GEAR TECHNOLOGY

MARCH/APRIL 2001
The Journal of Gear Manufacturing
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- SUBMERGED INDUCTION HARDENING
- AUSTEMPERED GEARS AND SHAFTS
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- DRY HOBBING TECHNOLOGY
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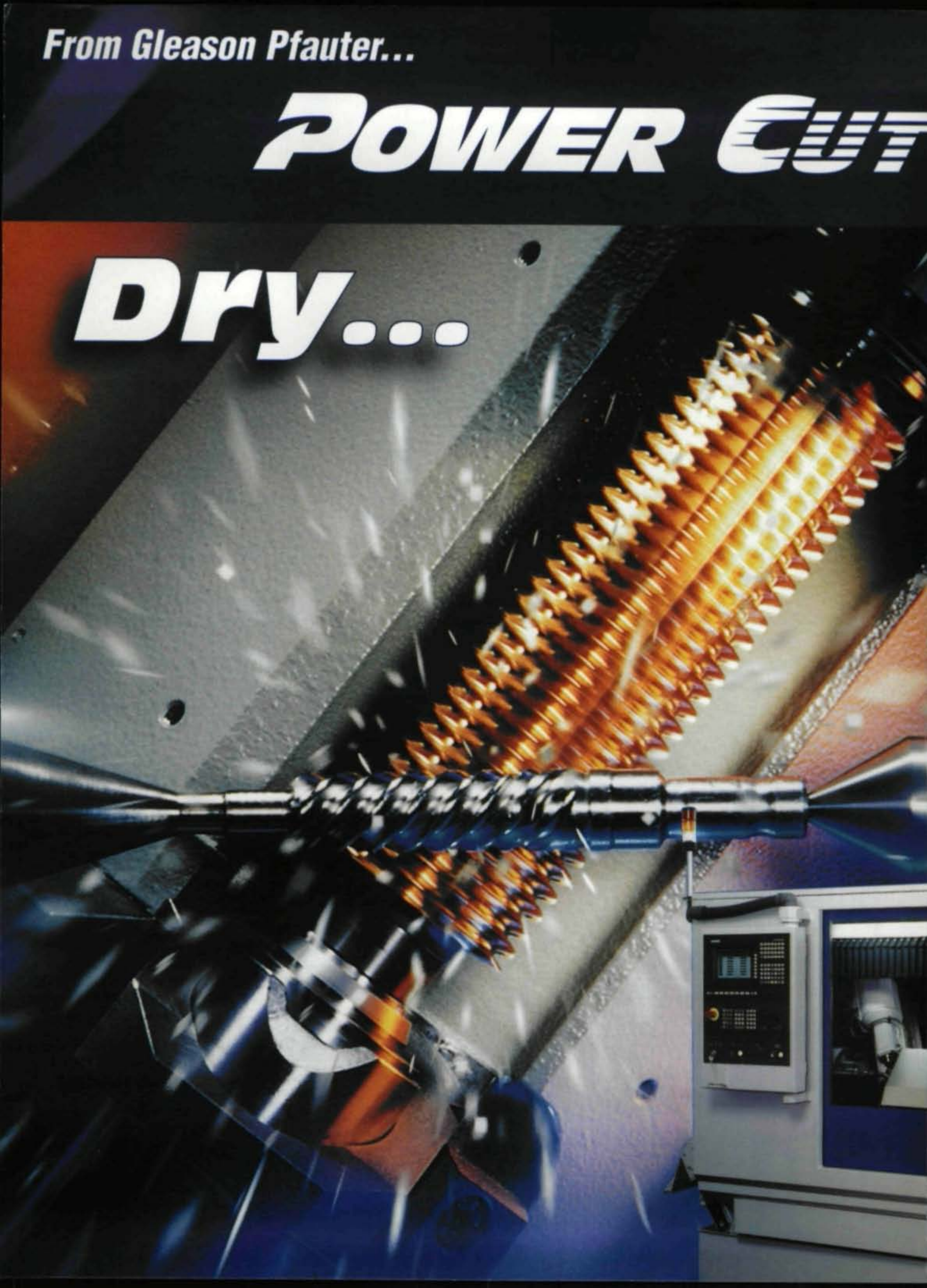
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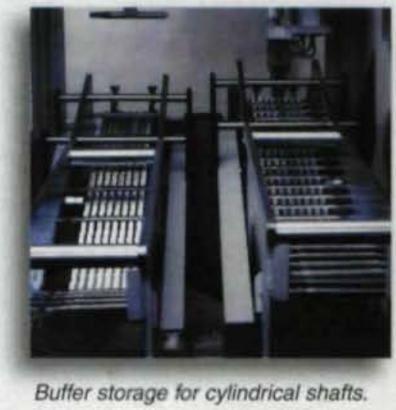

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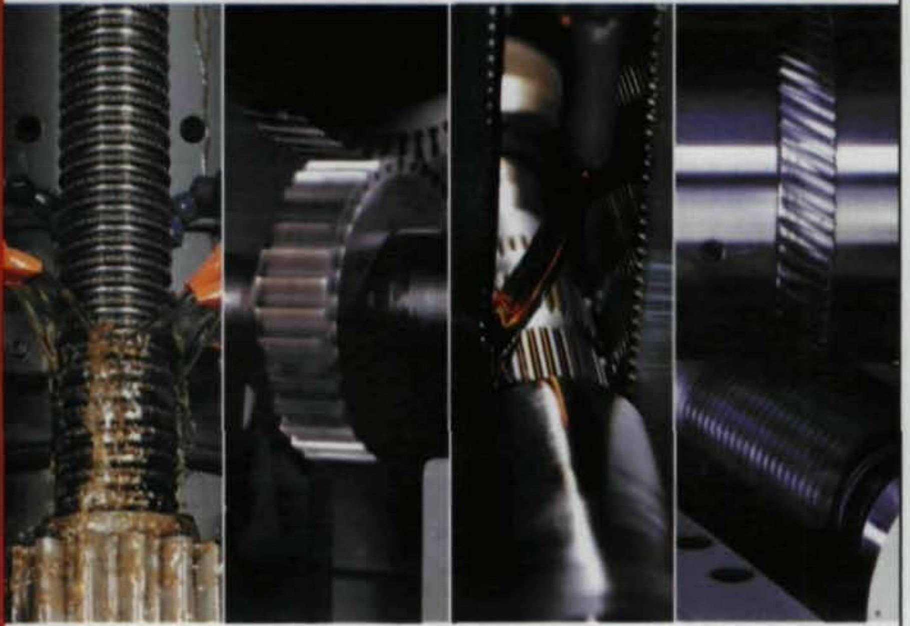

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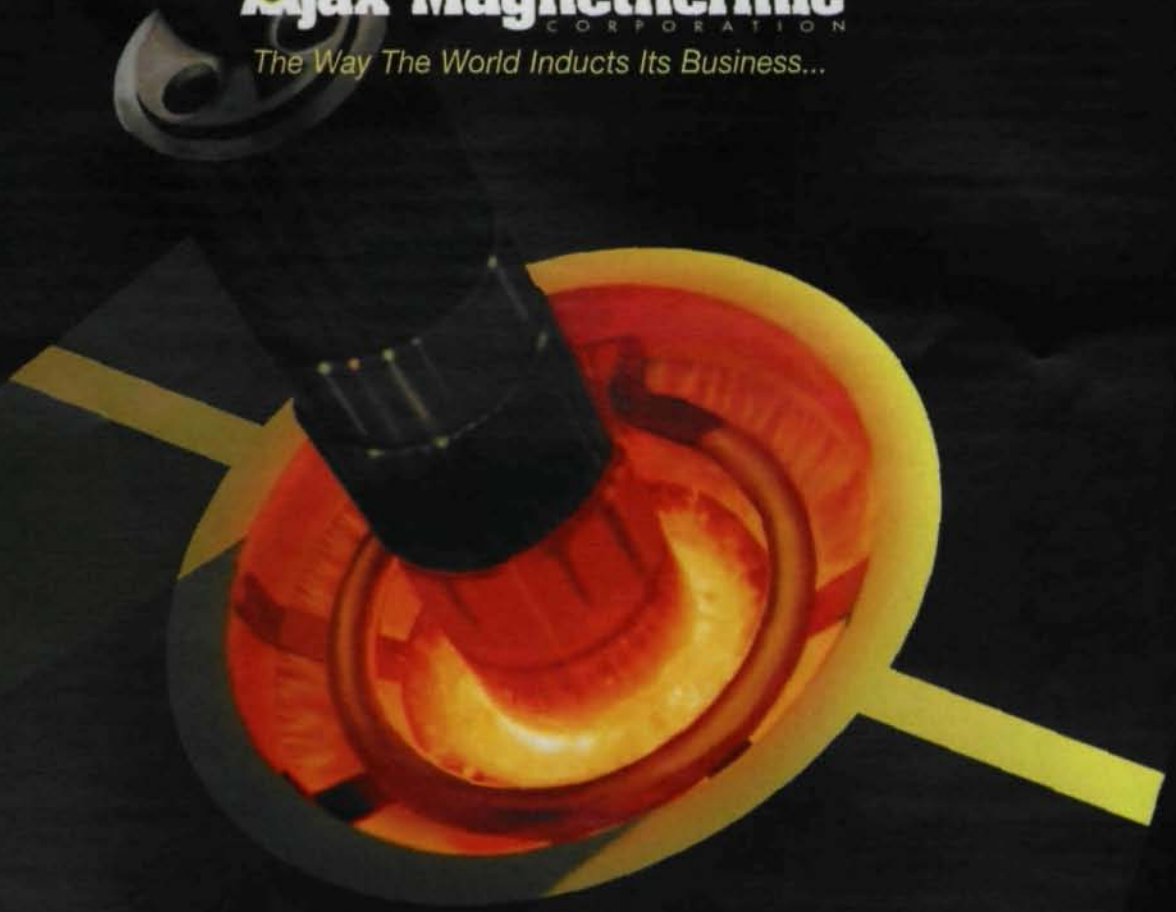

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CIRCLE 117

Out of the Cave:

Returning the Personal Touch to Business

Ever since the first cavemen bartered clamshells and spears, business has been about people interacting.

In simpler times, commerce was conducted according to the look in someone's eye or the feel of his handshake. Today we have computers, fax machines, modems, e-mail and cell phones—all powerful tools that have increased our productivity. Those devices have shrunk our world, but, in some ways, they've also distanced us from each other by reducing personal interaction. In the name of efficiency, profitability and progress, we've found ways to place orders, sell products and exchange information without ever coming into contact with another human being.

We're losing touch with the personal aspects of business, and that's unfortunate. Reaching out and interacting with the people who work with you is one of the most effective, but overlooked, business tools.

Those of us who work in sales know that a personal touch can be good for business. That idea was illustrated recently by an article I read in *Machinery Market* about a report called *Corporate Carelessness*, published by the British Royal Mail. According to the report, 52% of the manufacturing and engineering companies surveyed said they had not renewed a supplier's contract because of poor service. Only about 5% of companies said that price was the main reason for firing a supplier, while 25% blamed unhelpful staff.

Another study performed by the Small Business Administration found that 68% of customers seek new suppliers because they perceive that the sales staff of the existing supplier doesn't care about them.

I'm reminded of a television commercial from several years ago in which the president of a big company learned that one of his best and oldest customers was taking his business elsewhere. The president called a meeting and handed out plane tickets to all his salespeople so that they could fly around the country and reacquaint themselves with all of their customers. The president himself went to visit the old friend who had given up on them.

Maybe it's unrealistic in today's business world for us to achieve the kind of personal service portrayed in commercials. Most of us don't have the time or money to give all our customers that much attention.

But that doesn't mean we should forget about them, either. Our busy lives lead us to focus on projects and deadlines rather than the people who need those projects or who help us meet those deadlines.

Our work lives are filled with stacks of documents, one just like another. Invoices, purchase orders, contracts, blueprints—they're a blur. The stacks on our desks today aren't much different from the ones that were there last year. Also, we're so used to receiving anonymous, computer-generated junk mail that when we receive a message from an actual person, our routine is interrupted. That interruption gives power to the message.

I'm a big believer in personal correspondence, and not just because it helps with sales. Not everything that's beneficial to your business is measurable in terms of immediate impact on the bottom line. Since starting this magazine, we've made a conscious and concerted effort to stay in touch with the people who have helped us put it together, from our technical editors to the people we interview to the authors who write for us. For example, after an issue goes out, we try to send copies to each author along with a personal note—thanking them for their contribution, forwarding any feedback we've received, encouraging them to let us know if they have ideas for future articles. These people aren't our paying customers, but they're essential to what we do. Without them, *Gear Technology* would be just another magazine. I believe that by maintaining personal relationships, we assure the continued success of this endeavor and the ability of our magazine to help you with your pursuits.

All of the personal attention that I'm advocating can be very time-consuming. I'm not suggesting that you abandon important projects for the sake of catching up with a colleague. Nor am I in favor of ignoring the things that make us more efficient, effective and profitable. But losing sight of the personal aspects of business may, in the long run, be harmful.

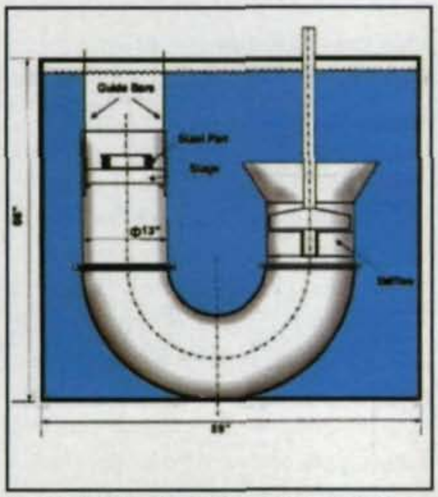
The cavemen communicated with handshakes and discerning looks because they had no other choice. Today we have many ways to communicate, and the number increases every day. But even with those choices, we can't let ourselves forget that effective communication will always be personal.

Michael Goldstein

Michael Goldstein, Publisher and Editor-in-Chief

Intensive Quenching

Every heat treater knows that the greater the part cooling rate during quenching, the better the part performance. However, the conventional wisdom with heat treated parts is that quenching a part too quickly will result in harmful tensile and residual stresses, greater distortion and the possibility of part cracking. But engineers and researchers at IQ Technologies Inc. (IQT) of Akron, OH, are out to prove that controlled, rapid cooling through the martensite range can actually result in higher quality hardened steel with beneficial compressive residual surface stresses on a through hardened part.



A specially designed quench tank keeps water or salt/water solution moving over the quenched part.

IQT's IntensiQuench^{SM} process has been used successfully to quench splined shafts, sprockets and other steel parts, such as coil springs, torsion bar samples, bearing products and gear blanks. It can also be applied to gears, says IQT President Joe Powell, but some applications may require special modification of the quenching equipment. Results of the process have been validated in hundreds of laboratory and field experiments, which demonstrate improvements in mechanical properties, microstructure, compressive residual stress and part lifetime when compared with parts quenched in oil using traditional methods.

During conventional quenching, martensite forms first in the thinner sections of a part, since those sections cool more rapidly than the thicker sections. The difference in cooling rates results in distortion and possible cracking. The IntensiQuench process uses a highly agitated quenchant (usually water) to cool the part rapidly but uniformly, according to Powell. Moreover, the process quenches parts three to six times faster than other methods, without the usual distortion, he says.

The unique, 6,000-gallon quench tank is equipped with four 18-inch impellers rotated by 10-hp variable speed motors to keep the water or salt/water solution moving over the part. In addition, the quench tank is equipped with a temperature and concentration control system to ensure the proper conditions of the cooling medium.

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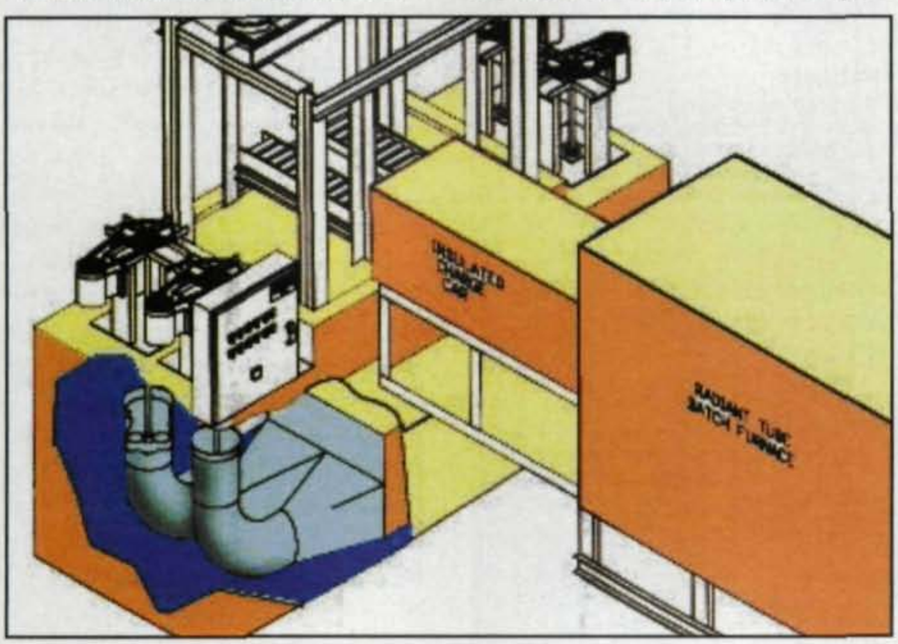
Those controls are essential, because one of the keys to the IntensiQuench process is to interrupt the cooling of the part at the critical temperature when compressive stresses on the surface are at their maximum. The part is then held at that temperature, allowing the continued, even formation of martensite, resulting in higher uniform surface compression and increased strength in the parts.

Depending on the application, the beneficial surface compressive stresses created through the process can sometimes take the place of carburization or shot peening, Powell says. He adds that the ability to increase the amount of martensite formed in a given steel allows the part designer to use a less expensive steel or one with lower alloy content and still achieve the same hardness.

The IntensiQuench process relies heavily on sophisticated computer modeling, Powell says. By performing finite element analysis and a series of calculations, the process software can determine



Intensive quenching can be installed in-line with any heat source. Shown above are quench tanks used with a batch furnace.

a part's thermal and stress profiles. That allows the process to accurately predict the critical holding temperature and to achieve the optimum hardened depth with compressive stresses.

The quenching process can be used with induction, atmosphere, salt, vacuum or any other type of heat treatment, and it has been used successfully with most common steels, Powell says.

Circle 300

NDT Process Finds Cracks By Shaking Parts

An infrared NDT process has been developed that detects closed cracks by forcing their two sides to rub together, then photographing the resulting heat—all in less than a second.

The ThermoSoniX test station finds closed cracks in parts by using ultrasonic energy to force the cracks' sides to rub together, which creates heat, and imaging that infrared energy with the station's camera.

Suitable for quality control, the nondestructive testing technique was developed at Wayne State University in Detroit. A commercially available version of that technology is the ThermoSoniX test station, manufactured by Indigo Systems Corp. of Santa Barbara, CA.

The test station can be used in gear manufacturing to supplement or replace other inspection methods, like dye penetrant, Magnaflux, and visual inspection using a microscope.

To detect cracks, the station directs a pulse of high-frequency sound at a part surface. The pulse lasts 50–200 milliseconds and has a frequency of 20 kHz.

The sound makes the part vibrate. If there's a crack, even a closed crack, its two sides will vibrate as well. But, they won't vibrate in unison. They'll rub, creating heat. The station's infrared camera detects that heat, showing the crack's location on the part surface.

The station can detect temperature changes as small as 0.02°C. The NDT process raises a crack's temperature a few degrees Celsius. Consequently, the cracks look like "explosions," process developer Bob Thomas says.

Also, the process can detect cracks vertical to a part surface—without being perpendicular to them. Vertical cracks can be hard to detect. Process developer "Skip" Favro says looking at a vertical crack is like looking at a knife's cutting edge—"There's not much to see."

Consequently, inspection devices can better detect a crack when they're perpendicular to the crack, so it looks like a sheet, not a line. The ThermoSoniX test station can detect cracks regardless of their orientation to a part surface.

According to Thomas, the NDT process can be automated for high-volume inspection. However, Austin Richards, Indigo Systems' project manager for the test station, explains that the station is mainly intended for hand inspection of low-volume, high-cost parts. The station can be automated to inspect up to 30 parts per second.

The NDT process can inspect metals, like steel and iron, ceramics and composites. "It can do basically any solid," Thomas says.

Richards, who holds a doctorate in physics, estimates the station can detect cracks 4 or 5 millimeters beneath a part's surface and likely can inspect parts weighing up to 100 kilograms. The station itself weighs 150 pounds and fits on a 3-foot-by-5-foot surface, like a desktop.

For the process to work, a part must be solid and be a good emitter of infrared energy with wavelengths of 3–5 microns. Richards describes that wavelength range as: "A great waveband if you want to see tiny bits of changes in surface temperature."

The station provides real-time displays of cracks. Also, it uses no consumables, as with dye penetrant and Magnaflux, and no radiation, as with X-ray processes.

Also, X-ray imaging can't effectively detect some types of cracks, like compression cracks. During manufacture, a part can crack at high temperature, but that crack can close as the part cools, becoming a nearly invisible compression crack.

The deeper the compression crack is, the more the crack weakens the part. A shallow crack may not weaken a part too much, but any crack can be dangerous because it can grow as the part is used.

As a drawback, the test station can be quite loud. "It's a good idea to wear hearing protection," Richards says.

Also, he describes the station—with its computer, software and camera—as more complicated to set up initially than dye penetrant or Magnaflux is.

"But," he says, "once it's up, it's easy to use."

The station costs about $85,000 and consists of a part platform, a piezoelectric converter that provides ultrasonic energy, a hard metal probe that transmits the energy to the part, a pneumatic actuator that holds the converter, an infrared camera, a mechanical structure that holds the camera, and a computer that controls the station.

"Most of that cost is the infrared camera," Richards says.

A major part of the camera is the detector. That part detects infrared heat. But, it can't do so if it's generating heat itself. Consequently, the detector is cooled by a miniature, closed-cycle helium refrigerator to the temperature of liquid nitrogen—about –350°F.

The camera records a part's image and transmits the 12-bit digital image data to a digital framegrabber, which allows for recording and storing of images in a computer's memory.

As for the cost to operate the station, Richards says: "There's no consumables, you're just buying electricity."

The NDT process was developed by physics professors Favro and Thomas, with electrical engineering professor Xiaoyan Han and their students at Wayne State University. Favro and Thomas are members of the university's Institute of Manufacturing Research.

Favro and Thomas had performed nondestructive testing with infrared cameras for years. They had been using flash lamps to warm a part, then detecting defects as the part cooled. The defects were broken glue joints, corrosion, and delaminations—the popped-apart horizontal layers of a composite material.

Also, that old method detected those defects only if they included air gaps. A defect's gap would reflect heat to the part surface above the defect, making that surface area warmer than the surrounding surface.

"All the kinds of defects we were seeing were parallel to the surface, not perpendicular," says Thomas, explaining that most cracks which people look for in materials are cracks perpendicular, or vertical, to a part surface.

To detect vertical cracks, Favro and Thomas developed another NDT technique and experimented with it in summer 1999. Favro recalls the vertical cracks "lit up like a Christmas tree" using the new process.

They filed for a patent that September. "It happened very fast," Favro says.

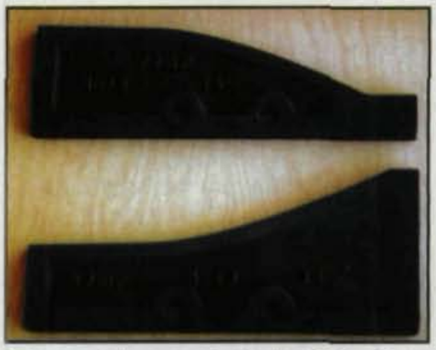
Indigo Systems obtained a license to manufacture products based on Favro and Thomas's technique and developed the ThermoSoniX test station from it.

Circle 301

Vintage Machines Still Producing

Some technologies are worth preserving, says Bennie R. Boxx, president of B&R Machine & Gear in Sharon, TN.

