is run by computer chips, did he spend the time and effort to build a mill wheel? For the pure love of the thing, apparently. Dr. Hiebert doesn't need the electricity the mill could produce, and presently the mill doesn't do anything.

The retired surgeon justifies his "ancient landmark under construction" by saying that he "likes projects" which force activity and involve problem solving. He enjoys the act of pulling all the pieces of a project together. He also confesses to a fascination with moving water and explains that he spent a lot of time as a kid poking sticks in water just to see what would happen. Therefore, it seemed only logical, once he acquired property which had a stream running through it and once before had been occupied by a mill, to build another one.

To build gears for the sheer pleasure of the process: Now Addendum understands that kind of man.

Meanwhile, at the other end of the time warp . . .

Last December, when astronauts on the space shuttle Columbia had to abort their space walk because the door to the hatch was jammed, gears were at the heart of the problem. It seems that a screw fell from its hole and became embedded in the gears of the hatch, probably during liftoff, according to NASA spokesman Bruce Buckingham. The loose screws were discovered after the gearbox was removed from the hatch and taken apart.

We checked with Bruce again in January, while the Atlantis was on its way to meet the Russian space station Mir and pick up astronaut John Blaha, who had been on the station since last September. To make sure the same thing didn't happen again, before launch, technicians took apart the hatch on Atlantis, checked the gearboxes and the screws and applied a coat of Loc-Tite to the screws, just in case. The ounce of prevention worked. The hatch opened without a hitch, John Blaha wasn't stranded with his Russian friends and a multi-million dollar screw-up (sorry about that) was avoided. Sometimes, the down-to-earth methods are the best after all.

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