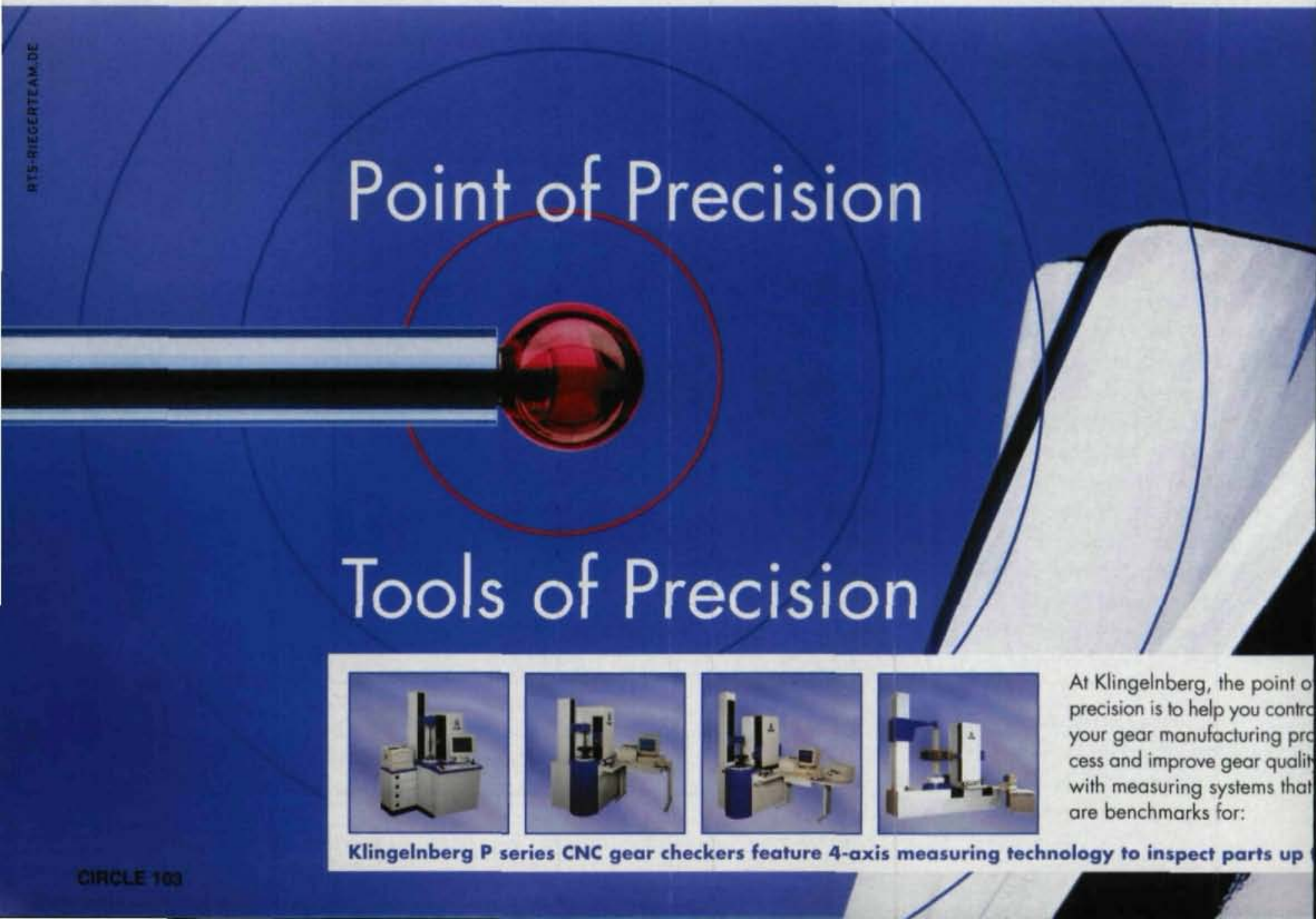
B&R is home to one of America's few remaining model 77GP Gleason Planers, a versatile machine capable of cutting bevel gears up to 80 inches in diameter.



The machine was built in 1917. Since then, the technology for cutting bevel gears has been updated many times. Still, B&R's machine has recently come back into demand, Boxx says.

Much of that demand comes from the steel mill industry, which often requires large bevel gears with pitches as coarse as 0.4 DP. Boxx says that most modern bevel gear machines aren't capable of cutting gears in that pitch range.

B&R uses near-net-shaped forged gear blanks in specialty alloy steels for its large bevel gears. The blanks are machined on the Gleason planers and



then heat treated.

However, running machines that use technology which has been largely forgotten has challenges of its own, Boxx says. One challenge is finding the tooling to make the machines operate. The Gleason planers use top and bottom formers, which are templates used to guide the blades that cut the gear profile. The tooling was originally manufactured by Gleason in standard 14.5- and 20-degree pressure angles.

However, steel mills often require bevel gears with 25- or 27.5-degree pressure angles, Boxx says. When B&R received an order for such gears in 1999, Boxx discovered that the tooling would have to be custom-manufactured.

B&R turned to Trogetec Inc. of Riverton, WY, for help. According to company president Sandor J. Baranyi, Trogetec had never worked with Gleason planers before, but the project was intriguing. "We had the feeling that we could fill the order based on our preliminary design study," Baranyi says. He determined that Trogetec would be able to modify its EZGearPlot version 3.0 software so that it could create the patterns for the formers.

The first time Trogetec created the formers, the process had to be created on the fly. "We didn't have the software yet," Baranyi says, "but we were able to piecemeal it together."

Since that time, Trogetec has released EZGearPlot–GP version 2.0, which, in addition to its gear design functions, is able to create CAD files for manufacturing the formers for Gleason gear planer models *54*, *77*, *144* and *192*. The user enters the gear set's design parameters and the model of the gear planer. "We plug in the data and it goes like a cinch," Baranyi says.

Once the CAD files for the formers are created, the tooling is manufactured from 0.50-inch thick cold-rolled plate using CNC abrasive waterjet cutting technology.

The result is that B&R's Gleason planer is back in business. "Since we started getting the formers made, this machine runs 24 hours a day," Boxx says.

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Dry Hobbing Process Technology Road Map

Glenn Schlarb and Kurt Switzer

This paper was first presented at the 1999 Fall Technical Meeting of the American Gear Manufacturers Association. It has been updated for Gear Technology.

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Introduction

Recent trends in gear cutting technology have left process engineers searching for direction about which combination of cutting tool material, coating, and process technology will afford the best quality at the lowest total cost. Applying the new technologies can have associated risks that may override the potential cost savings. The many interrelated variables to be considered and evaluated tend to cloud the issue and make hobbing process development more difficult.

Considerable work has been done cooperatively between the tool manufacturers and material vendors to improve the capabilities of the substrates being used. Efforts by both high-speed steel and carbide manufacturers are yielding materials that allow a continuous expansion of the envelope of productivity gains in gear production.

With today's advances in gear manufacturing equipment, there is a necessity to advance the capabilities of tools. In order to exploit new machine potential, extensive tool developments have taken place in recent years. Building on the successes (and failures) of earlier efforts, there has been an explosion of new technology with both new coatings and new materials.

The days of having one broad-range coating and limited material selection are long gone. The difficulty now is to determine the best combination possible for a given application, taking into consideration the specific gear manufacturer's expectations.

Table 1—High Speed Steel Compositions.

Alloy Type	C Carbon	Cr Chromium	W Tungsten	Mo Molybdenum	V Vanadium	Co Cobalt	Total Alloy
M4	1.4	4.3	5.8	4.5	3.6	—	19.6
Rex 54	1.45	4.3	5.8	4.5	3.6	5.0	24.7
Rex 45	1.3	4.1	6.3	5.0	3.1	8.3	28.1
T15	1.6	4.0	12.3	—	5.0	5.0	27.9
Rex 76	1.5	3.8	10.0	5.3	3.1	9.0	32.7
Rex 121	3.4	4.0	10.0	5.0	9.5	9.0	40.9

Table 2—Cemented Carbide Compositions.

Grade	% WC Tungsten Carbide	%Cobalt	%Alloy carbides	Transverse Rupture Strength
C2	90	10	0	500 ksi
C4	94	6	0	360 ksi
C5	71	13	12% TaC, 4% TiC	380 ksi
C6	73.5	10	8.5% TaC, 8% TiC	325 ksi

The purpose of this paper is to:

- Describe current technologies of gear cutting tool materials, specifically the relative properties of high-speed steels (HSS) and carbide grades.
- Describe thin-film coating technologies used for both wet (water-soluble or oil) and dry cutting processes, and discuss the properties and merits of those coatings.
- Discuss tool configuration requirements necessary for higher material removal rates and for dry cutting.
- Present application parameters for the use of tools under dry cutting conditions and results of successful and failed applications.
- Discuss the evaluation of the failure modes most common to dry cutting processes.
- Present a systematic approach to aid in the application of the technologies. By evaluating costs and risks associated with various processes for applications, the process engineer can implement new technologies where the savings/risk factor is most favorable.

The scope of this paper is limited to applications of tools in the 10–20 NDP range. However, the concepts presented can be modified and applied to other applications.

Systematic Approach

1. The first step, before making any changes to optimize an existing process, is to fully understand the current process parameters, costs and failure modes. Define the variables, such as part data, material, hardness, machinability, machine capacity and restrictions, tooling rigidity, chip removal issues, speed, feed, number of cuts, and shift strategy. Tool design characteristics, material properties and coatings must be defined. Define the measurables of the present process, such as cycle time, part change time, parts per hour, and downtime for hob change. Costs, such as tool price, sharpening costs and recoating costs, should be known. How much wear is generated for the current number of parts produced? Is the failure mode pure flank wear, or is chipping

or cratering also causing tooth damage? Without a firm understanding of present costs, how can an organization identify the best potential option offering the greatest chance for improvement with the least risk?

2. Perform theoretical evaluations of cycle time possibilities at various hob diameters and numbers of threads and gashes. Hob speed, chip load and feed scallop size will be the limiting factors, within the constraints of machine speed and horsepower capacity.

3. Look at material options, such as carbide, high speed steel and traditional materials, for wet and dry cutting applications.

4. Look at coating options for wet versus dry applications.

5. Look at cost per part (CPP) evaluations of the best options from the above choices.

6. Develop a test matrix to try one or two of the choices that show the best cost predictions.

7. Test tools for initial use and throughout sharpening and recoating, evaluating wear performance, part quality, performance through subsequent operations, etc.

8. Compare actual results to estimates.

Tool Materials

The following paragraphs provide a brief summary of commercially available substrate materials and coatings commonly used in the gear cutting industry. Although some of the information may seem academic, it is essential to have a good understanding of the characteristics of tool materials and coatings in order to maximize efficiency of the application.

Far from the days when conventional (cast) M2, M42 and T15 alloys were the predominant materials in gear cutting tools, the tool designer now has an extensive selection of quality high speed steel materials from which to select. In the United States, the newest generations of materials are manufactured by particle metallurgy (PM) for improved manufacturability, toughness and general cutting performance. Due to the prevalence of vacuum hardening and tempering, many of those alloys have evolved over recent years to optimize their heat treatment response.

Although there is a multitude of high speed steels available worldwide, such steels can be generally categorized into one of several groups based on their physical properties. In order to limit the scope of this discussion, only those materials readily available in the United States are covered.

The most common material in domestic gear cutting tools today is CPM M4 (Crucible particle metallurgy). Typically used in the hardness range of 64–66 HRc, it has very good wear resistance, has excellent edge toughness and is generally applied on a wide range of applications, cutting workpiece materials with hardnesses up to 38 HRc. Since M4 contains no cobalt (Co), it has a relatively low red (hot) hardness. Table 1 shows a comparison of some common gear cutting tool steels.

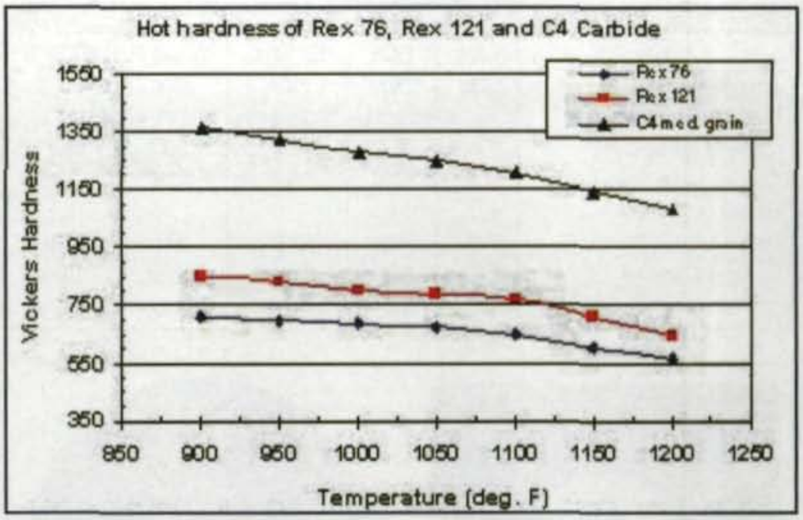

Figure 1—Hot Hardness of HSS and Carbide Materials.

Upgrade considerations to the base M4 material might be considered to take two paths, increased wear resistance or increased red hardness. CPM 54 is a fairly new alloy based on the M4 grade but with slightly higher carbon for higher hardness and with 5% cobalt for improved red hardness. At the high end of abrasion resistance is CPM T15 with an attainable hardness of 66–68 HRc and applicability to workpiece materials up to 48 HRc.

More aggressive applications (e.g. harder workpiece, faster cutting speeds) may require tools with even higher red hardness. CPM Rex 45, with 8% cobalt, is often recommended as an upgrade from CPM M4. Both Rex 54 and Rex 45 contain some amount of cobalt for red hardness, as shown in Table 1. Rex 45 might be selected where red hardness is more critical than wear resistance and Rex 54 where additional red hardness and high abrasion resistance are required.

Applications that generate high heat due to very hard or very abrasive workpiece materials can benefit from high performance steels, like Rex 76 and T15. Again, the selection criteria is based on whether wear resistance is most important (T15) or wear resistance and excellent red hardness are most important (Rex 76).

Cemented carbides are also good candidate materials for gear cutting applications, and as with the high speed steels, there are a wide variety of carbide grades from which to choose. Typical grades for hob manufacture, shown in

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Table 3—Properties of Common Physical Vapor Deposition (PVD) Coatings.

	TiN	TiCN	TiAlN-X	TiAlN-F	TiAlN-H
Hardness (HV 0.05)	2200	2800	2800	2600	2500
Coefficient of Friction (against steel, dry)	0.4	0.4	0.4	0.4	0.2
Compressive Stress (GPa)	−2.5	−3.5	−3.5	−2.5	−2.3
Oxidation onset temperature (°C)	600	400	800	800	800
Coating Color	Gold	Blue gray	Violet gray	Violet gray	Dark gray

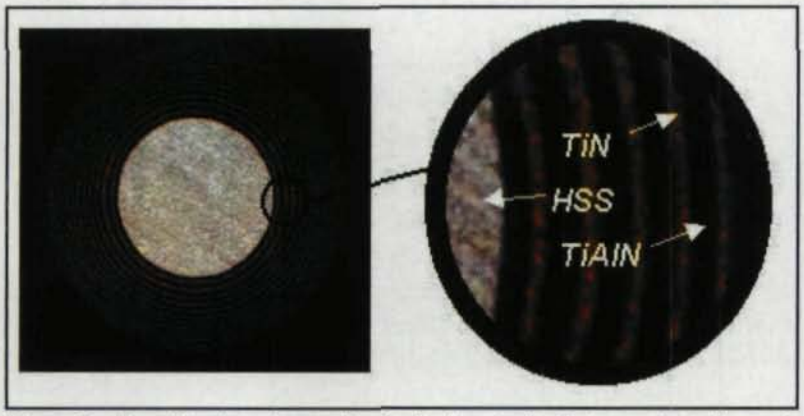

Figure 2—Magnification of ground spherical crater in high speed steel sample showing multi-layered coating.

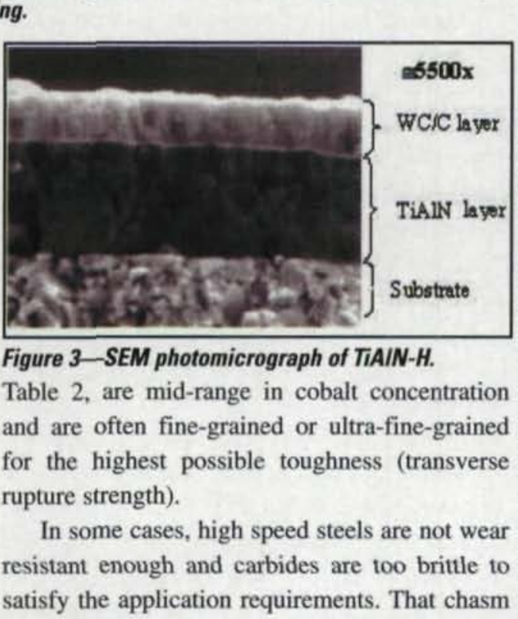

Figure 3—SEM photomicrograph of TiAlN-H.

Table 2, are mid-range in cobalt concentration and are often fine-grained or ultra-fine-grained for the highest possible toughness (transverse rupture strength).

In some cases, high speed steels are not wear resistant enough and carbides are too brittle to satisfy the application requirements. That chasm in the road of application development has led to the development of very specialized high speed steel "bridge" materials.

Rex 121, shown in Table 1, is a good example of that type of material. By comparing the total amount of alloy content (right column), it is clear that the alloy falls into a class of its own. Rex 121 is hardenable to more than 70 HRc and has wear resistance and red hardness levels unprecedented in the high speed steel family. Figure 1 compares Rex 121 hardness at elevated temperatures with Rex 76 and with C4 cemented carbide. Rex 121 is recommended in steel tool applications where Rex 76 is performing without chipping but with excessive wear, and in carbide tool applications where chipping is uncontrollable (perhaps due to workpiece material or design considerations).

Coating Technologies

The advent of commercial physical vapor deposition (PVD) coatings in the early 1980s had a tremendous impact on the gear cutting industry. Titanium nitride (TiN), the first and still most common tool coating, resulted in significant performance gains that allowed tools to run for two to 10 times their normal life. Soon applications were being designed around the expected performance from coated tools—that is, where a coated tool historically gave additional performance gains, the coating was now necessary for the application to work at all.

Today, there is a vast array of PVD coatings appropriate for gear cutting applications. Many of the coatings are unique in both composition and marketing name, but the most common tool coatings can generally be classified as titanium nitride (TiN), titanium carbo-nitride (TiCN), titanium aluminum nitride (TiAlN-X or TiAlN-F) and hard/soft combination coatings, like TiAlN-WC/C (TiAlN-H).

Table 3 shows some physical properties of those coatings. Oxidation onset is a measure of the thermal stability of the coating, which determines its ability to withstand the high temperatures encountered at the cutting edge. With the exception of TiAlN coatings, it is desirable to maintain a cutting edge temperature below the oxidation onset temperature in order to obtain the most benefit from the coating. See below for a more detailed explanation of the thermal characteristics of TiAlN coatings. The hardness value generally correlates with the abrasion resistance of the coating, with higher hardness providing better wear resistance.

Titanium nitride, a gold colored coating, accounts for the vast majority of coated gear cutting tools due to its proven performance base and its relatively low cost. TiN exhibits good thermal stability and can be used in a wide range of applications.

Titanium carbo-nitride (TiCN) is a specialized coating for cutting abrasive workpiece materials in applications that have a relatively low temperature at the cutting edge. Successful applications might include cast iron, alloy steels and fiber reinforced polymers.

Titanium aluminum nitride (TiAlN) coatings are typically used in high-heat generating applications, including dry cutting. Here the intent is to cause the aluminum component of the coating to oxidize, resulting in a thin layer of Al_2O_3 at the surface that is constantly replenished as it is worn away. The Al_2O_3 provides resistance to adhesive wear and also acts as an insulating layer to aid in keeping the frictional heat in the chip. In many cases, a decline in coating performance has been observed when the cutting edge temperature is not sufficient to oxidize the coating.

TiAlN-X is a single-layer coating with a very high hardness that is typically recommended in dry cutting or very high temperature applications.

The choice of coating material was much simpler before the advent of commercial multi-layer and hybrid coating combinations. Coatings can be applied in discrete or graded chemistries and in almost any combination of layers and layer thicknesses. By way of example, consider the TiAlN/TiN multiple-layer coating system TiAlN-F, shown in Figure 2. Here the two component layers, TiAlN and TiN, are deposited as discrete layers and the total layer thickness is on the order of 4–6 microns. There can be multiple advantages in such coating combination systems. First, the coating has a higher toughness due to the inhibition of crack propagation through the layers. Toughness is also enhanced by the distribution of internal compressive stresses due to the presence of the TiN interlayers. Finally, the range of applicability can be extended by the incorporation of the two dissimilar coating types.

Hard/soft coating combinations were of significant interest to many gear manufacturers when they were first introduced. Those coatings are designed to exploit the wear resistant properties of hard coatings as well as the low friction coefficient (high lubricity) features of coatings like tungsten carbide/carbon (WC/C) or molybdenum disulfide (MoS_2). It is well known that the MoS_2-type soft coatings perform poorly with aqueous coolants and can even be susceptible to ambient humidity. The WC/C coatings do not exhibit that behavior and also have the advantage of higher hardness.

Figure 3 shows a scanning electron microscope (SEM) photograph of Balzers Balinit® Hardlube (TiAlN-H), which is a good example of that type of coating system. Originally designed to aid in chip flow and evacuation in deep drilling and tapping applications, it was suggested that additional benefit could be gained in gear cutting by a reduction of frictional heat generated by chip flow on the rake cutting face.

Field testing has shown that the benefit of the coating systems in gear cutting is marginal, and that similar or better performance can generally be obtained by the use of more conventional TiAlN coatings. It is acknowledged that the coatings do have significant advantages for applications like deep-hole drilling, for which they were originally designed.

To round out the discussion on coatings and materials, consideration should be given to tool reconditioning requirements. Today, tool reconditioning often means recoating after resharpening, and that can lead to issues of declining tool performance from excessive coating buildup. Since every application is different, the point at which coating thickness begins to significantly affect cutting performance will vary. Table 4 shows guidelines for stripping and recoating based on experience with production applications, although it is generally agreed that the best performing reconditioned tools are stripped before recoating.

It should be noted, in the case of carbide substrates, that "conventional" chemical stripping is not a recommended option. Although it can be made to work, leaching of the cobalt binder from the cemented carbide by the stripping solution leads to degradation of the surface integrity, and recoating can be risky. Furthermore, tool markings and bore or shank diameters may be affected. Since regrinding of the tooth form to remove a coating can lead to large reconditioning costs, the use of non-recoatable coatings like TiAlN-H should be carefully considered.

Recently, a new chemical stripping technology was introduced that can safely strip most common PVD coatings from C2–C4 type (ISO K-grade) cemented carbides. That proprietary technology is still fairly new and is being scaled to production levels at Gleason Cutting Tools Corp.

All high speed steels are appropriate for stripping, and all of the noted coatings are strippable by chemical methods. Unlike carbide substrates, proper stripping techniques result in no leaching of alloy constituents or damage to the substrate.

Application Parameters

Speed recommendations for wet and dry hobbing are shown in Table 5. Cutting speed is a function of the part material, part hardness, hob material and hob hardness.

The axial feed rate is a function of the chip thickness, which depends on the edge toughness of the tool material, hob outer diameter, number of gashes, threads, depth of cut, etc. For that reason, Table 5 shows a recommended chip thickness rather than a straight feed recommendation.

The shift strategy for wet applications is generally a small, incremental shift amount after each part is cut. The hob is shifted one pass across its face width. The shift amount per part is determined based on the wear developed. A life factor in terms of lineal meters per hob tooth (LM/T) in

Table 4—Tool Reconditioning Guidelines.

Coating Type	Strippable?	Recoatable?	Number of Recoatings
TiN	Yes	Yes	3–7
TiCN	Yes	Not recommended	—
TiAlN-X	Yes	Yes	2–4
TiAlN-F	Yes	Yes	2–4
TiAlN-H	Yes	No	—

Table 5—Application Parameters.

	Wet cutting	Dry HSS	Dry Carbide
Speed (Surface meters/minute)	100 SMM	150–200 SMM	250–300 SMM
Chip Thickness (mm)	0.20–0.25 mm	0.25–0.30 mm	0.05–0.15 mm

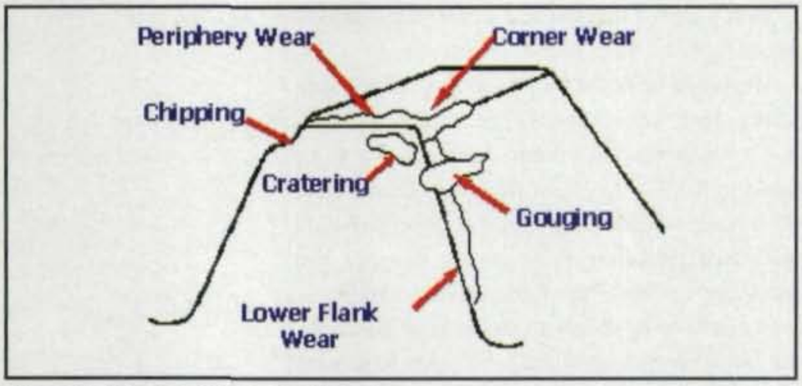

Figure 4—Six main types of tool wear.

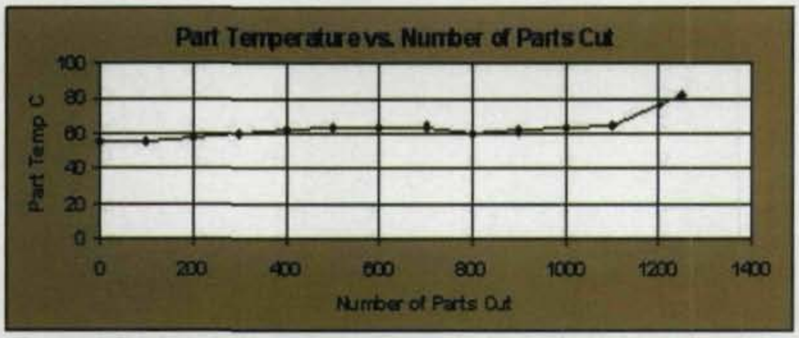

Figure 5—Chart of part temperature vs. number of parts.

the shiftable engagement zone can be determined. Conversely, a life factor developed empirically for one application can be applied to a similar application to determine the shift amount per part. If tool life is good, multiple parts are cut in each shift position to increase the lineal-meters-per-hob-tooth life factor for a desired amount of wear.

The shift strategy for dry applications is somewhat different. A larger shift amount equal to approximately one axial pitch should be used. The hob is shifted across the total usable face width and then returns to the initial shift position. An offset is used to more evenly distribute wear over the flanks of the teeth. The offset amount is equal to the axial pitch divided by the number of passes to be used. The hob is shifted at one axial pitch per part as before. The shift strategy provides time for the hob's built-up heat to dissipate when teeth are not in the cut.

Climb cutting is the preferred cutting method for a dry process versus the conventional cutting method. The thicker chip at the start has less tendency to weld to the cutting face. Chips welding to the cutting face can cause scuffing or tearing on the part flank, as the chips may get trapped and interfere with the finish cut. However, climb cutting produces slightly hotter part temperatures and has higher power consumption.

Tests of like hand, climb hobbing versus opposite hand, conventional hobbing on a dry cutting process revealed no significant difference in tool life or part quality.

Tool Configuration Changes

With dry carbide hobbing, generally high cutting speed and low feed is employed to achieve a fast cycle time, with good surface finish and small feed scallops on the part flanks. Since carbide is low in toughness, chip thickness is limited to a range of 0.050–0.150 mm. The hob can be made with low numbers of threads (one or two) to keep the chip load down. The hob diameter is kept small to maximize rpm. Gashes are maximized to reduce feed scallop and chip load. However, an adequate gash size is required to allow for the removal of chips from the cutting zone. The number of gashes, the gash size, and the sharpenable length of tooth are the trade-offs to be considered. Since the hob is generally recoated, and several layers of coating can begin to cause flaking or adherence issues, we generally recommend establishing a sharpenable tooth length that will result in six to eight uses.

Since cycle time is minimized, the volumetric rate (cubic inches per minute) of material being removed is maximized, and chip flow becomes critical. Too small of a gash size may allow chips to wedge into the bottom (chip packing) and lead to a catastrophic failure. A larger gash radius, back angle, and grinding the backs of gashes improves chip flow. With dry hobbing, no coolant is available to help flush chips out of the cut. A 5° hook sharpening on the face helps direct chip flow away from the cutting zone and reduces power consumption and heat generated. With carbide, gash sharpening is limited to straight gash due to manufacturing limitations. With high speed steel hobs, spiral gash angles can be used, even at low thread angles, to help equalize cutting chip curl angles and assist in chip flow away from the cutting zone.

Edge preparation of carbide hobs after sharpening and prior to coating helps reduce chipping tendency. A cutting edge radius of 0.0003–0.0005 in. is generally recommended. A larger "edge prep" amount causes the tool to act dull, increas-

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Table 6—Carbide vs. HSS dry cutting of pinions.

Workpiece Data		Results	Carbide TiAlN-X Dry	Rex121 TiAlN-X Dry
Generating Module	1.40	Parts per hob use	3,360	6,700
Gen. NPA	15	Cutting Cycle time	0.16 minutes	0.10 minutes
HA	20° LH	Floor to Floor time	0.26 minutes	0.20 minutes
Face Width	29 mm	Tool cost per part	$0.19	$0.08
Number of Teeth	23	Machining CPP	$0.22	$0.17
LM/part	0.627	Total CPP	$0.41	$0.25
		LM/T	5.3	8.8

Table 7—TiAlN-H vs. TiAlN-F cutting automotive gear.

Workpiece Data		Results	Rex121 TiAlN-F	Rex121 TiAlN-H
Generating Module	1.41	Parts per hob use	720	1,800
Gen. NPA	15°	Cutting Cycle time	0.17 minutes	0.20 minutes
HA	20° RH	Floor to Floor time	0.23 minutes	0.29 minutes
Face Width	30.8 mm	Tool cost per part	$0.47	$0.16
Number of Teeth	35	Machining CPP	$0.23	$0.25
LM/part	1.15	Total CPP	$0.70	$0.41
		LM/T	1.99	4.97

Table 8—Rex 121 vs. M35 dry cutting truck gear.

Workpiece Data		Results	Rex121 Dry TiAlN-FW	M35 Dry TiAlN, single layer
Generating Module	3.02	Parts per hob use	980	686
Gen. NPA	20	Cutting Cycle time	1.3 minutes	1.3 minutes
HA	0	Floor to Floor time	1.5 minutes	1.5 minutes
Face Width	31.9	Tool cost per part	$0.40	$0.58
Number of Teeth	35	Machining CPP	$1.27	$1.28
LM/part	1.16	Total CPP	$1.67	$1.86
		LM/T	5.75	4.28

Table 9—Rex 76 TiAlN-F cutting spline part with oil coolant

Workpiece Data		Results	Rex 76 TiAlN Oil	Rex 76 TiAlN-F Oil
NDP	8/16	Parts per hob use	74	216
NPA	30°	Cutting Cycle time	1.83 minutes	2.3 minutes
HA	0	Floor to Floor time	1.98 minutes	2.45 minutes
Face Width	292 mm	Tool cost per part	$3.69	$1.26
Number of Teeth	19	Machining CPP	$1.93	$2.13
LM/part	5.55	Total CPP	$5.62	$3.39
		LM/T	1.6	4.67
		Notes:	152 SMM, 1 pass @ 1.9 mm shift, hob peeled back 1.5 mm	122 SMM, 8 passes @ 5.0 mm shift, 0.15 mm wear

ing the heat generated and reducing the tool life factor. Edge preparation of high speed steel hobs is generally not required beyond the standard burr removal process in preparation for coating.

The static cutting clearance is a result of the outer diameter, cam clearance angle and a function of the steepness of the pressure angle. Relative velocity of the side of the tooth and the space of the gear material as yet uncut, moving toward the side of the tooth, creates a dynamic cutting clearance condition that also can affect the wear at various parts of the teeth. Static and dynamic cutting clearance evaluation must be considered in hob design. Tools that must be short-pitched to low pressure angles and low protuberance angles may not be ideal candidates for dry cutting.

Tools with low clearance angles also tend to cause "pressure welds," which are small particles of part material that are forced onto and adhere to the flank of the part under high heat and pressure. The welded particles are not troublesome for parts that are subsequently shaved, but are a problem for parts to be rolled. Part material may also adhere to the hob tooth face or flank near the lowest clearance area of the form. Commonly called "material pickup," that may cause tearing on the surface finish of the part due to the pickup material acting as a (dull) cutting edge. Material pickup can also be misinterpreted as hob wear.

Failure Mode Evaluation

A key to testing is evaluation of how the tool's cutting edge eventually fails. Figure 4 shows a schematic representation of the six main types of tool wear modes.

Abrasive Wear

Abrasive wear is the desired failure mode after cutting a substantial number of parts. Tool life wear criteria need to be established up front. The present application under wet conditions can be a source of valuable tool life information. Wear should be evaluated under a microscope at a magnification that can resolve the coating, substrate material, wear and material pickup. A 25X or higher magnification should suffice. Wear for carbide or dry high speed steels should be limited to 0.15–0.20 mm (0.006–0.008 in.), which will be fully cleaned up by 0.20–0.25 mm (0.008–0.010 in.) stock removal at sharpening. Use of a tool monitoring system, such as a tool card that tracks the number of parts cut for each use, number of passes, amount of measured wear, amount removed by sharpening, and tooth length remaining, is recommended. That helps track tool costs through the life of the tool. The life factor for each run can be expressed in terms of "lineal meters per tooth engaged for 0.XX mm amount of wear."

Cratering

Cratering as a failure mode generally indicates the feed rate being used is aggressive enough to erode coating and substrate material from the cutting face. The crater begins to form away from the edge, then progresses deeper and closer to the edge. Once the crater reaches the edge, the edge becomes weakened and a chip breaks away, resulting in an edge with no clearance and in eventual peel back failure. The feed rate should be balanced to allow both crater and abrasive flank wear to develop at a controlled rate.

Chipping

Chipping failures are caused by the cutting load exceeding the edge strength of the tool material. A chip leads to more catastrophic damage and therefore is to be avoided. The feed rate is the controlling factor for chip thickness and load on the cutting edge. Rigidity of the part as clamped can also contribute to chipping failures.

Thermal Degradation

The heat generated in dry cutting is dissipated into the chips, the hob and its holding system, the part, the part fixture and the air. Heat in the part causes thermal size changes to dimension over pins (DOP) and lead that must be compensated. Heat in the hob and its fixture may cause distortions that affect involute quality. Heat at the cutting edge interface can reach 900°C, causing oxidation of the coating. That is acceptable and even desirable in the case of TiAlN coatings, as the heat causes a microthin layer of Al_2O_3 that provides additional wear protection.

The feed rate can have a dramatic effect on part temperature. Using an aggressive enough feed rate to cause heat to go into the chip keeps part and hob temperature down. Too aggressive of a feed can cause a high chip thickness that overloads the edge strength of the tool, causing chipping. Too light of a feed rate at high cutting speeds will cause excessive enveloping cuts with thin chips, resulting in rapid tool wear and high part and hob temperatures.

For small parts, measuring part temperature can be an effective way of monitoring the hob's wear condition. As coating on the tool wears through to the substrate material, part temperatures elevate quickly and rapid edge failure follows. After monitoring of a process for "wear amount versus number of parts cut" and "part temperature versus number of parts cut," an empirical stop point temperature limit can be established. Figure 5 shows an application where the part temperature is monitored and the process is stopped at 80°C. Due to variability in sharpening, edge preparation, and reconditioning, the number of parts produced when the 80°C point is reached varies. By using part temperature rather than piece count, the maximum number of parts per use can be safely achieved each run, with less risk of catastrophic failure.

Machine Considerations

The trend toward dry cutting is led by changes in machine design with regard to chip evacuation, thermal stability, and high-speed, direct-drive hob head and work table capability. The entire machine design and construction has been re-engineered to be dry cutting capable. Dry cutting may be possible on existing equipment; however, modifications for chip evacuation may be required.

Application Results

Results of various applications are represented in Tables 6–9 to show comparisons of some successful and marginal results. (At the customer's request, part specifications were changed slightly to keep the application anonymous. But, all applications shown are based on actual test or field results. The tables' data can still be used for general comparison to similar applications.)

Conclusion

Implementation of a new hobbing process, such as dry cutting, requires a discipline of monitoring all process measurables, tracking tool wear, and documenting assignable causes of various wear modes under different parameters. The best method for gear processing is the result of a thorough evaluation of process parameters and costs associated with each of those parameters.

When properly applied and monitored, dry cutting process technologies can result in improved productivity and reduced total cost. A good working relationship with tool supplier, tool maintenance supplier, coating supplier and equipment supplier is required to assure consistency of results achieved.

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Mitsubishi Starts Marketing its Gear Cutting Products Itself in North America

Thomas P. Kelly

Mitsubishi International Corp. started marketing its gear cutting machines and tools directly to North American customers from its new gear cutting technology center.

Mitsubishi's gear cutting machines and tooling were previously marketed through a dealer network, which reported to Mitsubishi Heavy Industries of America, located in Addison, IL.

Thomas P. Kelly was named president of the new center, located in Wixom, MI, a Detroit suburb.

Kelly said the center was created because of gear cutting's high levels of technical specialization and the technology's rapidly changing nature and requirements. He added the center was located in Wixom because it would be close to automotive OEM powertrain plants and those of Tier 1 suppliers.

According to Kelly, the center provides a showroom for Mitsubishi's gear cutting machines and tooling and provides greater capabilities in:

- process development,
- prototype manufacturing,
- machine demonstrations,
- runoffs,
- proposal preparation,
- technical presentations,
- operator training, and
- maintenance training.

Mitsubishi designs, develops and manufactures gear cutting machines and systems and special gear cutting tooling.

AMT Elects New Directors and Officers

The Association For Manufacturing Technology (AMT) elected its 2000–2001 directors and officers at its 2000 annual meeting, held in San Francisco, CA.

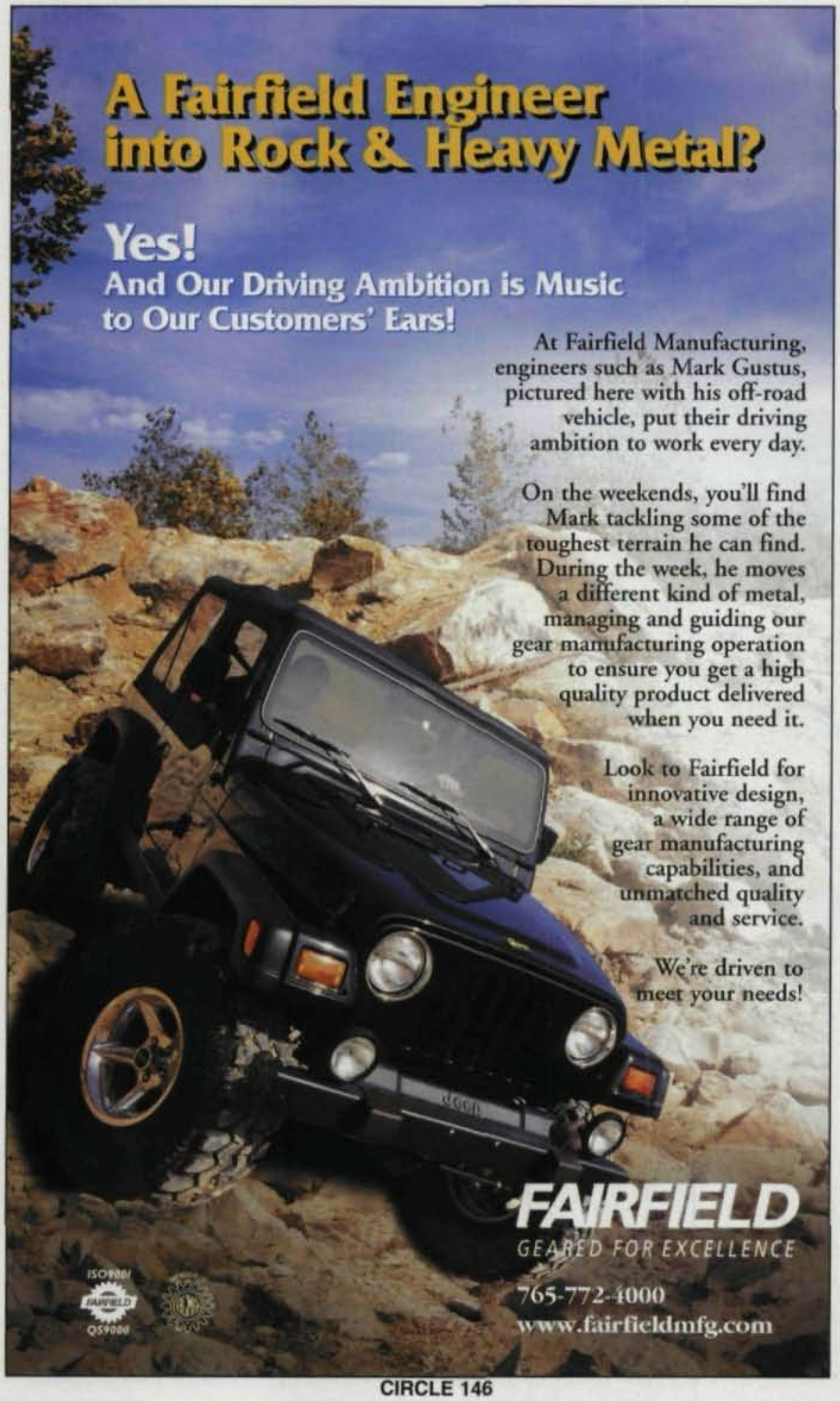
Kim W. Beck was elected by the board to be its chairman. Beck is president of Automatic Feed Co., located in Napoleon, OH. He replaced Stanley A. Woleben as chairman. Woleben is president of Armstrong-Blum Manufacturing Co. of Mt. Prospect, IL.

John J. Winch was elected to be first vice chairman. Winch is president and chief operating officer of The Minster Machine Co., located in Minster, OH.

The second vice chairman and treasurer is Lawrence J. Rhoades, president of Extrude Hone Corp. of Irwin, PA. The secretary is R. J. Weskamp, president of Wes-Tech Inc., located in Buffalo Grove, IL.

The other directors are:

- John L. Drake, CEO of Drake Manufacturing Services Inc. of Warren, OH;
- J. Patrick Ervin, president and COO of Hardinge Inc., Elmira, NY.
- John W. Fedor, president and CEO of Masco Machine Inc. of Cleveland;
- Roger H. Hayes, president, director and CEO of Huffman Corp., Clover, SC;



- Bradley L. Lawton, president of Star Cutter Co., Farmington Hills, MI;
- Kyle H. Seymour, president of Cincinnati Machine of Cincinnati;
- Charles T. Sherman, president of PH Group, Columbus, OH; and
- Douglas K. Woods, president of Liberty Precision Industries of Rochester, NY.

Falk Corp. Has New President

Gary H. Kaine has been appointed Falk Corp.'s new president and has been given the task of increasing its sales in the global industrial market.

Kaine joined Falk, a Hamilton Sundstrand company, after leading a successful turnaround at Sullair Europe, another Hamilton Sundstrand company. He was Sullair Europe's president from 1996 to 2000. Under Kaine, Sullair Europe went from losses to profits through restructuring and an emphasis on customer growth and increased productivity.

"My long-term commitment is to serve customers with greater speed, accuracy and quality through on-time product delivery, rapid introductions of new products to the market, and by focusing on e-business," Kaine said.

Falk Corp. manufactures industrial power transmission machinery. Hamilton Sundstrand supplies aerospace and industrial products and is a subsidiary of United Technologies Corp.

Metso to Develop Gear Service and Wind Power in Finland

Metso Corp. will build new technology facilities in Jyvaskyla, Finland, for developing its gear service capabilities and wind power technology.

The building program includes expanding production facilities for wind turbine gears. The market for wind power plants is increasing annually by 40 percent, with the greatest growth in the highest power classes. Metso said developing gears for such plants requires full-scale testing facilities and a remote diagnostics capability.

The company also said extra facilities are needed for gear production and for the growing field of gear service.

The new facilities will include a continuous testing laboratory able to test gear units that can generate up to 6 megawatts of power. As for gear service, the facilities will emphasize global development, training and support operations for maintaining wind power gears, integrated paper machine drives and heavy industrial gears.

The facilities were scheduled to be completed in October 2001.

Metso Corp. supplies process industry machinery and systems.

Caterpillar Gets Almost $19 Million for Two Projects

Caterpillar and its joint venture partners received almost $19 million from the Commerce Department's National Institute of Science & Technology for two research and development projects.

Caterpillar said one project, "Coating-Enabled Component Design/Technology Tools for Nanostructured Coatings," was intended to develop lighter, more efficient and more durable power transmission gears and other machine components.

The project was expected to benefit the economy, especially the automobile industry, by more than $6 billion annually.

The company said the other project, "Intelligent Flexible Laser Integration," was meant to overcome Europe's lead in laser-based manufacturing by developing a new high-powered laser that would be capable of multiple functions. The laser would be used to improve manufacturing and repair in fields such as commercial and naval shipbuilding, aircraft and automobile industries, and construction and mining.

That project was expected to benefit the economy by more than $12 billion over a six-year period.

Caterpillar's partners in the gear project include J.A. Woollam Co. and United Technologies Research Center. Caterpillar's partners in the laser project were Cutting Edge Optronics, MTS Systems Corp., Bender Shipbuilding and General Electric Corporate Research and Development.

Work on the multi-year projects was expected to take place in Mossville, IL, at Caterpillar's Technical Center, and at the partners' facilities.

Tell Us What You Think . . .

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If you would like to respond to this or any other article in this edition of *Gear Technology*, please fax your response to the attention of Randy Stott, managing editor, at 847-437-6618 or send e-mail messages to *people@geartechnology.com.*

TECHNICAL CALENDAR

March 6–7—Textron's Gear Institute Courses. Textron Technical Training Center, Traverse City, MI. Textron Power Transmission is offering spring courses at its Gear Institute. A two-day intermediate gear course will be held March 6–7. The course costs $595. A two-day maintenance course will be held March 20–21. It costs $395. Both courses will be repeated in April and May. A three-day advanced gear course will be held in April and May. That course costs $795. For more information, visit *www.TextronPT.com.*

March 19–23—Gleason Corp. Gear Fundamentals Course. Gleason Gear School, Loves Park, IL. Gleason Corp. is offering *Basic Gear Fundamentals*, a four-day program for people new to gear manufacturing who want a basic understanding of gear geometry, nomenclature, manufacturing and inspection. The program costs $895 and also will be held April 23–26 and on other dates throughout the year. For more information, visit *www.gleason.com.*

May 7–11—AGMA Training School for Gear Manufacturing: Basic Course. Richard J. Daley College, Chicago, IL. The American Gear Manufacturers Association is offering a basic course to gear companies' newer employees about setting up machines, inspecting gears, doing gearing calculations and understanding basic gearing. The course costs $650 for AGMA members and $775 for nonmembers. The course will be repeated in June, September and October. For more information, contact the association by telephone at (703) 684-0211, by fax at (703) 684-0242, or via e-mail at *fentress@agma.org*. Or, visit *www.agma.org.*

May 21–23—Fundamentals of Parallel Axis Gear Manufacturing. Pheasant Run Inn and Resort, St. Charles, IL. The three-day seminar is intended for entry-level gear-manufacturing employees and includes demonstrations of current gear-manufacturing equipment. To register, send your name, title, company, address, telephone and post office number to Koepfer America L.L.C., 635 Schneider Drive, South Elgin, IL 60177. Koepfer can also be contacted by telephone at (847) 931-4121 or by fax at (847) 931-4192.

***Additional events can be found on the technical calendars at* www.geartechnology.com *and* www.powertransmission.com.**

If you have an event you want included in the technical calendar, you can fax information about the event to* Gear Technology, *to the attention of Randy Stott, managing editor, at 847-437-6618.

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FOCUS ON HEAT TREATING

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Photo courtesy of Inductoheat

The Submerged Induction Hardening of Gears

D.W. Ingham and G. Parrish

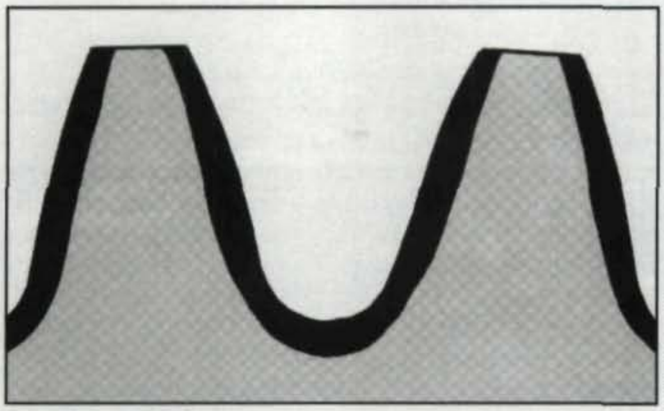

Fig. 1—Typical hardening pattern.

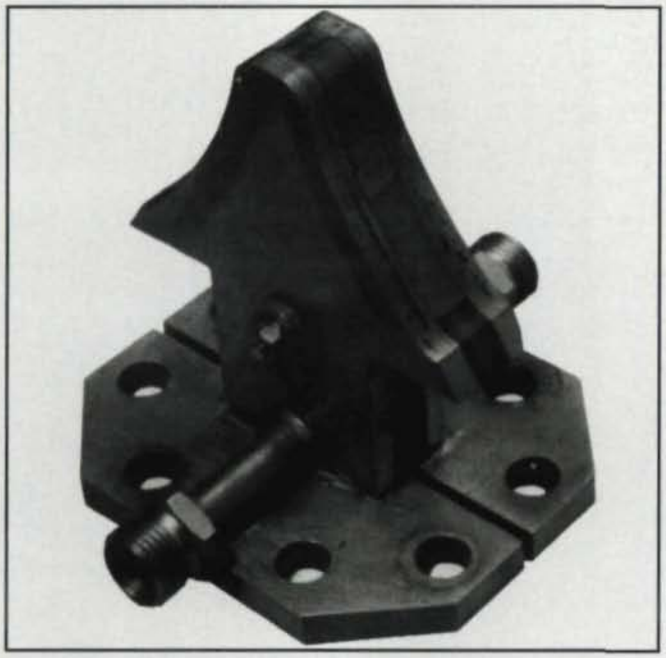

Fig. 2—The inductor.

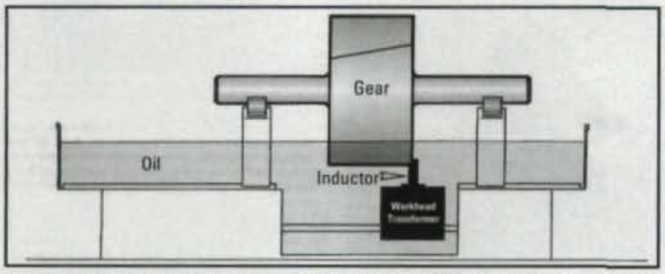

Fig. 3—Schematic diagram of the gear handling machine for tooth-by-tooth submerged induction hardening.

This article is based on papers previously presented in Heat Treatment of Metals, 1998.1 and 1998.2, published by: The Wolfson Heat Treatment Centre, Aston University, Aston Triangle, Birmingham B4 7ET, UK.

This article was also presented at the 1999 Fall Technical Meeting of the American Gear Manufacturers Association.

Printed with permission of the copyright holder, the American Gear Manufacturers Association, 1500 King Street, Suite 201, Alexandria, Virginia 22314. Copies of the paper are available from the Association. Statements presented in this paper are those of the Authors and may not represent the position or opinion of the American Gear Manufacturers Association.

Introduction

The tooth-by-tooth, submerged induction hardening process for gear tooth surface hardening has been successfully performed at David Brown for more than 30 years. That experience—backed up by in-depth research and development—has given David Brown engineers a much greater understanding of, and confidence in, the results obtainable from the process. Also, field experience and refinement of gear design and manufacturing procedures to accommodate the induction hardening process now ensure that gears so treated are of guaranteed quality. The process's purpose is to produce a continuous hardened layer, which extends along the tooth length and from the tooth's tip, down its flank, around the fillet and root area and up the opposite flank to the next tooth's tip (Fig. 1), and to ensure the depth of the hardened zone is sufficient, so the subsurface high tooth stresses are contained in the high strength regions.

In the submerged, tooth-by-tooth process, the inductor (Fig. 2), which has essentially the same shape as the space between two adjacent gear teeth, is energized and traversed along the tooth space, heating and austenitizing the neighboring tooth surfaces, including the root-fillets, as it goes. The heating operation occurs below the quenchant's surface so, as soon as the inductor has moved on, it is replaced by the surrounding quenchant; thus, heating and quenching are localized, progressive, and of short duration.

The heated and quenched zone is so localized that distortion and growth problems, which tend to plague carburize case hardening, are essentially avoided. High surface hardness and surface compressive residual stresses, imparted by the process, dramatically improve the contact and bending fatigue strengths.

This article deals with many aspects of the process itself, describes problem areas, considers applications and discusses the product's properties and quality.

The Induction Hardening Process

At David Brown, the frequency used for gear induction hardening is 9.6 kHz, and the range of tooth sizes processed is 8 to 38 module. Figure 3 is a schematic drawing of the facility, which is adjacent to a generator, water-cooling tank, oil-circulation tank and control console.

The gear handling machine rigidly supports the gear, accurately rotating, aligning and indexing it during processing. The water-cooled inductor is secured to a workhead transformer that is mounted on a carriage in the gear handling machine (Fig. 4). The workhead transformer can be set to traverse a distance of more than one meter on linear bearing tracks. The inductor's actual travel length is controlled by preset limit switches. The machine is meant for the process's submerged version, with the inductor at the bottom center position. Consequently, much of the handling equipment is in an open tank filled with quenchant during processing and drained for loading and setting up.

The generator, which provides up to 75 kW, converts the main power supply of 380 V, 50 Hz, to a medium frequency (9.6 kHz) supply at a nominal voltage of 500 V. That is transformed to a supply of 50-V energy by the 14:1 workhead transformer in the gear handling machine.

The water-cooling tank supplies three recirculatory lines:

a) to the inductor, which is capable of some heating via its own resistance and by radiation from the workpiece during processing;

b) to the quenchant's heat exchanger; and

c) to the generator and the workhead transformer.

The control console manages the induction hardening process by control of the inductor traverse speed, inductor energizing and de-energizing, quenchant flow, cooling water supplies, etc.

Over many years, David Brown performed research projects on the process, besides production hardening. Consequently, relationships between hardening parameters and hardened depth/pattern have been established, eliminating the need to establish parameters on separate test pieces.

The process is controlled by several significant parameters, these being:

1) The Inductor Workpiece Gap. The space between the inductor and the gear tooth is critical. The surface-to-volume ratio differences around the tooth profile demand different energy requirements. Consequently, the shaping of the inductor (Fig. 5) is important to optimize the coupling. The inductor is designed for rigidity to ensure accurate geometrical positioning.

Research has shown the heating effect is controlled by the inductor's design. The David Brown design includes two copper sides connected by a copper bridge along the root. Thermocouples in the body of

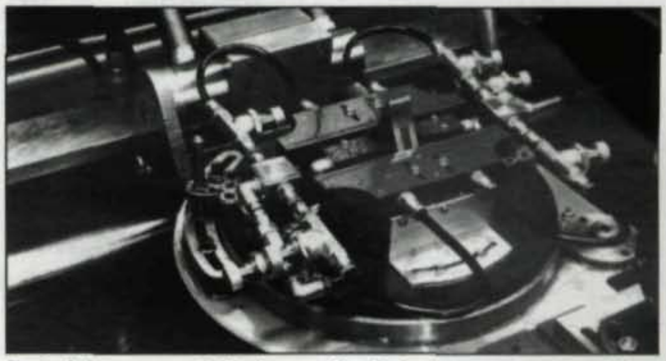

Fig. 4—Inductor surrounded by its quenching blocks, all mounted on the workhead transformer.

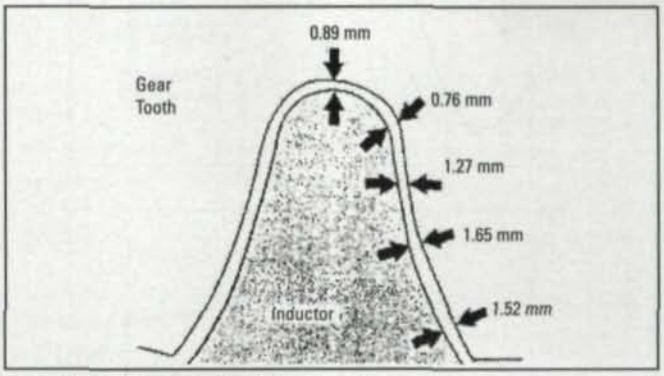

Fig. 5—Typical inductor-to-workplace coupling.

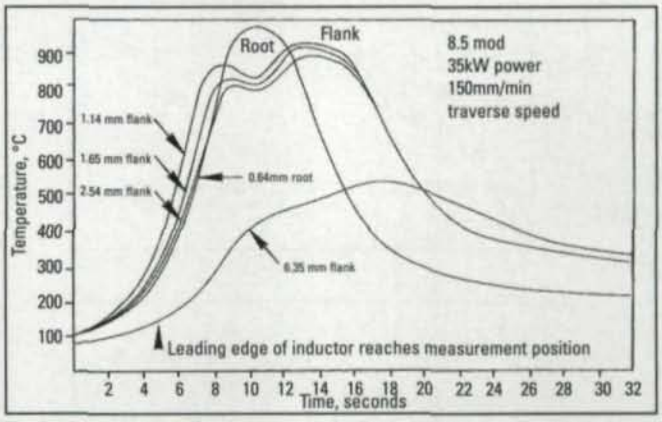

Fig. 6—An example of the temperature distribution within a gear tooth during an inductor pass. The depth and location of the temperature sensor is indicated against each temperature curve.

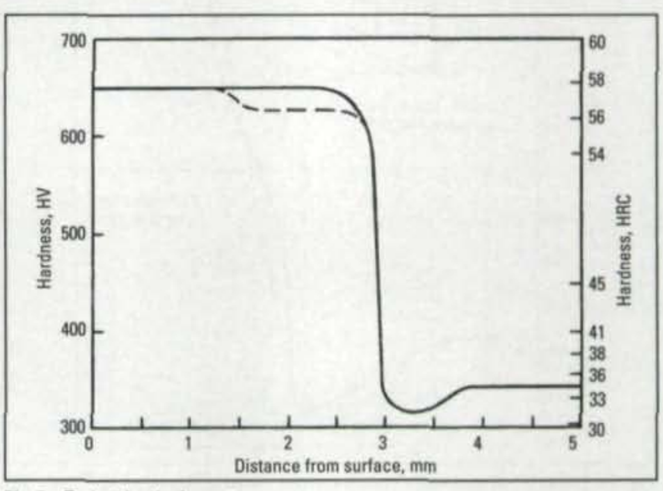

Fig. 7—Typical hardening pattern.

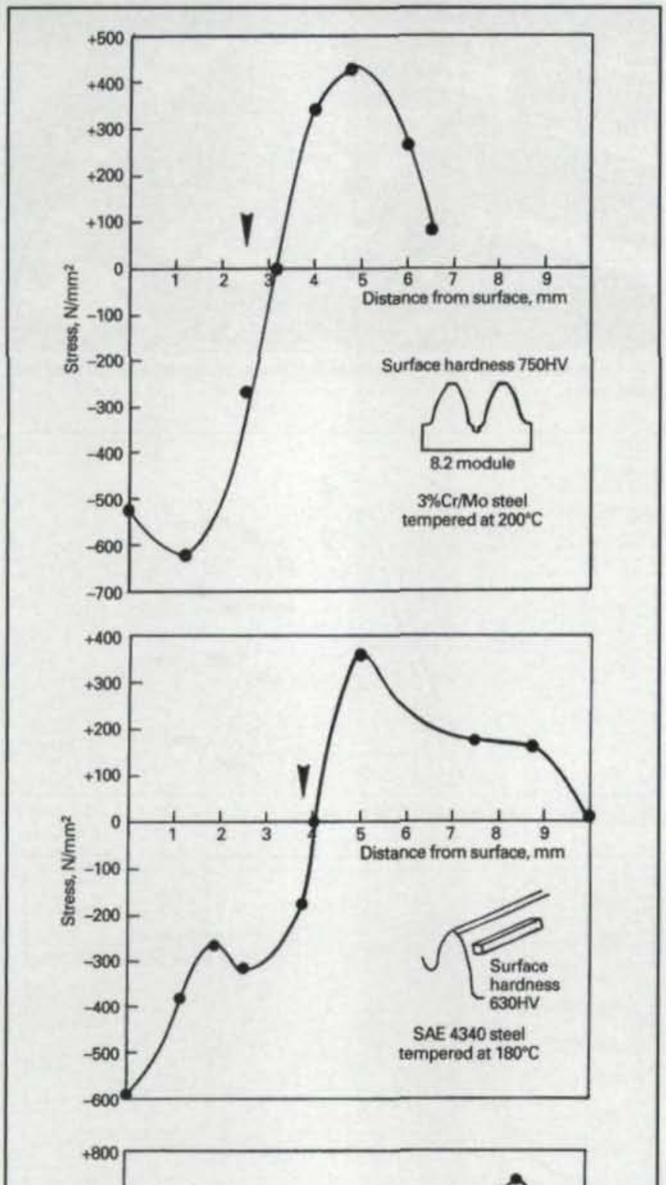

Fig. 8—Examples of residual stresses through an induction-hardened case. Test locations shown. Arrow denotes approximate effective case depth (to 450 HV).

a tooth being hardened have shown a typical temperature profile (Fig. 6). On the mid-flank position, two temperature peaks are experienced, coinciding with passage of the inductor's copper sides. In the root position, a single peak is found, associated with the copper bridge.

David Brown's practice involves the exclusive use of numerically controlled machine shaping of inductor blanks. The use of accurate shaping means it is only necessary for the operator to ensure that the inductor is aligned, central to the tooth space, and that the root gap is correct. When that is done, the inductor-to-workpiece gaps at other positions around the inductor will be correct.

2) The Power. As power is increased, the depth of heating is increased for a tooth size. It naturally follows that the larger the tooth size, the larger the power requirements.

3) Inductor Traverse Speed. Traverse speed determines the depth of heating by allowing more time for heat diffusion. Sufficient time should be available to allow transformation to austenite. Research by a dilatometry study showed that for an 817M40 (4340) steel in the quenched and tempered condition, three seconds were required to achieve carbon solution, and that a degree of coarsening with a slight reduction of hardness took place after nine seconds. Therefore, heating times within the three- to nine-second range are normal for the process, which means that if the inductor has an effective length (time above AC3) of 18 mm, the traverse speed range will need to be in the approximate range of 125 mm per minute to 350 mm per minute.

4) Quenching and cooling jets. Surrounding the mounted inductor are: a) the fore and aft quenchant curtain jets, which help stabilize the vapor phase that occupies the coupling space and hasten and control the quenching, and b) the side sprays—also curtain jets—which play on the tooth top edge and adjacent flank to control the heating pattern on the tooth's top and the amount of back-tempering on the adjacent tooth addendum. The settings for those jets, and the quantities of quenchant flowing through them, are important.

5) Power switching. When a tooth space is to be hardened, the inductor is automatically advanced into the tooth space to a distance equal to about half the inductor's length. At that point, the inductor is energized, and—after a short dwell at the entry—the inductor's traverse along the tooth space commences. Similarly, at the tooth's exit end, the inductor stops, dwells and is de-energized. That generally ensures a satisfactory hardening pattern at the tooth ends. But, experience has shown that on occasions, the exit pattern could be improved by canceling the dwell and running through on full power, or by running through and de-energizing during the exit. Those are minor adjustments aimed to ensure a good product.

Steels For Induction Hardening

At David Brown, we adopted the policy of using medium carbon alloy steels of the 4340 type composition for induction hardened applications. The

4140 type is also used in limited quantities. Those types will produce a pre-tempered surface hardness of more than 57 HRC, and a tempered surface hardness of typically 55 HRC. With today's inherently clean steels, the material's basic quality is not a problem for the hardening process.

The gear blanks are through hardened and tempered either as forgings or after rough machining. Tempering should be used to eliminate residual stresses in the gear; therefore, high tempering temperatures (>600°C) should be used. The resulting tempered martensitic microstructure is most suitable for induction hardening because it is homogeneous with respect to carbon, and the carbides' particle size is small, which favors easy solution during the short induction heating period, i.e. 3–10 seconds. The as-hardened and tempered strength need not exceed about 1,000 N/mm^2. Therefore, gear cutting and other machining operations are not difficult to perform.

Resulting Properties

*1) **Hardness.*** Figure 7 shows a typical hardness distribution. Induction hardened surfaces, for which the carbon content is nominally 0.40% C, usually have hardness values of more than 55 HRC, and up to 60 HRC, as hardened. Tempering at 200–250°C reduces hardness slightly to about 54–57 HRC. Two features should be noted: an added plateau of hardness (broken line), and a trough in the curve just below the case-core junction. The first feature, which is occasionally observed, may relate to the extent of carbon solution and the degree of carbon homogenization in the austenite phase, noting that for a steel such as 4340, it will take about three seconds to dissolve the carbides but more time to achieve a modest degree of homogenization. Solution and homogenization are better served by having the fine carbide characteristic induced by previous hardening and tempering. The trough at the hardened zone's end is attributed to short-term tempering. The end denotes where the temperature, due to induction heating, had attained the A1 value of say 725°C. But if the steel was previously tempered at 650°C, the core immediately beneath the case will have experienced heating within the 650–725°C range and hence some additional tempering.

*2) **Microstructures.*** An induction-hardened, low-temperature tempered material's hardened layer usually consists of fine tempered martensite, and the structure has a much refined austenitic grain-size—though that is not usually apparent. Process parameters are selected to avoid development of coarse *martensitic* microstructures, which can negatively influence the hardened layer's toughness.

An induction hardened layer's microstructure does not always appear martensitic, but sometimes tends to resemble the original quenched and tempered structure, though much finer. Still, induction hardening's hardness values are typical of the martensitic condition.

*3) **Residual Stresses.*** Heating of a steel surface by induction currents will be accompanied by thermal expansion and a superimposed contraction when the material

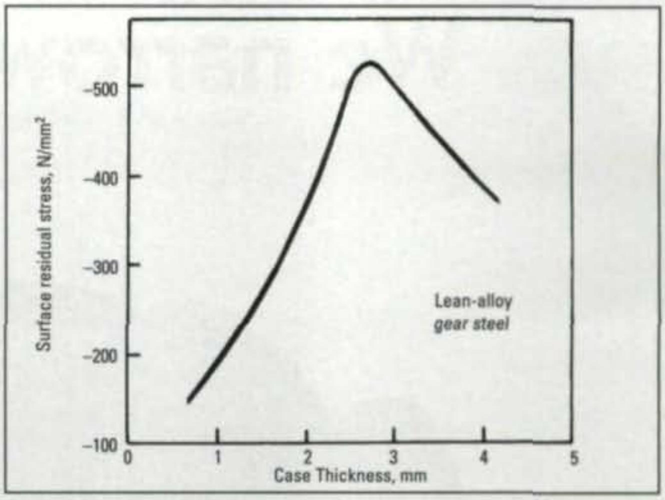

Fig. 9—Effect of case depth on surface residual compressive stress.[1]

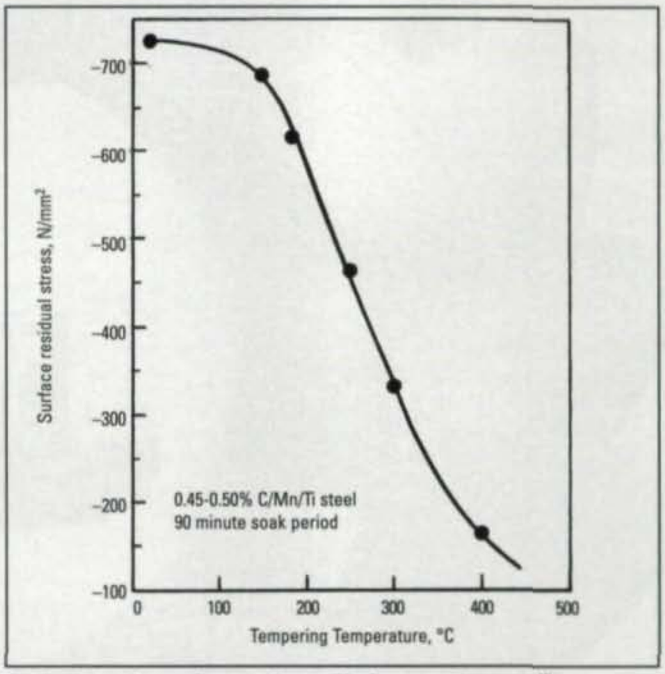

Fig. 10—Effect of tempering on surface residual compressive stress.[2]

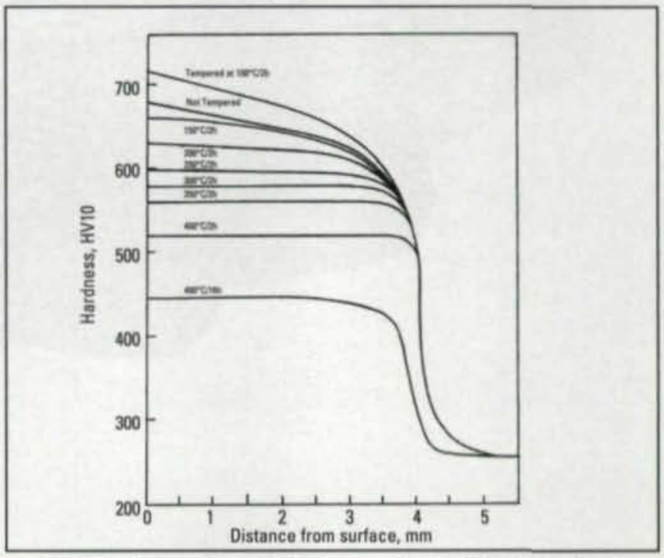

Fig. 11—Effect of tempering on the hardness profile of an induction hardened gear tooth flank (SAE 4140 steel).


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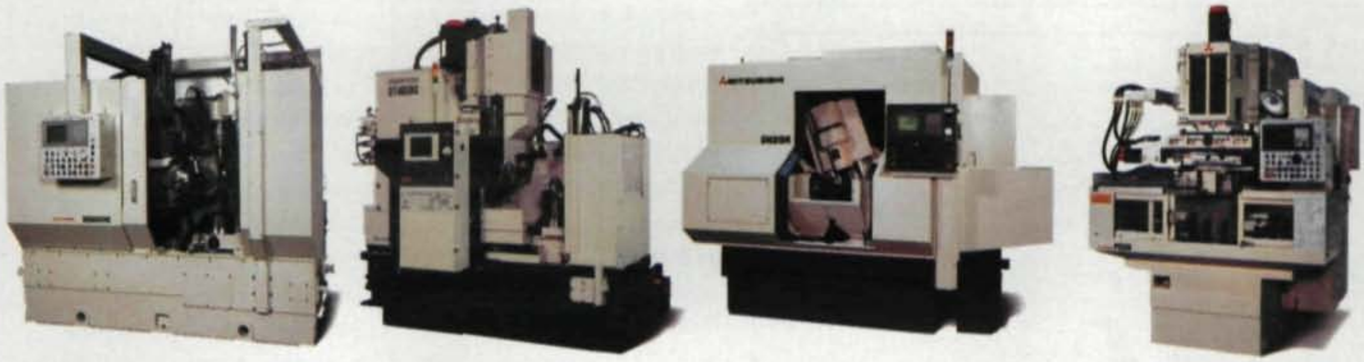

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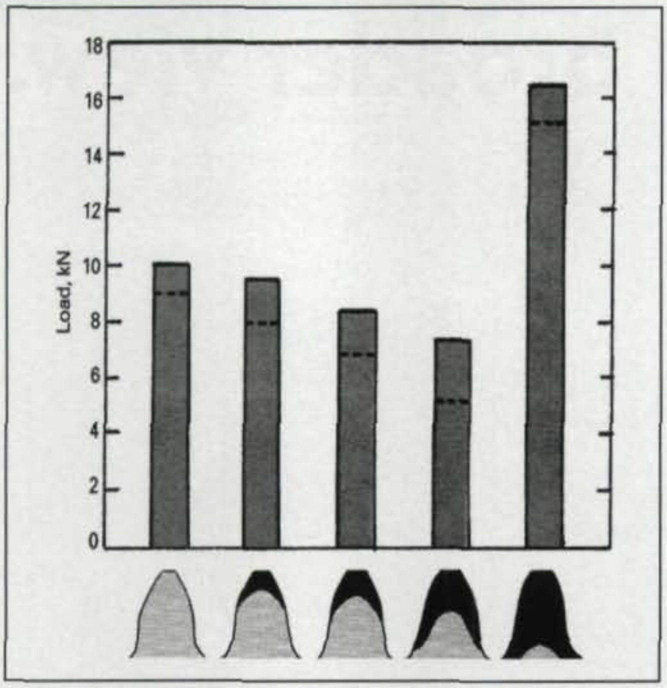


Fig. 12—Effect of the amount of flank hardening on the bending[4] fatigue strength of gear teeth. Steel 0.55% C, core strength 880 N/mm².

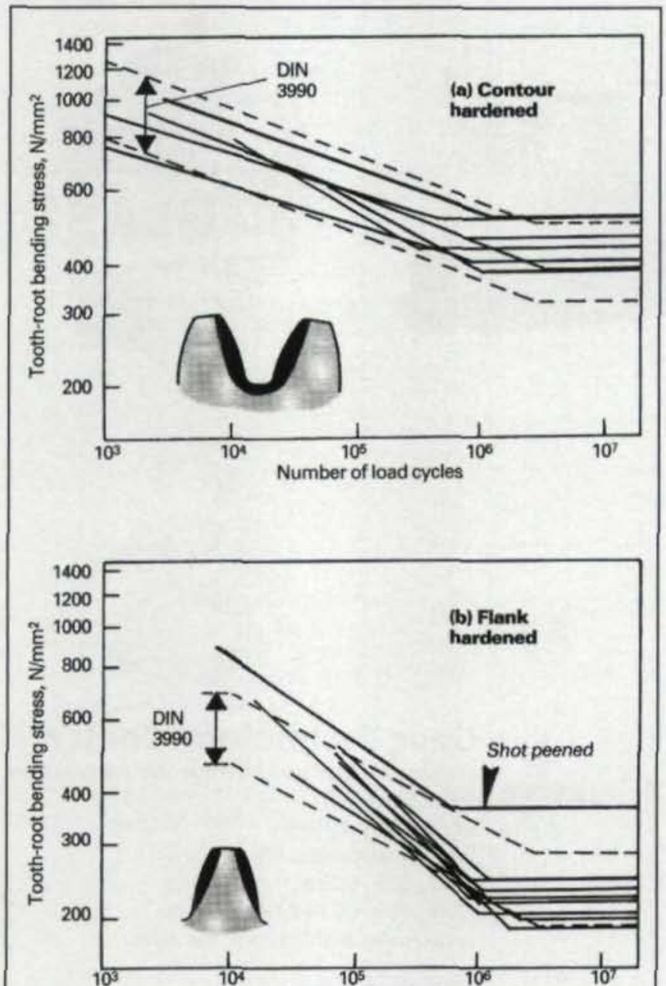


Fig. 13—The bending fatigue strength of inductor-hardened 8mm[3] module gear teeth (various steels): (a) contour hardened; (b) flank hardened. Broken lines denote scatter band for DIN 3990.

passes through the austenite transformation temperature range. As a result, yielding may occur somewhere in the heated layer, probably close to the eventual case/core junction, and will contribute to the residual stress distribution. But, the stresses' development will be mainly due to the martensitic transformation.

Martensite formation in the induction heated and quenched layer involves a volume increase above that of the underlying core material, placing the hardened surface in a state of residual compression, which is balanced by residual tension in the core, just beneath the case (Fig. 8). The change from compression to tension occurs at a depth where the hardness is about 40 HRC. But, unlike the carburizing and hardening process, which transforms the core before the carburized layer, an induction heated surface layer will lose heat during quenching to the quenchant and by conduction into the workpiece's cooler body. The outcome is a residual stress distribution where the compressive stresses in the hard case may have a high value at some distance from the surface but still within the case's harder part. Even so, the amount of surface compression is determined by the hardened layer's depth. The core tensile residual stresses, which peak just below the hardened layer, need to be carefully considered by gear designers, noting that a deeper case will push the "offending" residual tensile peak deeper, to where the applied bending stresses are of a low order. That feature results in the specification of a higher case depth than would be employed for carburized case depths.

The magnitude of the surface residual stresses developed during induction hardening is thought to be related to the depth of hardening (Fig. 9), though the stresses are modified by tempering, as Figure 10 illustrates. Tempering's effect on the hardness of an AISI 4140 induction hardened gear tooth surface is shown in Figure 11, noting that the most used tempering temperature range for induction hardened gears is 200–250°C.

4) Bending fatigue. It is crucial that the entire surface of the tooth root/fillet region is hardened. A missed area in that region, either along the fillet or at the tooth end, will lower the bending fatigue strength some 25%, compared with the tooth's strength before induction hardening (Ref. 3). Baumgartl (Ref. 4) confirmed the 25% loss (Fig. 12). With adequate root/fillet hardening, the fatigue strength will be 60% to 70% of that of a carburized gear (Ref. 3) when the surface hardness and the case depth are within reasonable limits, i.e. 590 Hv to 650 Hv, and minimum fillet case depth/module ratio is 0.25 to 0.30.

Fatigue tests employing a beam type test piece, with machined notches to simulate a 29 module gear tooth with a stress concentration factor of 1.4, produced fatigue limit values of 510 N/mm² for a 0.55% C plain carbon steel; 527 N/mm² for a 0.50% C chromium-vanadium steel; and 564 N/mm² to 630 N/mm² for steels 4140 and 4340. The trend was that the fatigue limit rose with core strength (772 N/mm² to 1,020 N/mm²), which perhaps reflected each steel's resistance to significant yielding under load. Pulsator tests (Ref. 3) on 8 mm module gears, produced the results shown in Figure 13 for full tooth space induction hardened and flank induction hardened teeth.

5) Contact fatigue. A surface's contact fatigue strength is related to its tensile strength and the surface material's hardness. Contact fatigue tests using discs and having no intentional sliding suggested that induction hardened surfaces had pitting fatigue strengths of about 80% of that of carburized and hardened surfaces (Fig. 14). Winter and Weiss confirmed that observation (Ref. 3). With actual gear tests, they concluded that induction hardened gears had 85% of the contact fatigue strengths of their case hardened counterparts. Their recommendation not to exceed 55 HRC surface hardness for the sake of tooth bending strength, is in line with current practice, noting that their contact fatigue plots, shown in Figure 15, represent surface hardnesses of 52 HRC and 61 HRC. When the surface hardness was 61 HRC, the contact fatigue strength was comparable to that of a case hardened gear of the same surface hardness. Unfortunately, with such surface hardness, some tooth bending failures occurred with the induction hardened gears. In other tests (Ref. 5) on gears of about 61 HRC, the induction hardened gear had a life (to the onset of pitting) that was 1.7 times that of a case hardened gear. Again, some induction hardened gears experienced tooth breakage, which may confirm Winter and Weiss's recommendation. But, during contact fatigue tests,

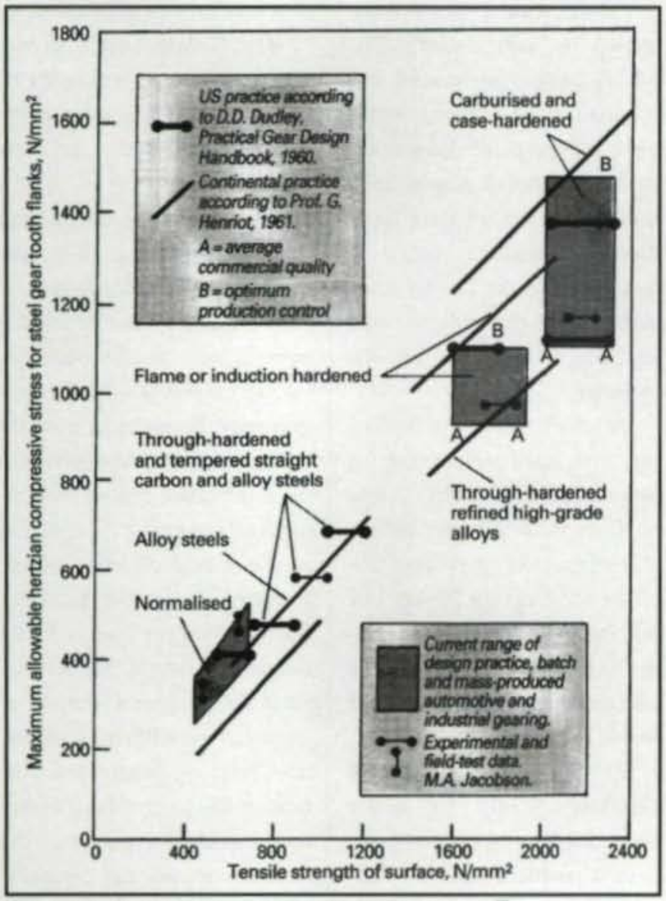


Fig. 14—The contact fatigue strength of gears. After Jacobson.(8)

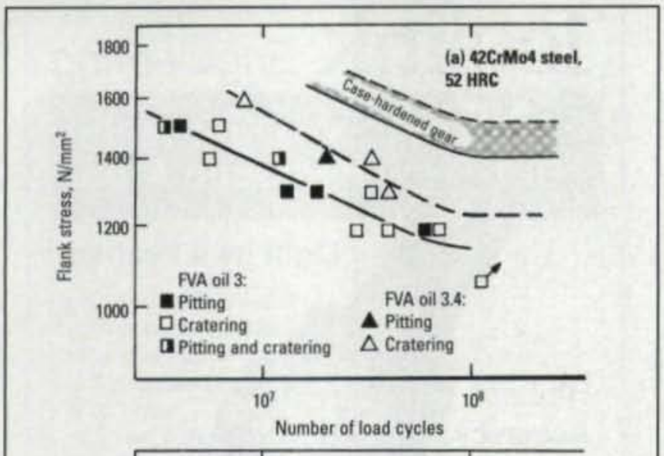


Fig. 15—Contact fatigue resistance of induction-hardened gear teeth run against **carburized teeth[3]: (a) 42CrMo4 steel/52 HRC; (b) Ck 45 steel/61 HRC. Performance of case hardened teeth shown shaded.**

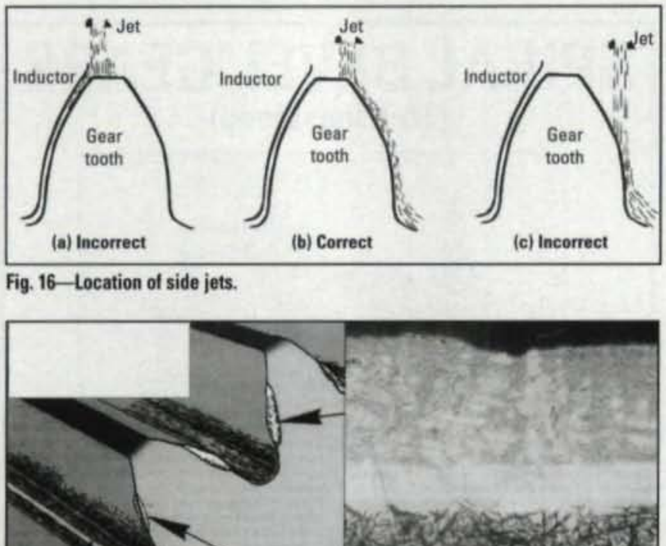


Fig. 16—Location of side jets.

Fig. 17—Overheating and melting: (a) overheating (x450); (b) melting (x100); (c) overheating with a trace of melting (x540). Steel: 817M40.

using narrow faced gears results in tooth breakage fractures initiated at the early contact damage on the tooth flanks.

Pitfalls

Induction hardening has problems. In the wrong heat treater's hands, the results can be disastrous. But, a number of problems have been recognized and eliminated during David Brown's years of experience. That recognition provided insight and a clearer understanding of the process.

1) Back tempering. The hardening of a single tooth means the tooth surface attains a temperature in excess of 720°C. The quenchant removes much of the heat, but some heat conducts through the tooth. That heat can—particularly with small pitch teeth—result in "back-tempering" of the adjacent, previously hardened tooth.

"Back tempering" is controlled by side cooling jets, which are positioned to impinge on the adjacent tooth's top edge and direct flow down its flank (Fig. 16). A consideration is that the adjacent tooth "sees" the conducted heat a little later than the heated tooth surface, and therefore the side jets need to be longer than the inductor.

A small amount of softening by back tempering is almost inevitable and should be accepted in the gear design. It is inherent in the process that all the teeth except the last one will experience the "back-temper" effect and that one tooth (the first) will have two flanks which experience the effect.

2) Root and Flank Cracking. Tooth root and/or flank cracking has never really been a problem with the submerged, tooth-by-tooth process using quenching oil as the coolant.

The tooth-by-tooth induction hardening process in other organizations had an early history of tooth cracking problems (Ref. 1), usually via the use of steels having too high a carbon content and/or too low a hardenability together with the use of higher quench rates.

3) Melting and Overheating. If the local temperature becomes too high due to, for example, too close a couple, there will be a risk of surface overheating or melting. Overheating produces a coarse martensitic microstructure in the as-quenched surface. A melted area produces a surface layer with a dendritic structure and a sublayer of overheated material (Fig. 17). Such occurrences are to be avoided, although localized occurrences at tooth end run outs can be dressed to remove the effects.

4) Unhardened areas. Figure 18 shows examples of induction hardened gears where small areas are left unhardened.

In (a), an inductor did not dwell at either end of a gear tooth, causing a small area, a "thumbnail," to receive insufficient heating to effect hardening. To correct that fault, attention must be given to how far the inductor is introduced into the tooth space before energizing and how long it dwells there in the energized state before starting its heating traverse. Such a defect may invite fatigue cracking during service.

In (b), a poorly shaped or damaged inductor led to a narrow band of unhardened surface at the tooth fillet. Within the hardened surfaces, the residual stresses are compressive. But in unhardened areas, such as those shown, there will be tensile residual stresses of a high magnitude (Fig. 19). A gear tooth with such a defect will have a very poor bending fatigue strength.

In (c), insufficient attention to process parameters led to the hardened layer being thin, or missing, near the tooth's end. It is normal for the end hardened pattern to differ a little from that further along the tooth; there tends to be a small amount of case thinning near the exit end at a point midway up the tooth face, as the top row in Figure 18 shows. In extreme circumstances, the thinner area may break out to the surface.

One very important factor in relation to tooth end hardening problems is having the correct tooth end shape, chamfers and beveled edges.

5) Uneven hardening patterns. Uneven hardening patterns are mainly due to poor positioning of the inductor in the tooth space or to a lack of inductor rigidity. Poor inductor alignment also causes uneven hardening.

6) Distortion and growth. Shape and volume changes are not, as a rule, viewed as being significant to induction hardening. Still, it is good to keep in mind that they do occur, though generally to small degrees, and good to know where the potential problem areas might be. Tooth profile movements due to induction hardening are illustrated in Figure 20, where the shape change is less than 0.012 mm.

Gear rims might also have a slight tendency to take on a diabola shape, when the gear diameter at the ends of the teeth is greater than the mid-face width. The extent of the shape change is affected by rim thickness and tooth face width; the thinner the rim and the greater the face width, the greater the risk of that form of distortion. Therefore, the designer must take that into account at an early stage of design. Given that tendency, it is not advisable to induction harden gear rims "shrunk" onto a center. Welded fabrication gear construction, on the other hand, is suitable.

The ends of small- and intermediate-sized teeth, which are required to be induction hardened, should be generously radiused. On the other hand, large pinion teeth, for which a deep case is specified and which are not planned to be flank ground, should be tapered about 0.1 mm over the end 1/20th of flank, at both ends of each flank, as well as having a 3 mm radius at the edges. That is done to counter

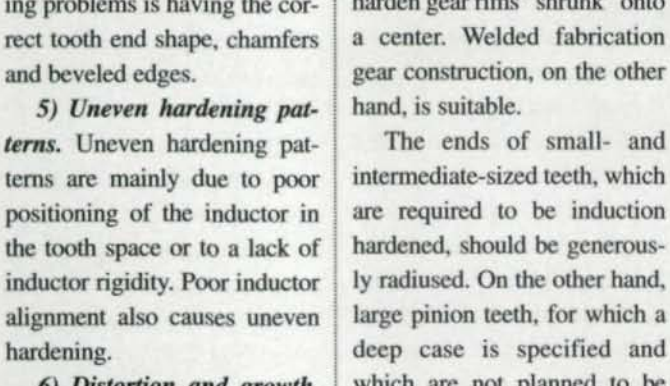


Fig. 18—Mis-hardened zones

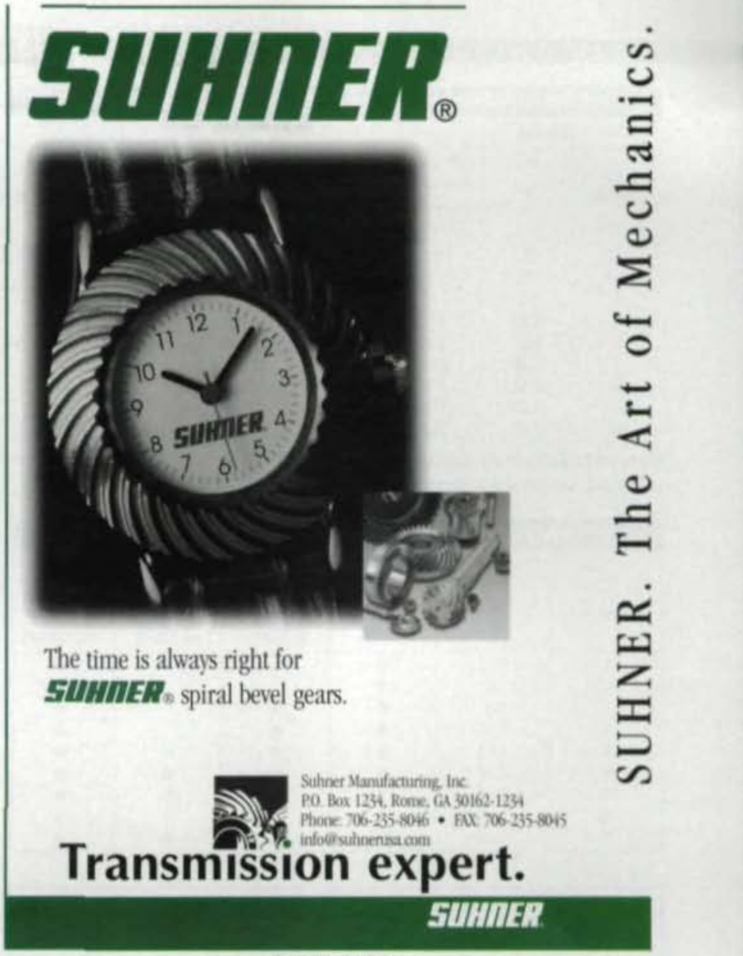


Table 1—AGMA gear ratings for various heat-treated conditions.

Gear tooth size		AGMA rating (kW)				
Module	DP	Through hardened to UTS of 772N/mm²	Through hardened to UTS of 1158N/mm²	Nitrided 4140	Induction hardened	Carbon case-hardened
2	12.7	1.5	2.9	3.3	3.6	4.2
2.5	10	3	5.6	6.6	7.2	8.3
3	8.5	5	9.4	11.1	12.1	14
4	6.35	11.6	21.8	26	28.3	32.9
6	4.23	38.7	72.9	84.5	94.9	111
8	3.18	88.6	167	194	218	256
12	2.12	282	530	615	691	815
20	1.27	1163	2192	2558	2875	3390
30	0.85	3521	6636	7723	8680	10258

Results based on 25 pinion teeth running against 75 wheel teeth; helical with face width 0.4 x centres.

Table 2—Appropriate heat treatment related to gear tooth size.

Gear tooth size		AGMA rating (kW)			
Module	DP	Nitrided	Induction hardened at 50kHz	Induction hardened at 10kHz	Carbon case-hardened
2	12.7	●			●
2.5	10	●			●
3	8.5	●	●		●
4	6.35	●	●		●
6	4.23	●	●	●	●
8	3.18	●	●	●	●
12	2.12			●	●
20	1.27			●	●
30	0.85			●	●

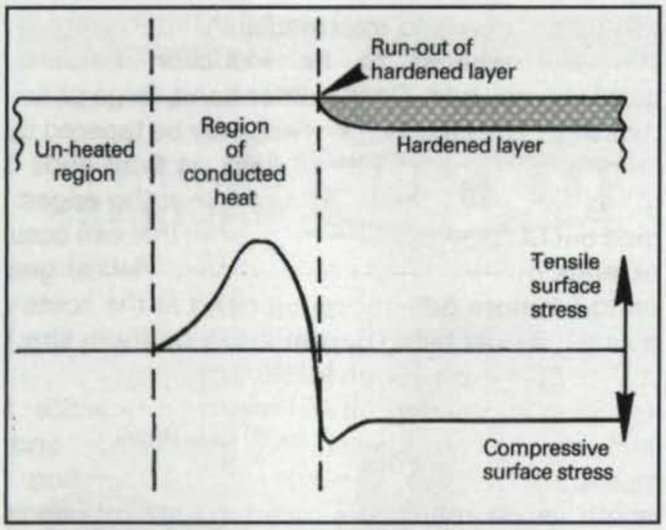


Fig. 19—Residual stress at the edge of a hardened layer.[4]

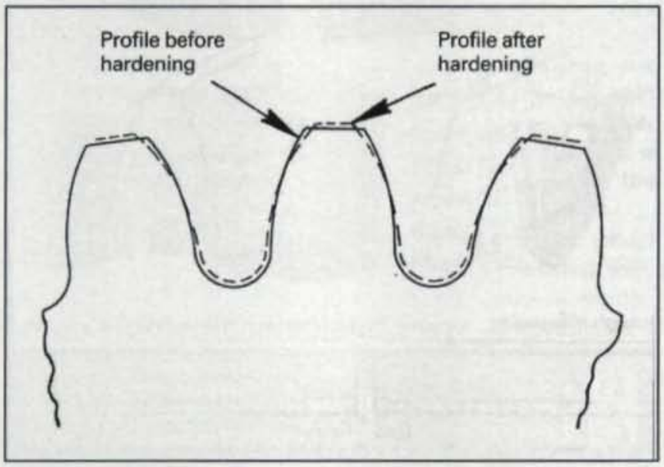


Fig. 20—Distortion in tooth form caused by hardening (greatly exaggerated).

the minor growth that can occur at the flank ends due to induction hardening, thereby causing hard meshing points in critical areas. Helical gear teeth need to be more generously rounded at the acute angle's edge, the amount depending on tooth size.

Applications

Induction hardening joins an array of heat treatment processes available to the designer. A process comparison of the AGMA 218 gear ratings for a range of gear tooth sizes is shown in Table 1. It can be seen that carburized and case hardened gears provide the best ratings for both tooth durability (contact fatigue) and tooth bending fatigue gear properties. But, for the larger tooth sizes, induction hardening provides a significant advantage over nitriding or through hardening.

The different heat treatment processes tend to suit a range of tooth sizes. Table 2 provides an overview of the data. Tooth-by-tooth induction hardening is suited to relatively large teeth—or 10 kHz frequency from 8 module to 30 module.

Induction hardening, because it requires a high level of technical and manual skill, is suited to larger gears, which—by their size and weight—are expensive to carburize.

Induction hardening might be beneficial when distortion and growth due to carburizing and hardening is large enough to require excessive amounts of corrective flank grinding, with a corresponding thinning of the case and the risk of grinding steps at the tooth fillet.

Induction hardening can be best used by ensuring a good combination with the mating gear, i.e. an induction hardened wheel with a carburized and hardened pinion, or a through hardened wheel with an induction hardened pinion.

After an induction hardening process is chosen, the engineer should design the gear accordingly.

1) Double helical gears should have a gap between the two helixes into which the inductor can pass when it has completed a tooth traverse. Modern hobbed gears will have that anyway, and gears that need to be finished by gear tooth flank grinding will have a substantial gap.

2) If there is a shoulder adjacent to the end of the gear portion, there should be a radial gap between the ends of the teeth and the shoulder.

3) A generous root fillet radius should be included and narrow tip widths should be avoided.

Typical David Brown applications for induction hardened gears are:

- Mill pinions on girth gear driven rotating mills where the pinion mates with a cast steel wheel (Fig. 21).
- Heavy-duty crane travel drive gearing where the needed contact accuracy by heavily loaded carburized gearing cannot be achieved in a continuously flexing gear case (Fig. 22).
- Sugar mill drive gears where price competitiveness is combined with heavy torque transmission (Fig. 23).
- Steel mill applications in both rolling mill main drives (Fig. 24), and in shear applications (Fig. 25) where each tooth frequently feels heavy shock loads, as well as coiler/uncoiler boxes.
- Cement mill drives where high torques are continuously applied for long periods (Fig. 26).

Fig. 21—Mill pinions on girth gear driven rotating mills.

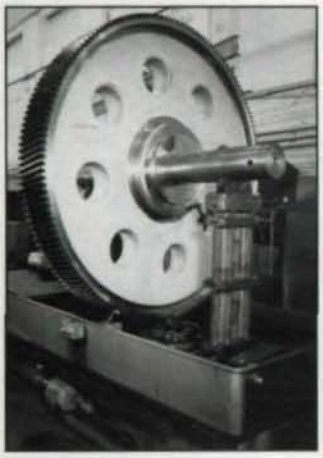


Fig. 22—Heavy-duty crane travel drive gearing.

Applications for induction hardened gears include a variety of applications where the economic balance requires a high strength, through hardened wheel and consequently an even higher duty pinion, or when the ratings demand a carburized pinion, but not a carburized wheel.

The whole range of industrial gear drives can benefit from properties produced by the process.

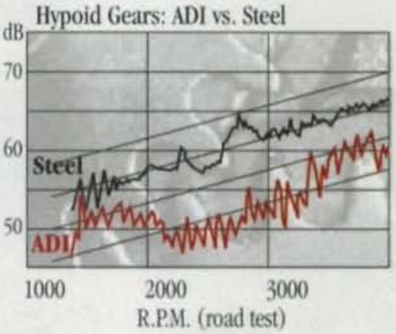
Conclusions

The submerged, tooth-by-tooth induction surface hardening process for medium and large gear manufacture has been used successfully by David Brown for more than three decades. It comes into its own for gears that cannot be surface hardened by other methods because of the gears' overall size or because of tooth size considerations. Also, it can compete with other processes for which strength requirements are too severe for through hardened gears but fall short of the strengths from carburizing and hardening.

For gears hardened by the process, the surface strength properties (bending and contact fatigue) are much higher (typically 40%) than the highest practicable through hardened gear but marginally less than carburized, case hardened gears (typically another 20% higher). Also, through hardened gears at the high strength levels must use low tempering temperatures, which can result in retention of internal stresses residual from the quenching process. The internal tensile stress can, combined with applied service loads, be detrimental to gear life.

Consequently, with suitable gear design modifications, the submerged induction hardening process serves as an alternative to either through hardening or carburizing.

Contact fatigue strength relates to surface hardness. Therefore, given adequate case thickness, one might expect an induction hardened gear to be



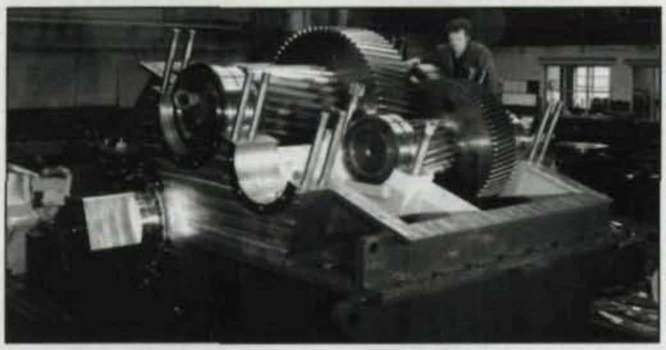


Fig. 23—Sugar mill drives.

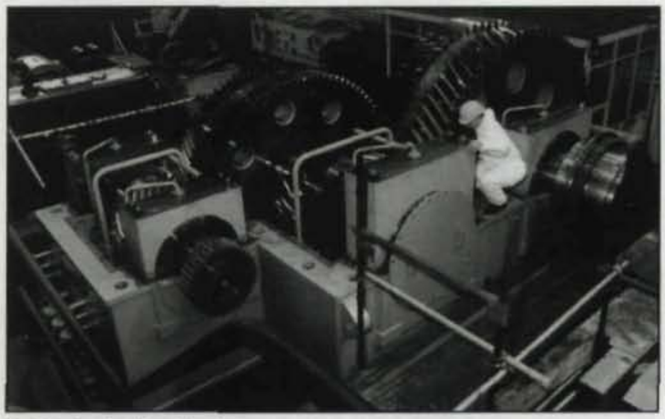


Fig. 24—Steel mill applications.

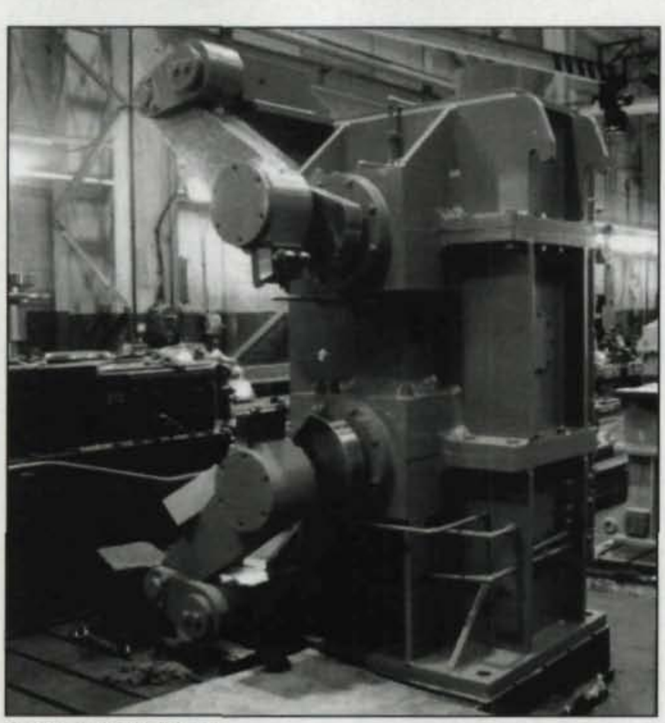


Fig. 25—Shear applications.

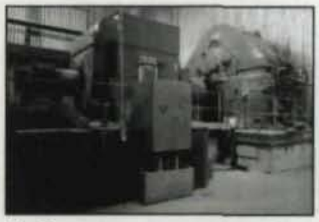


Fig. 26a

Fig. 26b

fairly comparable to a carburized gear of the same design and surface hardness. Gear testing seems to support that, and it is common for a carburized pinion to be run with an induction hardened wheel.

Induction hardening had problems in the past; in many induction hardening plants, the problems still abound. But, learning from experience and understanding the process, quality control techniques can be established that minimize the likelihood of process related service problems.

The process is gear tooth friendly. Finally, a more detailed technical appraisal of the process was published in Refs. 6 and 7.

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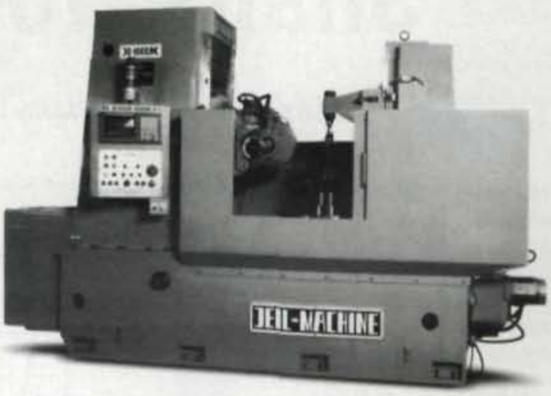

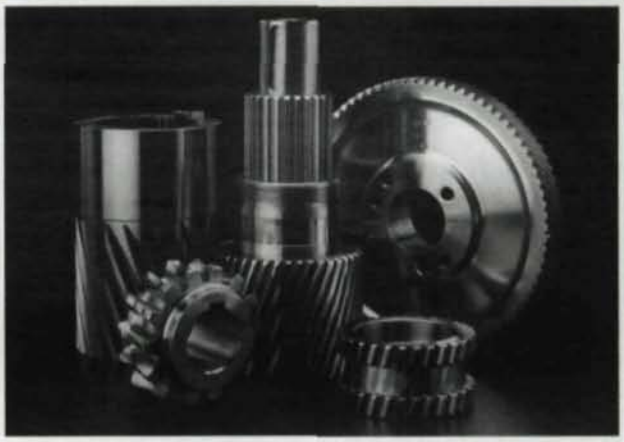

Austempered Gears and Shafts: Tough Solutions

Kristin Brandenberg, Kathy L. Hayrynen, Ph.D. and John R. Keough, P.E.

Definitions, Acronyms and Abbreviations

ADI: austempered ductile iron.

AGI: austempered gray iron.

Ausferrite: acicular ferrite and austenite.

Austempering: a special, isothermal heat treatment process that can be applied to ferrous materials. Austempering consists of austenitizing, followed by rapidly quenching to a temperature where the material is then transformed isothermally to form either ausferrite in cast iron or bainite in steel.

Austenite: a face-centered, cubic, non-magnetic phase found in iron and steel alloys.

Austenitizing: forming austenite by heating a ferrous alloy above its critical temperature—to within the austenite (steel) or austenite + graphite (cast iron) phase region from the phase diagram.

Bainite: an austenitic transformation product of acicular ferrite and carbide found in some steels and cast irons. Upon cooling, it forms at temperatures between those at which pearlite and martensite transformations occur.

Carburizing: the process by which the surface carbon concentration of a ferrous alloy is increased by diffusion of carbon from the surrounding environment.

Fatigue: failure of structures that are subjected to fluctuating and cyclical stresses.

Isothermal: that which is at a constant temperature.

Isothermal transformation (T-T-T or I-T) diagram: a plot of temperature versus the logarithm of time for an alloy of definite composition; used to determine when transformations begin and end for an isothermal heat treatment.

Martensite: a metastable iron phase supersaturated in carbon that is the product of a diffusionless transformation from austenite.

Residual stress: a stress that persists in a material that is free of external forces or temperature gradients.

Stress corrosion cracking: a failure that results from the combined action of a tensile stress and a corrosion environment; the corrosion environment lowers the stress levels for cracking due to tensile stress alone.

Tensile strength: the maximum engineering stress, in tension, that may be sustained without fracture.

Yield strength: the stress required to produce a very slight yet specified amount of plastic strain; a strain offset of 0.002 is commonly used.

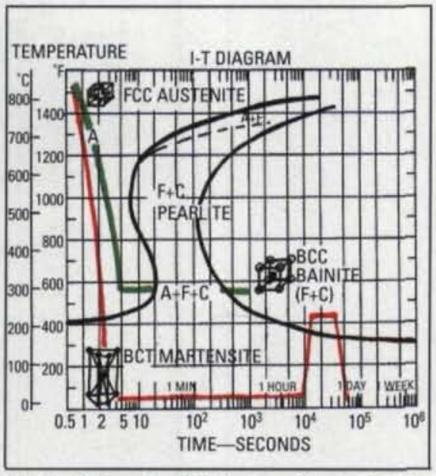

Fig. 1—Schematic I-T diagram illustrating the austempering (red) and quenching & tempering (green) processes.

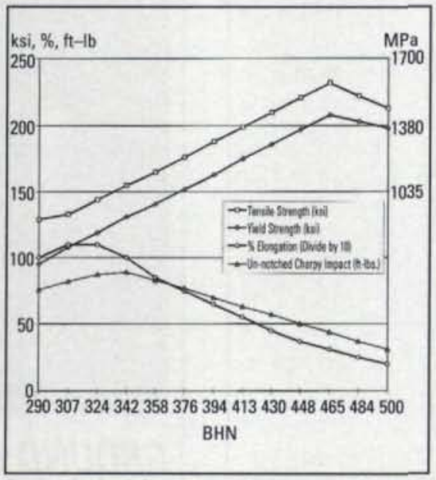

Fig. 2—Typical properties of austempered ductile iron as a function of Brinell hardness.

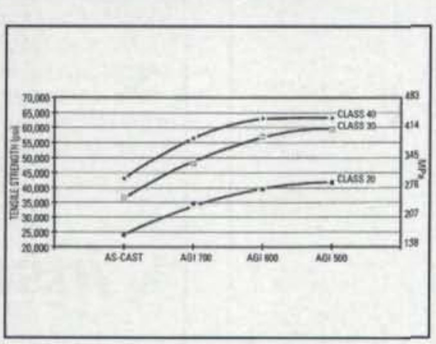

Fig. 3—Tensile strengths of austempered gray iron as a function of austempering temperature (F).

Abstract

Austempered irons and steels offer the design engineer alternatives to conventional material/process combinations. Depending on the material and the application, austempering may provide the producers of gears and shafts with the following benefits: ease of manufacturing, increased bending and/or contact fatigue strength, better wear resistance or enhanced dampening characteristics resulting in lower noise. Austempered materials have been used to improve the performance of gears and shafts in many applications in a wide range of industries.

Introduction

Austempering is a special, isothermal heat treatment process that can be applied to ferrous materials to increase strength and toughness. Figure 1 shows a schematic isothermal (I-T) diagram with both the austempering (green line) and the quenching and tempering (red line) processes outlined. Austempering consists of austenitizing, followed by rapidly quenching to a temperature in the range of 260–385°C (500–725°F), where the material is then transformed isothermally to form either ausferrite (acicular ferrite and carbon stabilized austenite) in cast iron or bainite (acicular ferrite and carbide) in steel. The quench

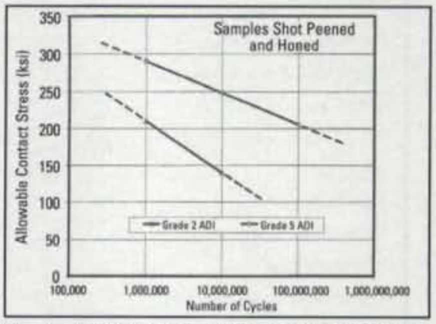

Fig. 4—Contact fatigue (90% confidence limits) from the ASME Gear Research Institute.

and temper process consists of austenitizing and then rapidly quenching below the martensite start temperature. The martensite that forms is very hard and brittle; subsequently, it must undergo a tempering step to acquire the desired combination of strength and toughness.

Because austempering is an isothermal process, it offers advantages versus quenching and tempering. Since the formation of bainite or ausferrite occurs over minutes or hours at a single temperature, distortion is minimized and cracking does not occur. Meanwhile, the formation of martensite occurs immediately as the metal temperature drops below the martensite start temperature. Because cooling is achieved at different rates in various sections, there is a non-uniform transformation, which can result in significant distortion and/or cracking.

Carbo-Austempering™ is a heat treat process used on certain steels where the surface of the part is carburized, followed by an isothermal quench at a temperature that produces a high carbon, bainitic case. When the process is applied to low-carbon steels, it results in the formation of a bainitic case and a low-carbon, tempered martensite core. For medium-carbon steels, bainite is formed throughout the cross-section of the part.

Austempered Irons

Austempering can be applied to ductile and gray iron castings to produce beneficial properties relevant to numerous applications. In the case of gears and shafts, austempering yields austempered ductile irons (ADI) and austempered gray irons (AGI) with better strength, wear resistance, and noise dampening properties than either as-cast irons or other competitive materials. As seen in Figure 2, the tensile and yield strength of ADI increases with increased Brinell hardness. The different grades of ADI—achieved through a variation in the austempering temperature and time—can create a range of properties in ADI applicable to the specific requirements of the component design, as seen in Table 1.

Figure 3 shows the relationship of as-cast gray iron to AGI as a function of austempering temperature. Increased tensile strength can be achieved by austempering gray iron at various temperatures.

Contact Fatigue. Austempered ductile iron lends itself to increased contact fatigue strength and wear resistance. Figure 4 compares the allowable contact stress behavior of ASTM Grades 2 and 5 (ASTM 1050-700-07 and 1600-1300-00). Figure 5 demonstrates that the contact fatigue properties of various grades of ADI are comparable to gas nitrided steels and competitive with carburized and hardened steel.

Figure 6 illustrates that ADI has improved abrasion resistance when compared to steels and quenched and tempered ductile iron. ADI experiences less volume loss at similar hardness levels, resulting in a component with improved wear characteristics.

***Bending Fatigue*.** ADI also presents an increase in bending fatigue for gear applications. Figure 7 shows the comparative allowable tooth root bending stresses for ADI Grades 2 and 5. Figure 8 shows a comparison of tooth root bending fatigue in various materials. That figure demonstrates that ADI is competitive with cast and through-hardened steels. It also shows that shot-peened ADI has improved fatigue strength that is comparable to gas-nitrided and case-carburized steels. Shot peening can improve the allowable bending fatigue of carburized

Table 1—ASTM 897 Property Table for ADI

Grade	Tensile Strength (MPa/ksi)	Yield Strength (MPa/ksi)	Elong. (%)	Impact Energy (J/lb-ft)	Typical Hardness (BHN)
1	850/125	550/80	10	100/75	269–321
2	1050/150	700/100	7	80/60	302–363
3	1200/175	850/125	4	60/45	341–444
4	1400/200	1100/155	1	35/25	366–477
5	1600/230	1300/185	N/A	N/A	444–555

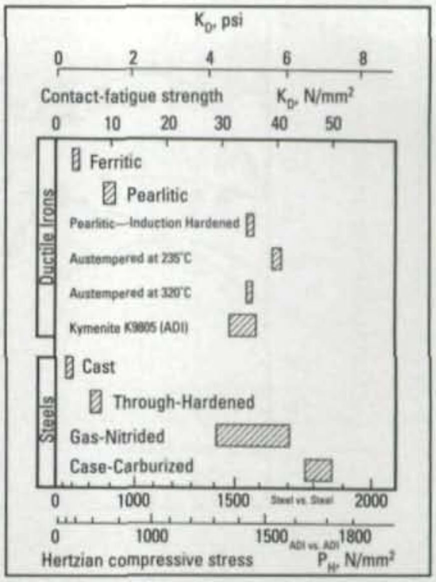

Fig. 5—Comparison of contact fatigue strengths of ADI with those of conventional ductile iron and steels used for gear applications.

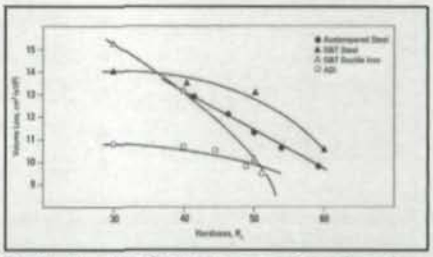

Fig. 6—Pin abrasion test, comparing volume loss at equivalent hardnesses[4].

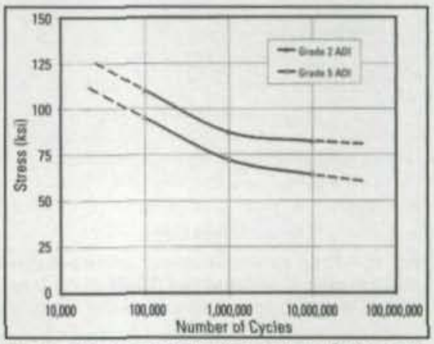

Fig. 7—Single tooth bending fatigue (90% confidence limits) from ASME Gear Research Institute.

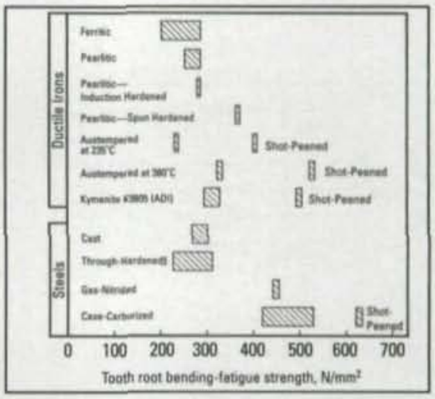

Fig. 8—Comparison of bending fatigue strengths of ADI with those of conventional ductile iron and steels used for gear applications.

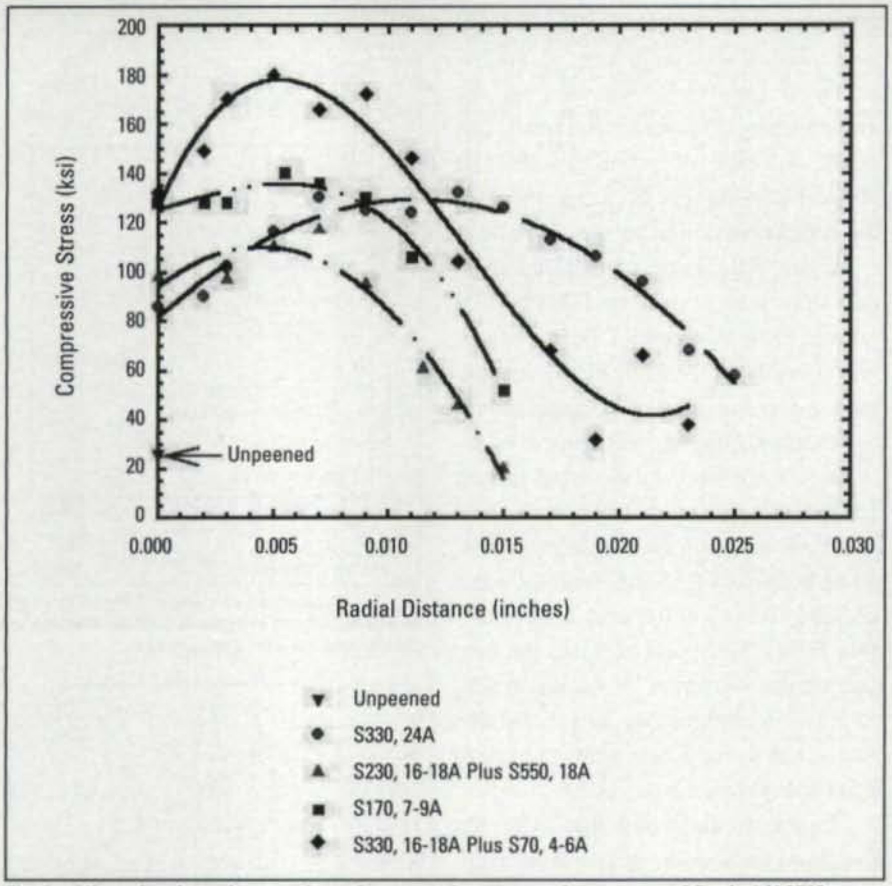

Fig. 9—Effect of various shot-peening schemes on the compressive stresses of Grade 4 (ASTM 1400-1100-01) ADI.

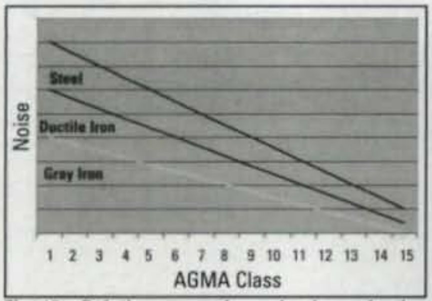

Fig. 10—Relative comparison of noise reduction as a function of material and AGMA class (courtesy of Wells Manufacturing, Dura-Bar Division).

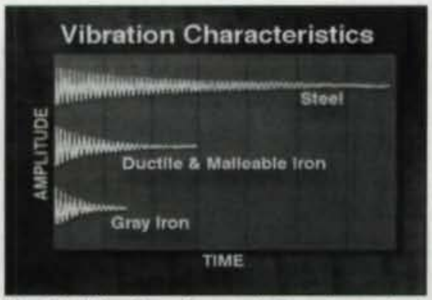

Fig. 11—Vibration characteristics of gray iron, ductile iron and steel (courtesy of Wells Manufacturing, Dura-Bar Division).

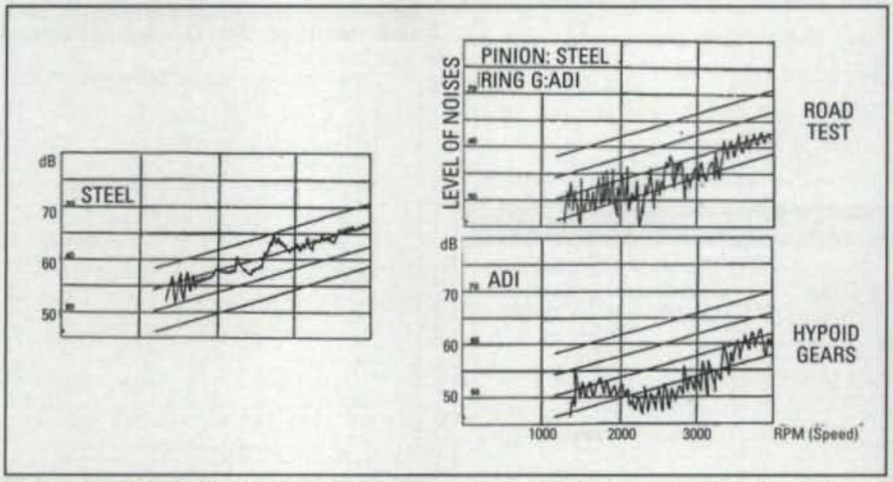

Fig. 12—Comparison of noise in hypoid gears during vehicle road tests, from the ASME Gear Research Institute Report A4001.

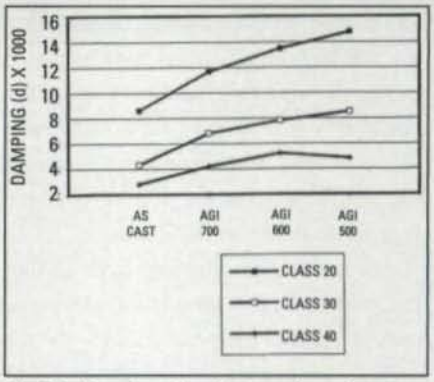

Fig. 13—Damping of austempered gray iron compared with as-cast.

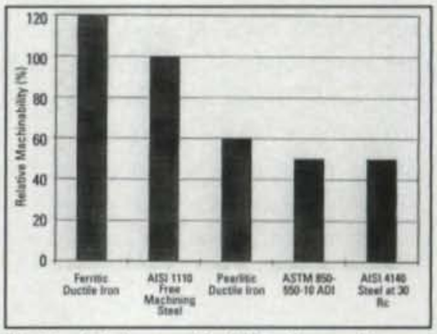

Fig. 14—Relative machinability of several ferrous materials.

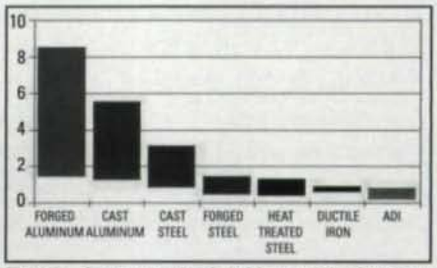

Fig. 15—Cost per unit of yield strength of various materials.

Fig. 16—ADI Hypoid Ring and Pinion Gears.

Fig. 17—ADI gear segments for a 19-foot diameter rotary railcar dumper.

and hardened steels by 30%, while it increases the allowable bending fatigue of ADI by 75%.

The bending performance of ADI can be greatly enhanced by shot peening and fillet rolling. In Figure 9, several shot-peening combinations are measured for their effect on residual compressive stresses. The as-austempered surface compressive stress observed was less than 30 ksi while the maximum shot-peened surface compression was more than 130 ksi.

Noise Reduction. ADI and AGI are not only competitive in bending and contact fatigue, but they also can greatly reduce the noise found in gears made of other materials. ADI can reduce noise by more than 2 dB compared with carburized and hardened 8620 steel gears[6].

As seen in Figure 10, gray and ductile iron are quieter than steel. That is due to the presence of graphite in ductile and gray iron, as well as the ausferrite matrix in austempered irons. The graphite nodules in ductile iron and the graphite flakes in gray iron create a dampening effect that significantly reduces vibration in those materials. That allows for the possibility that gears machined to lower AGMA classes could be as quiet as those machined to more precise grades. Figure 11 schematically shows the relative dampening characteristics of steel as compared with ductile and gray iron.

A study done on a hypoid gear set, shown in Figure 12, compares the noise of that gear set when using steel, ADI or a combination of both materials. Note the improvement in noise level when both the ring gear and pinion are made of ADI.

The austempering of gray iron also increases the noise reduction capabilities of gray iron. As seen in Figure 13, the damping characteristics of gray iron are increased when austempered, giving the higher strength AGI better noise reduction characteristics than its as-cast counterparts. In fact, an AGI with a tensile strength of nearly 60 ksi can have the noise dampening capabilities of a fully damped, Class 20 gray iron.

Manufacturability. ADI and AGI offer an opportunity for increased manufacturability of a part. Rough machining can be done prior to heat treatment. In the as-cast condition, the material is much easier to machine, resulting in a lower cost to manufacture. Though many applications can be heat treated after final machining, finish machining after heat treatment increases the strength characteristics of ADI and AGI, giving them superior fatigue strength than prior to finish machining. Figure 14 compares the relative machinability of several ferrous materials. Note that ductile iron in a ferritic or pearlitic condition is easier to machine than 4140 steel or ADI. If ductile iron is machined prior to heat treatment, one can gain the advantage of better machinability. Furthermore, machining of ductile iron, gray iron, ADI and AGI results in a compact, discontinuous chip that is easily handled and is fully recyclable. Dry machining techniques

Fig. 18—ADI inboard constant velocity joint for light vehicles (Courtesy of Delphi).

Fig. 19—ADI gear and axle for commercial lawnmowers.

Fig. 20—ADI limited slip differential gear housing.

Fig. 21—ADI hay baler knotter gear.

can be easily applied to as-cast gray and ductile irons. The increased ease of manufacturability related to cast irons goes beyond improved machinability. Iron castings are generally nearer net shape and less expensive than steel forgings and castings. Figure 15 shows a comparison of relative material cost of different materials per unit of yield strength. Taking into account all material and processing costs, ADI and AGI are relatively less expensive to manufacture than other commonly used materials.

Another benefit of austempering is reduced distortion and the elimination of quench cracking. When General Motors Corp. switched to ADI hypoid differential gears from the traditional carburized and hardened 8620 steel process in the 1970s, the company was able to eliminate the need for press quenching.

Applications of ADI and AGI Gears

As previously shown, ADI and AGI gears have higher bending and contact fatigue strengths, improved wear resistance and reduced noise levels. Figure 16 is an example of a hypoid gear set that realized a reduction in noise when switched from a steel application to ADI.

Fig. 22—AGI gear for timing on a light vehicle engine.

Austempering can also give benefits to larger than average gear sets, such as the large gear segments shown in Figure 17. Figures 18 through 21 show various applications of ADI gears, from agricultural applications in knotter gears (Figure 21) to light vehicle applications of differential housings (Figure 20) and CV joints (Figure 18) to a gear-and-axle set used in commercial lawnmower engines (Figure 19). Figure 22 shows an AGI distributor gear used in the late 1970s.

Austempered Steels

Medium- and high-carbon steels can be successfully austempered along with powdered metal mixes that have sufficient hardenability and nearly full density. In general, the steel that is selected must have an isothermal transformation (I-T or T-T-T) diagram that exhibits the following characteristics:

1. A pearlite start time (nose) that is sufficiently delayed to avoid its formation on quenching to the austempering temperature.
2. A reasonable bainite transformation time.
3. A martensite start temperature that is low enough to allow for the formation of bainite.

Austempered steel offers several advantages when compared with conventional quenched and tempered steels. Because austempered steel is formed by an isothermal transformation, the likelihood of distortion is reduced, and the presence of quench cracks is eliminated. The bainitic microstructure produced by austempering is more wear resistant than tempered martensite, as illustrated in the pin abrasion test results of Figure 6. In addition, bainitic steels are more resistant to hydrogen embrittlement and stress cor-

Table 2—Gross and Bain Comparative Data for 0.74% C Steel Parts[7]

	Quenched & Tempered	Austempered
Rc Hardness	50	50
UTS (MPa/ksi)	1701/246.7	1949/282.7
Yield Strength (MPa/ksi)	839/121.7	1043/151.3
Elongation (% in 6 inches)	0.3	1.9
%RA	0.7	34.5
Impact* (J/ft-lb)	3.9/2.9	47.9/35.3

rosion cracking. For example, at high hardness levels (> 38 Rc), martensitic bolts are subject to stress corrosion cracking. Austempered bolts do not exhibit that behavior. For given high hardness levels (> 40 Rc), austempered parts exhibit higher strength and toughness than comparable quenched and tempered parts, as shown in Table 2.

Above a certain hardness level, the fatigue strength of conventional quenched and tempered steel drops significantly, as illustrated in Figure 23. That does not occur in austempered structures. In fact, the fatigue strength continues to increase up to the maximum bainitic hardness.

Austempered Steel Applications

There is a range of applications for austempered gears as shown in Figures 24 and 25. The gears vary in section size from the 1 mm thick wave plates pictured in Figure 24 to the large gear segments shown in Figure 25.

Powdered metal steel parts of sufficient density can also be austempered. Examples include the metal sprag races shown in Figure 26.

Austempered steel applications are not limited to gears. Output shafts are also austempered for high strength and toughness with low distortion.

Carbo-Austempered™ Steel

Low- to medium-carbon steels are good candidates for Carbo-Austempering™. Typically a high-carbon, bainitic case (50–60 Rc) is produced on a component with a lower carbon, tempered martensite core (< 40 Rc). In some instances, advantages have been realized in medium-carbon alloy steels with a high-carbon, bainitic case (45–55 Rc) on a medium-carbon, bainitic core (45–50 Rc).

Carbo-Austempering™, like austempering, is a low-distortion heat treatment process when compared with conventional carburize, quench and temper heat treatments. During Carbo-Austempering™, the transformation begins in the center, or core, of the part. That results in the formation of compressive stresses as the outside layer or case transforms last during the heat treat process. The residual compressive stresses on the surface of a Carbo-Austempered™ steel result in improved high-load, low-cycle fatigue properties versus conventional carburized and hardened steel. That is illustrated in Figure 27, which contains rotating bending fatigue curves for both Carbo-Austempered™ and conventionally carburized and hardened 8822 steel. Note the superior performance of the Carbo-Austempered™ steel in the low-cycle regime (< 10^5 cycles).

Similar results were obtained with single tooth bending fatigue testing of Carbo-Austempered™ 8620 steel. That is illustrated in Figure 28, which contains single-tooth gear fatigue curves for 8620 steel that has been both Carbo-Austempered™ and carburized, quenched and tempered. The Carbo-Austempered™ gears will carry loads up to 40% greater than their carburized, quenched and tempered counterparts in the

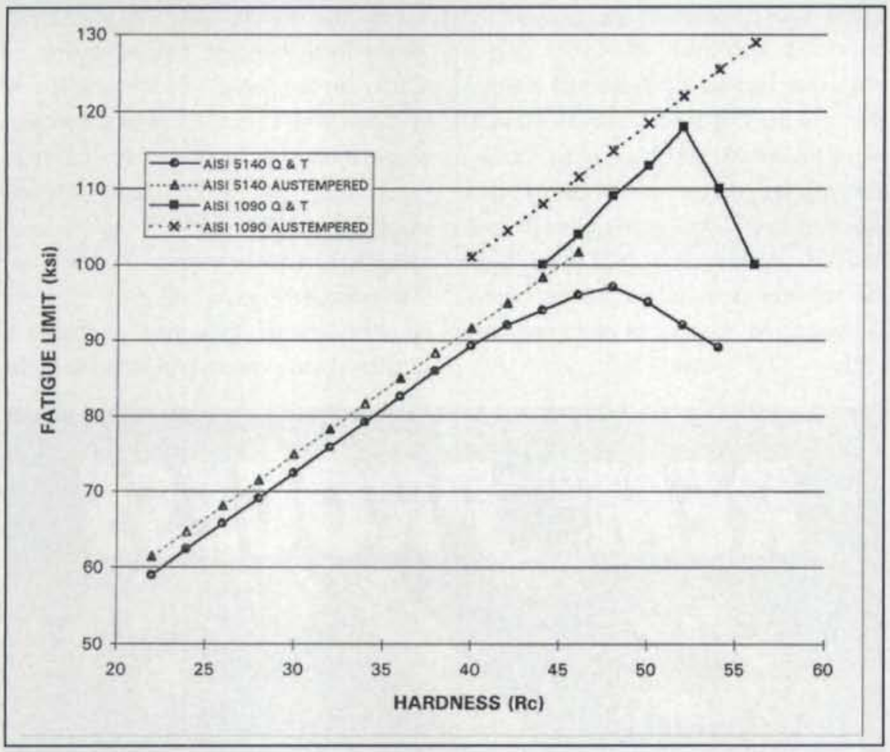

Fig. 23—Fatigue strength of bainite vs. tempered martensite.

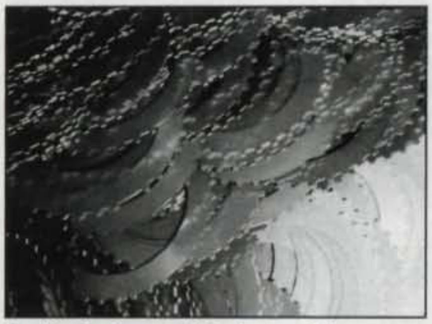

Fig. 24—Austempered steel wave plates.

Fig. 25—Austempered steel large gear segments.

Fig. 26—Austempered steel, powdered metal sprag races.

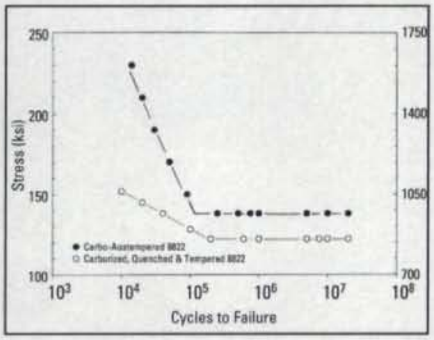

Fig. 27—Rotating bending fatigue properties of Carbo-Austempered™ vs. conventionally carburized and hardened 8822 steel.

low-cycle regime. Additionally, the Carbo-Austempered™ gears have an endurance limit that is 17% greater than the carburized, quenched and tempered gears.

Carbo-Austempered™ steels also exhibit superior toughness or impact properties in comparison with conventional carburized and hardened steel. Figures 29 and 30 illustrate such a comparison of both v-notched and unnotched impact specimens from 5120 steel, respectively. The notched impact energy of the Carbo-Austempered™ specimens is almost twice that of the carburized and hardened specimens in Figure 29. The difference in performance for the unnotched bars is significantly higher, with the average Carbo-Austempered™ impact energy being in excess of 22 times that of the carburized and hardened 5120 shown in Figure 30.

Carbo-Austempered Steel Applications

Carbo-Austempered™ components perform well when exposed to overload type conditions. Typical applications include input and output shafts (Figures 31 and 32), clutch components, starter clutches, pump shafts and gears.

Austempering— What It Is, And What It Isn't

Austempering is a high-performance heat treatment, but it is not a panacea. The application, as with all material/process combinations, must fit. ADI makes a quiet, low-cost gear or shaft in its allowable loading range, but it will not outperform carburized and hardened alloyed, low-carbon steel in bending or contact fatigue. So, if a current product in carburized steel is failing in bending fatigue or pitting, ADI would not be a solution. However, if the contact and bending loads are in ADI's range, a considerable cost and noise advantage can be expected.

Carbo-Austempered™ steels will outperform 60 Rc carburized and hardened steels in impact and bending fatigue, but at 58 Rc maximum hardness, Carbo-Austempered™ steels are limited to slightly lower contact loads. Therefore, Carbo-Austempering™ can be used in applications where spike overloads in bending occur. At hardnesses in excess of 40 Rc, austempered, medium-carbon steels outperform through-hardened martensitic components in impact strength and notched fatigue loading. However, below 40 Rc, evidence would indicate that martensitic structures will outperform bainitic structures.

Thus, designers should use austempering (as would be the case with other material/process combinations) as one option in their design "tool kit." The designer should work closely with the material provider and the heat treater to determine if austempering would provide a benefit to his or her drive component application.

Summary

The austempering process offers the designers of gears and power transmission components a viable, cost-effective, high-performance alternative to many conventional material/process combinations. Austempering of irons and steels results in increased levels of fatigue strength, wear resistance and toughness. Benefits in the areas of noise reduction and manufacturability have also been documented.

Acknowledgments

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- Delphi
- AGCO
- General Motors Powertrain Division
- Ford Motor Co.
- Torsion Control Products
- General Motors Allison Transmissions
- Purolator
- Wells Manufacturing, Dura-Bar Division
- Auburn Gear

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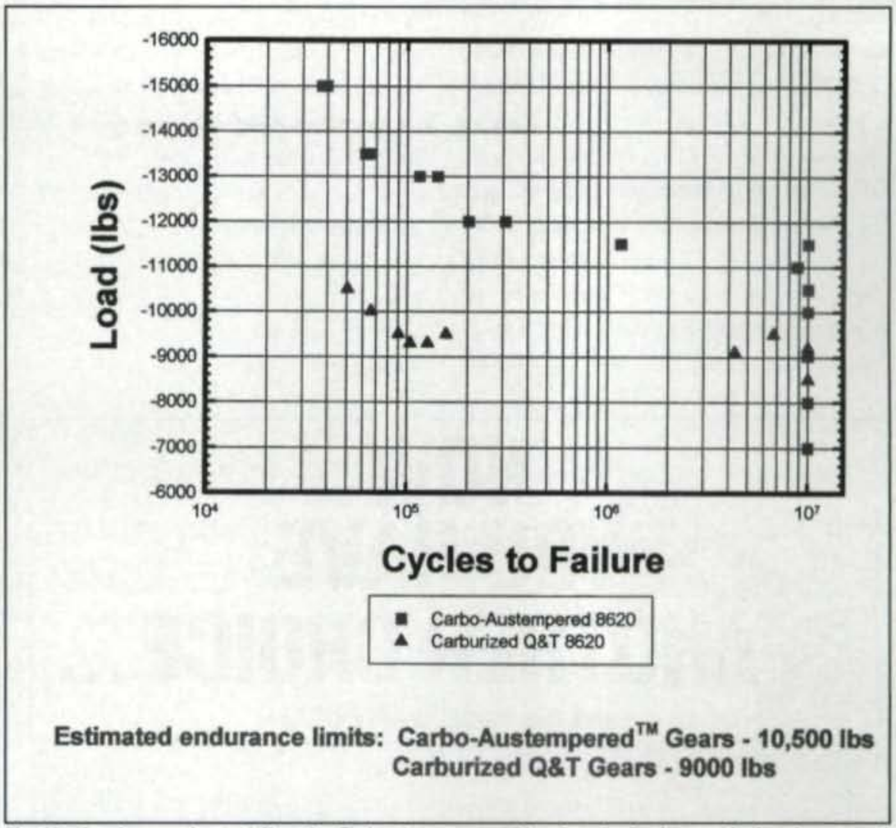

Estimated endurance limits: Carbo-Austempered™ Gears - 10,500 lbs
Carburized Q&T Gears - 9000 lbs

Fig. 28—Load vs. cycles to failure for Carbo-Austempered™ and carburized, quenched and tempered 8620 steel gears.

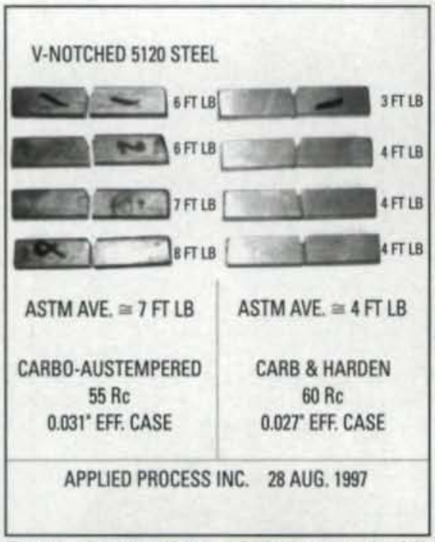

Fig. 29—A comparison of fatigue strength of V-notched Carbo-Austempered™ and carburized and hardened steel of similar hardness.

Fig. 30—A comparison of fatigue strength of unnotched Carbo-Austempered™ and carburized and hardened steel of similar hardness.

Fig. 31—Carbo-Austempered™ steel transmission output shaft for medium-duty truck and bus (Courtesy of GM Allison Transmission).

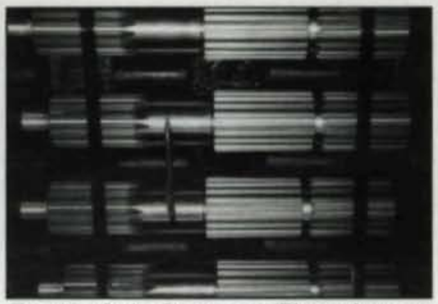

Fig. 32—Carbo-Austempered™ steel output shafts for heavy-duty automotive transmissions.

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Additional Resources

www.appliedprocess.com
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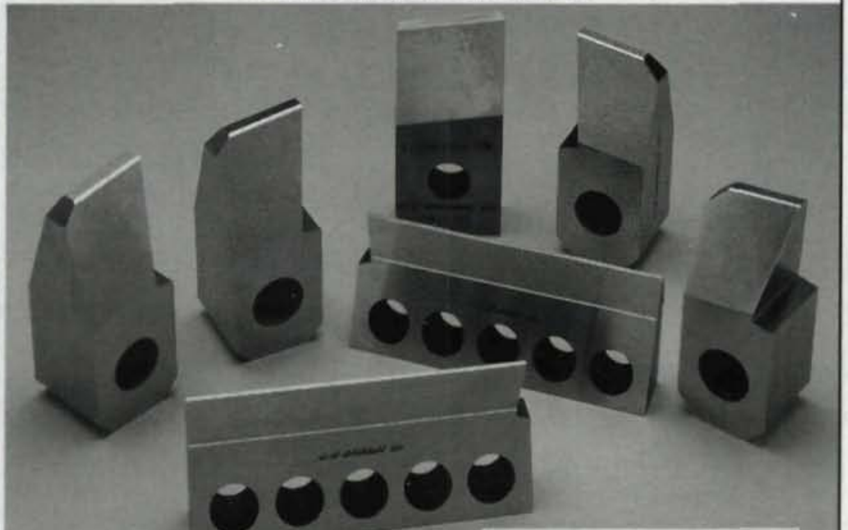

The Calculation of Optimum Surface Carbon Content for Carburized Case Hardened Gears

Philip C. Clarke

Introduction

For high-quality carburized, case hardened gears, close case carbon control is essential.

While tight carbon control is possible, views on what optimum carbon level to target can be wider than the tolerance.

Part 5 of ISO standard 6336 makes an attempt to specify a target and the tolerance for the highest quality grade as eutectoid carbon percentage plus 0.20% or minus 0.10%.

That implies that either a method exists to calculate eutectoid carbon content from alloy content or the values have been determined for a wide range of steels and are widely available. Unfortunately, neither is true. Also implicit is that the eutectoid carbon content is the optimum. But no rationale is given.

A simplistic interpretation is to use the eutectoid carbon content from the iron-carbon phase diagram—see Figure 1. The value is 0.77%, which seems reasonable at first glance. However, experienced heat treaters realize that the higher alloy steels would develop excessive retained austenite if targeting 0.77% with the above tolerance.

In practice, the optimum carbon for a grade of steel is determined by experience and is chosen to minimize the risk of forming undesirable phases, including retained austenite, carbides, bainite and pearlite.

The conclusion is that any calculation of optimum carbon content must reflect the need to minimize such risk.

The objective of this paper is to define a readily available methodology to calculate optimum carbon content from alloy content and austenitizing temperature at the hardening stage.

Continuous Cooling Transformation (CCT) Diagrams

To avoid undesirable transformation products, we turn to the effect that carbon content, alloy content and austenitizing conditions have on the formation of phases during cooling.

CCT diagrams are one of the most effective ways of representing transformation behavior, and more than 1,000 diagrams representing the whole range of carburizing alloys, carbon levels and austenitizing conditions are available in the public domain.

Figure 2 is typical of an experimentally determined CCT diagram with hardnesses and microstructures. Temperature is the vertical linear axis and time is the logarithmic horizontal scale.

More than 600 selected CCT diagrams (Refs. 1–7) have been translated into mathematical form (Refs. 8–9) by multiple linear regression analysis and subsequently became one of the cornerstones of the STAMP and AC3 programs (Refs. 10–11), which have a mature pedigree in calculating CCT diagrams, microstructure and case hardness pro-

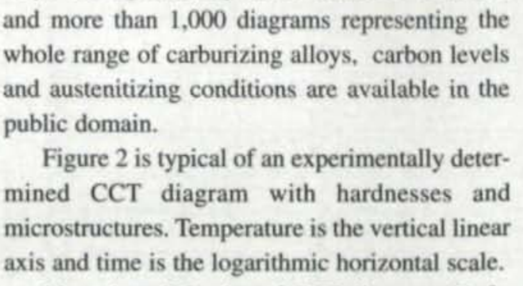

Fig. 1—Iron-carbon phase diagram.

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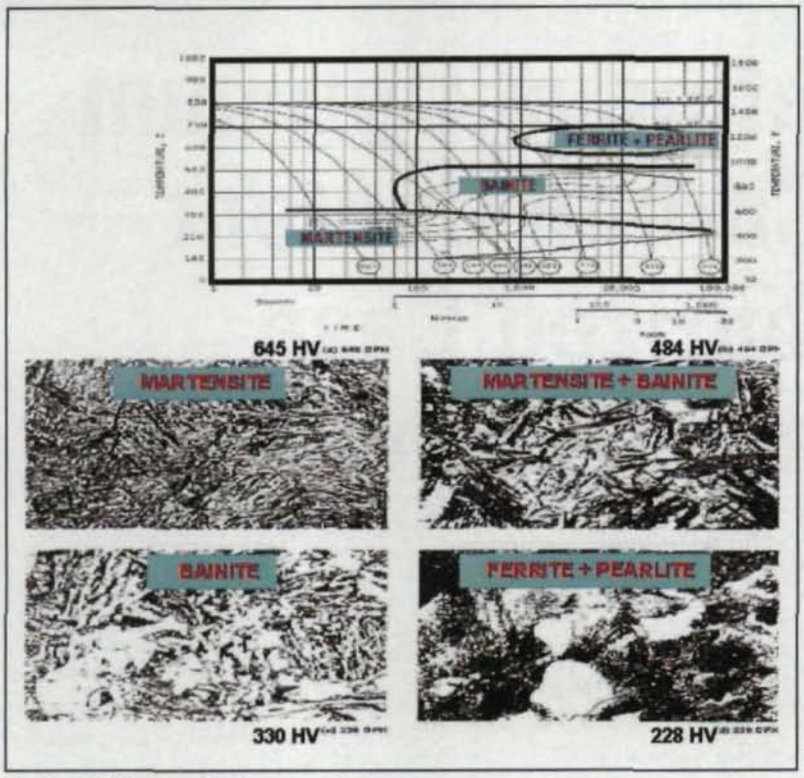

Fig. 2—CCT diagrams, hardnesses and microstructures.

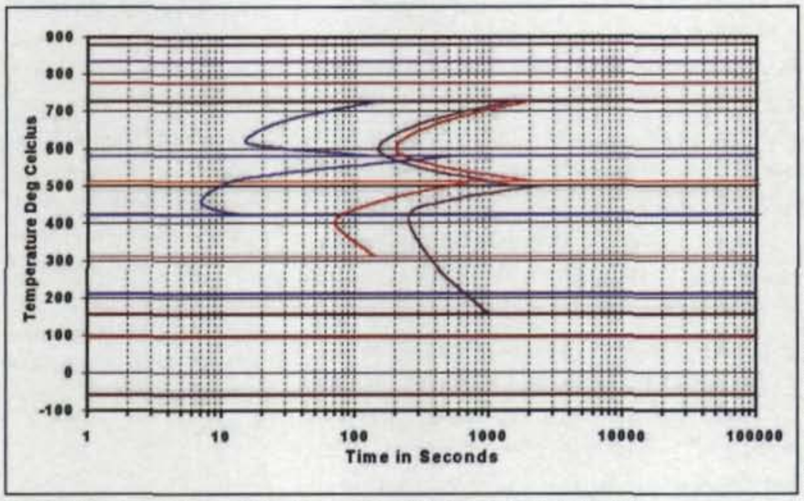

Fig. 3—Effect of carbon on CCT diagrams for 0.2% C, 0.50% C and 0.90% C.

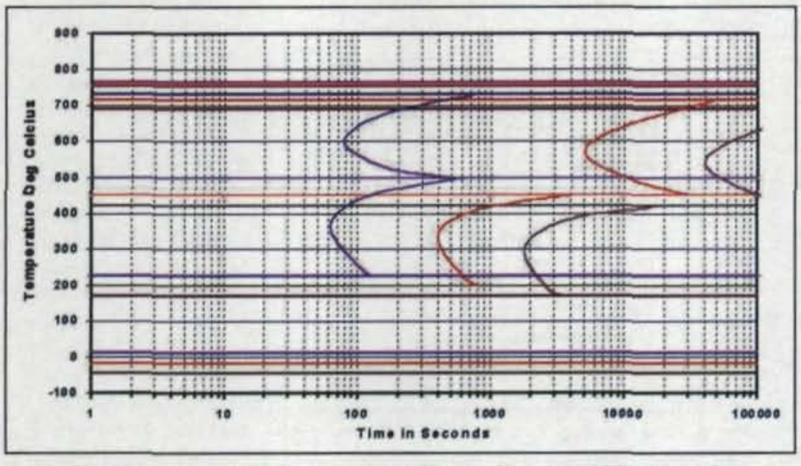

Fig. 4—Effect of nickel on CCT diagrams for 0% Ni, 1.5% Ni and 3.0% Ni at 0.70% Carbon.

files from alloy content, carbon profile, austenitizing conditions, part geometry and cooling media.

The CCT equations create the ability to analyze the effects of carbon and alloy content on transformation products.

Figure 3 is a calculated example of the effect of carbon on those transformations. Increasing the carbon content pushes the boundaries of the undesirable products—bainite, ferrite and pearlite—to the right, increasing hardenability.

The martensite transformation temperatures are lowered, increasing the amount of retained austenite at ambient temperatures.

Figure 4 is a calculated example of the effect of nickel on the CCT diagram at a carbon level of 0.70%. The effects of nickel are similar but less pronounced compared with carbon.

The key to defining the optimum carbon level is to examine how certain features vary with carbon content. The features chosen by the method described later are those that exhibit the greatest sensitivity to carbon content and have a large influence on case hardenability.

Those are:

- Bainite nose time,
- Pearlite nose time,
- Cementite nose time, and
- Martensite start temperature.

The nose times are the lowest values on the start of transformation curves. For example, the bainite nose time for 0.20% carbon in Figure 3 is 7 seconds, and the pearlite nose time at *1.5%* nickel in Figure 4 is 5,000 seconds.

Multiple Linear Regression Equations

The bainite, pearlite and cementite nose times and the martensite start temperature can be calculated from the equations in the shaded area on page 55.

The effects of carbon content, austenitizing temperature and alloy content calculated using those regression equations are illustrated in Figures 5–7.

Characteristic features of Figure 5 include:

- The bainite nose time and hardenability peaks close to 0.80%.
- The pearlite nose time and hardenability decreases with carbon and drops below the bainite line at 0.64%.
- Cementite only forms when the nose time is less than the pearlite nose time, which occurs at 1.02%.

If a tolerance band of –0.1% to +0.2% is applied, then the permitted carbon levels are 0.56% to 0.86%. That band is described as the carbon hardenability window.

The ISO 6336 standard implies a target carbon of 0.66% for that window, which would be considered too low in practice.

The effect of carbon on the martensite start temperature for austenitizing temperatures typical of direct and reheat quench case hardening cycles is shown in Figure 6.

Also included on Figure 6 is the martensite start temperature of 147°C calculated from the Koistinen and Marburger equation (Ref. 13), which results in 25% retained austenite on quenching to an ambient temperature of 30°C. That demonstrates that while all carbon levels for reheat quenching are acceptable, the carbon level for direct quenching would need to be restricted to less than 0.88%.

Carbon Hardenability Windows

The effect of chromium on carbon hardenability is illustrated by Figure 7. Characteristic features include:

- For 0% chromium, the upper limit is set by the bainite nose time.
- For 2% chromium, the upper limit is set by the *pearlite nose time.*
- Increasing the chromium content moves the window to lower carbon levels.
- Increasing the chromium content reduces the carbon content at which cementite can form from 1.00% to 0.87%—quite close to the upper limit (0.83%) of the window.

Those features demonstrate the affinity of chromium for carbon and promotion of carbide formation.

Defining the Method of Calculating Optimum Carbon Content

The Criteria. The criteria chosen to define the method for the avoidance of undesirable transformation products are:

1. Cementite

If the cementite nose time is less than both the pearlite and bainite nose times at 0.85% C, then use the cementite nose time to replace the bainite nose time in criterion 3.

2. Pearlite

If the pearlite nose time is less than the bainite nose time at 0.5% C, then use the pearlite nose time to replace the bainite nose time in criterion 3.

If the pearlite nose time is less than the bainite nose time at 0.85% C, then use the pearlite nose time to replace the bainite nose time in criterion 3.

3. Bainite

To minimize bainite, calculate the carbon content corresponding to maximum hardenability

MULTIPLE LINEAR REGRESSION EQUATIONS

T = Austenitizing temperature, in degrees Celsius and
t = Austenitizing soak time, in minutes.

BAINITE NOSE TIME (BTAU IN SECONDS)

(1) $C \le 0.50\%$

$$\mathrm{Log}_{10}(\mathrm{BTAU}) = -3.79 + 8.68 \bullet C - 5.35 \bullet C^2 - 1.70 \bullet Mn \bullet C + 1.56 \bullet Mn + 0.79 \bullet Cr + 0.92 \bullet Mo + 0.41 \bullet Ni + 0.32 \bullet Mo \bullet Ni + 0.0058 \bullet T + 0.00021 \bullet T \bullet \log_{10}(t)$$

(2) $0.50\% \le C \le 0.80\%$

$$\mathrm{Log}_{10}(\mathrm{BTAU}) = \mathbf{a} + \mathbf{d} \bullet (C - 0.8)^2$$

Where:
a equals the lower of:
$\log_{10}(\mathbf{t}_2) - \mathbf{g}_2/40$
or
$\log_{10}(\mathbf{t}_1) + 0.50$
and
$\mathbf{d} = (\log_{10}(\mathbf{t}_1) - \mathbf{a})/0.09$
$\mathbf{t}_1$ = BTAU at C = 0.50% from Eq. 1
$\mathbf{t}_2$ = BTAU at C = 0.85% from Eq. 4
$\mathbf{g}_2$ = is the gradient of the curve BTAU vs. C at 0.85% from Eq. 4.

(3) $0.80\% < C < 0.85\%$

$$\mathrm{Log}_{10}(\mathrm{BTAU}) = \mathbf{a} + \mathbf{b} \bullet (C - 0.8)^2$$

Where:
$\mathbf{b} = 400 \bullet (\log_{10}(\mathbf{t}_2) - \mathbf{a})$
and **a**, $\mathbf{t}_2$ are as defined previously in Eq. 2.

(4) $C \ge 0.85\%$

$$\mathrm{Log}_{10}(\mathrm{BTAU}) = -7.30 + (1.69 - 0.36 \bullet Ni)/C + 0.57 \bullet Mn + 0.57 \bullet Cr + 1.81 \bullet Mo + 0.93 \bullet Ni + 0.0065 \bullet T$$

PEARLITE NOSE TIME (PTAU IN SECONDS)

(5) $C \le 0.60\%$

$$\mathrm{Log}_{10}(\mathrm{PTAU}) = -3.45 + 2.77 \bullet C + 2.67 \bullet Mo \bullet C - 0.75 \bullet Ni \bullet C - 3.00 \bullet C^2 + 1.26 \bullet Mn + 1.52 \bullet Cr + 4.54 \bullet Mo + 0.98 \bullet Ni - 0.30 \bullet Cr^2 - 1.45 \bullet Mo \bullet Cr + 0.00233 \bullet T$$

(6) $0.60\% < C < 0.80\%$

$$\mathrm{Log}_{10}(\mathrm{PTAU}) = \mathrm{Log}_{10}(\mathbf{t}_1) + 5 \bullet (C - 0.6) \bullet \mathrm{Log}_{10}(\mathbf{t}_2/\mathbf{t}_1)$$

Where:
$\mathbf{t}_1$ = PTAU at C = 0.60% from Eq. 5
$\mathbf{t}_2$ = PTAU at C = 0.80% from Eq. 7

(7) $C \ge 0.80\%$

$$\mathrm{Log}_{10}(\mathrm{PTAU}) = -3.96 + 0.95/C + 0.73 \bullet Mn + 0.54 \bullet Cr + 3.33 \bullet Mo + 0.65 \bullet Ni + 0.00340 \bullet T$$

CEMENTITE NOSE TIME (CTAU IN SECONDS)

$$\mathrm{Log}_{10}(\mathrm{CTAU}) = -1.24 + (-6.76 - 0.11 \bullet Mn - 0.16 \bullet Cr + 1.69 \bullet Mo - 0.06 \bullet Ni + 0.00602 \bullet T)/C + 3.42 \bullet C^2 + 0.00047 \bullet T \bullet \mathrm{Log}_{10}(t)/C^2$$

MARTENSITE START TEMPERATURE (MS IN °C)

(8) $C \le 0.50\%$
(Andrew's Formula, Ref. 12)

$$MS = 512 - 453 \bullet C - 71.5 \bullet Mn \bullet C - 67.6 \bullet Cr \bullet C + 217 \bullet C^2 + 15 \bullet Cr - 9.5 \bullet Mo - 16.9 \bullet Ni$$

(9) $0.50\% < C < 1.10\%$

$$MS = T_2 + (T_1 - T_2) \bullet (C - 1.1)^2/0.36$$

Where:
T_1 = MS at C = 0.50% from Eq. 8
T_2 = MS at C = 1.10% from Eq. 10

(10) $C \ge 1.10\%$

$$MS = 436 + 40 \bullet Cr - 5 \bullet Mo - 7 \bullet Ni - 0.339 \bullet T - 0.023 \bullet (Mn + Ni \bullet Cr) \bullet T$$

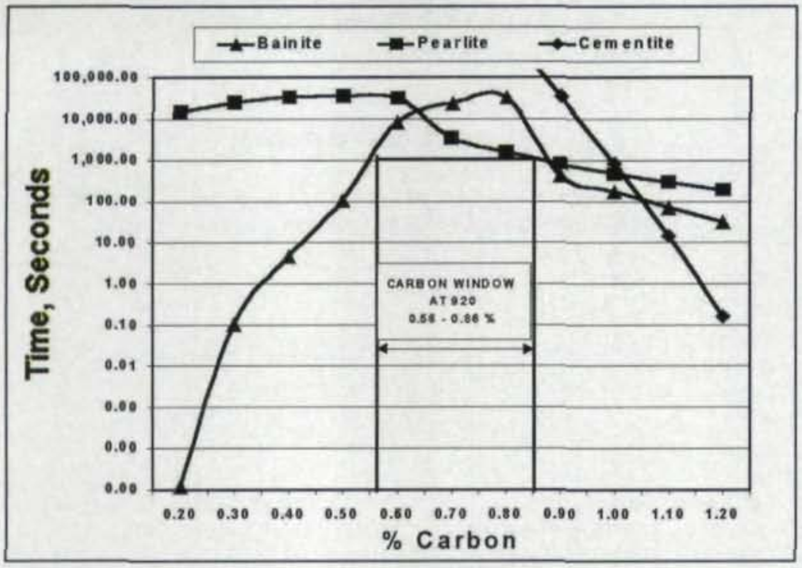

Fig. 5—Effect of carbon on nose times for SAE 8620 at 920°C.

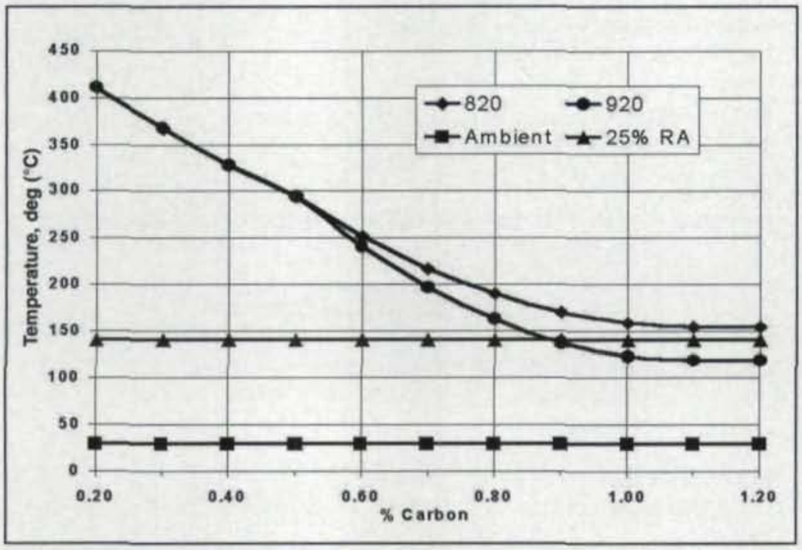

Fig. 6—Effect of carbon on martensite start temperature for SAE 8620 austenitized at 820°C and 920°C.

on the bainite nose time versus carbon curve between 0.50% and 0.85%.

4. Excessive Retained Austenite

The upper carbon limit must be more than 0.10% below the carbon level calculated to leave 25% retained austenite measured optically after quenching and tempering.

Procedure. The principle is to calculate the carbon content within the carbon hardenability window, which minimizes the risks of transformation to non-martensitic products—in particular bainite, pearlite and carbide—while avoiding excessive retained austenite.

The procedure is based on the variations of bainite, pearlite and cementite nose times and on the carbon content corresponding to 25% retained austenite.

To calculate the optimum carbon from alloy content and austenitizing conditions:

1. Calculate the bainite and pearlite nose times at 0.50% C.
2. Calculate the bainite, pearlite and cementite nose times at 0.85% C.
3. Find the lowest nose times at 0.50% C and 0.85% C.
4. Use the lowest nose times to calculate the optimum carbon for case hardenability by log linear interpolation.
5. Calculate the carbon content equivalent to 25% retained austenite from the Koistinen and Marburger equation (Ref. 13).
6. Calculate the final optimum carbon by averaging the carbon content from step 4 and the carbon content from step 5 minus 0.10%.

The formulas. The formulas, derived from the multiple linear regression equations, are:

At 0.5% Carbon

Bainite: $10^{(-0.79 + 2.41 \cdot Mn + 0.79 \cdot Cr + 0.92 \cdot Mo + 0.41 \cdot Ni + 0.32 \cdot Mo \cdot Ni + 0.001 \cdot T)}$

Pearlite: $10^{(-2.82 + 1.26 \cdot Mn + 1.52 \cdot Cr + 5.85 \cdot Mo + 0.60 \cdot Ni - 0.30 \cdot Cr \cdot Cr - 1.45 \cdot Mo \cdot Cr + 0.00233 \cdot T)}$

At 0.85% Carbon

Bainite: $10^{(-5.31 + 0.57 \cdot Mn + 0.57 \cdot Cr + 1.81 \cdot Mo + 0.51 \cdot Ni + 0.0065 \cdot T)}$

Pearlite: $10^{(-2.84 + 0.73 \cdot Mn + 0.54 \cdot Cr + 3.33 \cdot Mo + 0.65 \cdot Ni + 0.0034 \cdot T)}$

Cementite: $10^{(-4.46 - 0.13 \cdot Mn - 0.19 \cdot Cr + 1.99 \cdot Mo - 0.07 \cdot Ni + 0.0084 \cdot T)}$

Calculation of Optimum Carbon, C_H, for Case Hardenability by Log Linear Interpolation:

$$C_H = 0.65 + IF(LOG_{10}(N_{0.85}/N_{0.5}) > 1, 0.2, IF(LOG_{10}(N_{0.85}/N_{0.5}) < -2, 0, 0.2 \cdot (LOG_{10}(N_{0.85}/N_{0.5}) + 2)/3)$$

Where:

$N_{0.5}$ = lowest nose time at 0.50%
$N_{0.85}$ = lowest nose time at 0.85%

Carbon equivalent, C_M, to 25% Retained Austenite at an Ambient Temperature of 30°C:

$$C_M = 1.1 - \sqrt{(0.36 \cdot (117 - MS_{1.1})/(MS_{1.1} - MS_{0.5})}$$

Where:

$$MS_{0.5} = 339.75 - 35.75 \cdot Mn - 18.8 \cdot Cr - 9.5 \cdot Mo - 16.9 \cdot Ni$$

and

$$MS_{1.1} = 436 + 40 \cdot Cr - 5 \cdot Mo - 7 \cdot Ni - 0.339 \cdot T - 0.023 \cdot (Mn + Ni \cdot Cr) \cdot T$$

Calculation of Final Optimum Carbon:

$$C = (C_H + (C_M - 0.1))/2$$

Results

The formulas have been used to form the basis of a spreadsheet. Examples for selected steels are tabulated in Appendix 1.

Points to emerge from Appendix 1 include:

- For direct quenching, the retained austenite carbon tends to dominate the final optimum carbon.

- For reheat quenching, the nose time equations tend to dominate.
- The highest nickel steels have the lowest optimum carbons.

Conclusions

1. A definitive method to calculate optimum carbon levels for carburized case hardened gears has been described.
2. The optimum carbon level minimizes the risk of forming undesirable transformation products, including retained austenite, carbide, bainite and pearlite.
3. The method uses multiple linear regression equations, derived from more than 600 published CCT diagrams, to calculate key points on the CCT diagrams.
4. The accuracy of the coefficient, $\alpha = -1.1 \times 10^{-2}$ in the Koistinen and Marburger equation:

$V\gamma = e^{\alpha \times (MS-Tq)}$

Where:

$V\gamma$ = % retained austenite,

MS = martensite start temperature,

Tq = ambient temperature,

needs to be re-evaluated because it was based on light microscopy measurements of retained austenite, and more accurate methods of measuring retained austenite by X-ray diffraction and electron microscopy are available and have demonstrated that light microscopy can give seriously misleading results.

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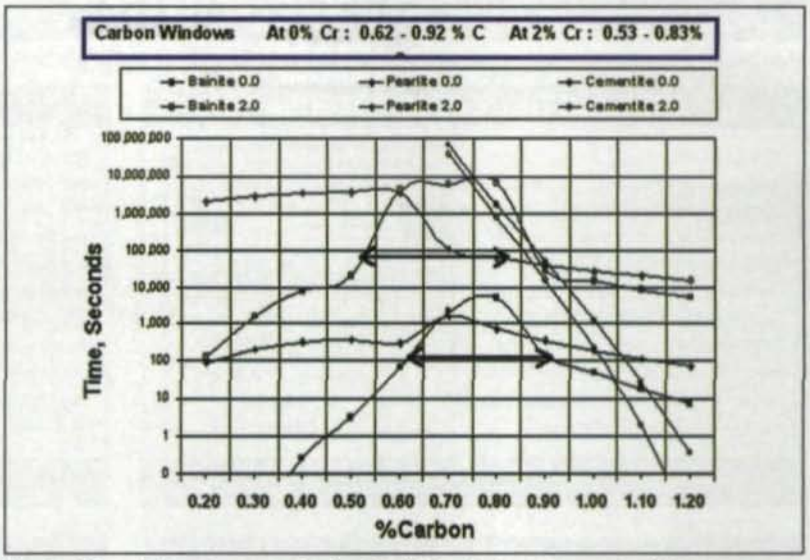

Fig. 7—Effect of chromium on carbon hardenability windows at an austenitizing temperature of 920°C.

Appendix 1 —Results of Sample Calculations

Grade	Base Composition %Mn	%Cr	%Mo	%Ni	Aust Temp. (°C)	% Optimum Carbon
16MnCr5	**1.00**	**1.00**	**0.00**	**0.00**	**820**	**0.70**
655M13	0.45	0.82	0.11	3.20	930	0.62
17CrNiMo6	0.48	1.62	0.29	1.52	930	0.73
8620	0.74	0.47	0.19	0.47	930	0.77
4320	0.52	0.47	0.24	1.73	930	0.71
8822	0.84	0.47	0.34	0.51	930	0.75
655M13	0.45	0.82	0.11	3.20	820	0.72
17CrNiMo6	0.48	1.62	0.29	1.52	820	0.76
8620	0.74	0.47	0.19	0.47	820	0.78
4320	0.52	0.47	0.24	1.73	820	0.79
8822	0.84	0.47	0.34	0.51	820	0.79

Appendix 1 —Supplementary Calculations

Grade	Pearlite		Bainite		Cementite	% Carbon for	MS deg C at	
	0.5% C	0.85%C	0.5% C	0.85% C	at 0.85%C	25% Ret Aust.	0.5%C	1.1%C
16MnCr5	**91**	**7**	**71**	**4**	**1,733**	**1.10**	**285**	**179**
655M13	201,210	308,704	16,176	142,786	91,002	0.72	253	65
17CrNiMo6	321,558	276,565	29,007	121,691	240,623	0.83	264	111
8620	2,554	1,338	37	1,049	285,216	0.87	295	115
4320	46,420	39,135	779	14,564	319,331	0.81	281	98
8822	86,492	17,254	187	5,217	618,630	0.85	289	111
655M13	91,698	101,056	10,561	12,181	2,762	0.82	253	110
17CrNiMo6	152,126	89,359	19,412	9,924	10,681	1.10	264	155
8620	736	179	17	13	13,463	1.10	295	154
4320	18,577	9,733	435	591	15,689	1.02	281	138
8822	36,669	3,775	95	140	37,969	1.10	289	151

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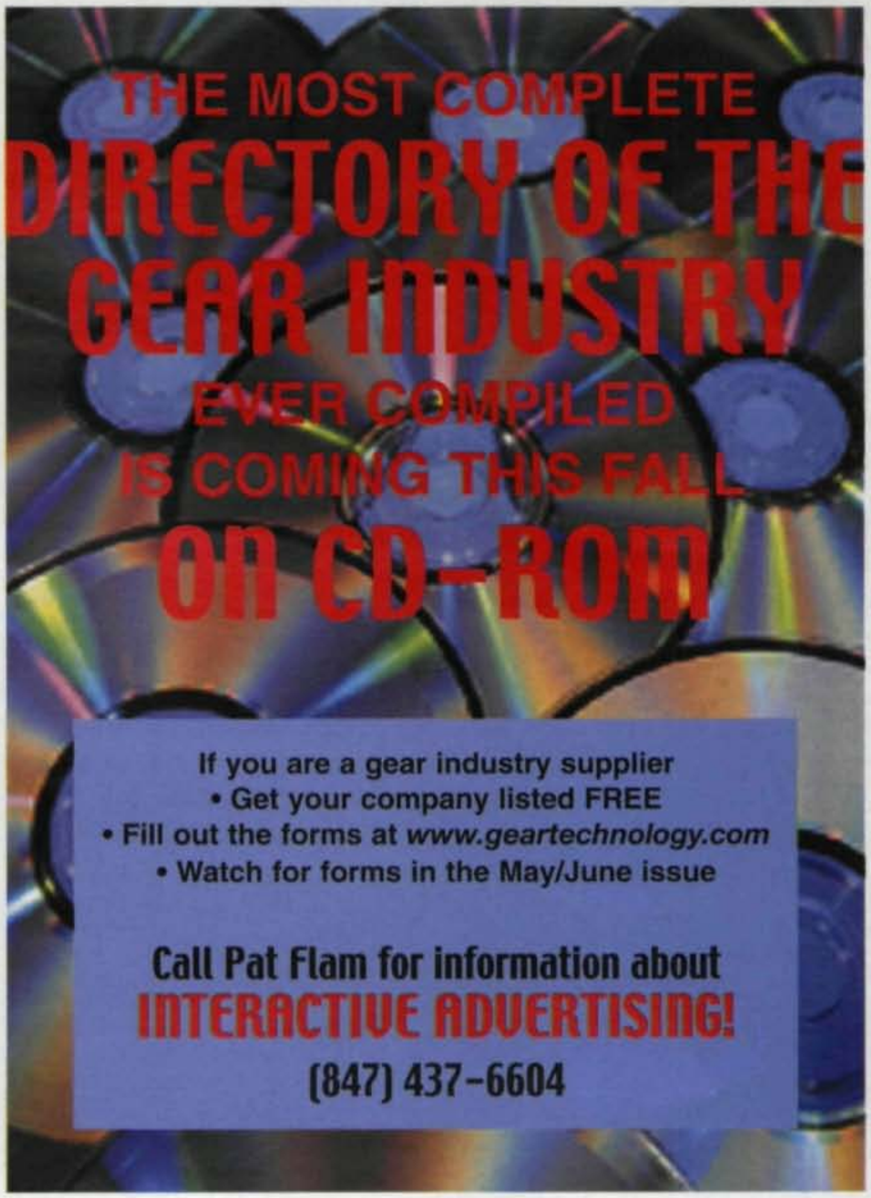

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GEARS WITH EARS

When you're manufacturing fun, very often you need gears.

The Addendum team recently went on a behind-the-scenes gear-finding mission with Jerold S. Kaplan, Principal Engineer, Show/Ride Mechanical Engineering at Walt Disney Imagineering in Lake Buena Vista, FL. We found that at least part of Disney's magic comes from good, old-fashioned mechanical engineering.

Kaplan's job is to help design, build and maintain a wide variety of mechanical devices. Gears are everywhere at Disney World, helping to power roller coasters, theme rides, animated characters and other attractions, Kaplan says. The gears range in size from very tiny up to several feet in diameter, and they're made of a variety of materials, from plastic to case-carburized steel.

One of Kaplan's recent gear-related projects is a four-story floating video display in the shape of the Earth. The globe is part of the Epcot theme park's *IllumiNations: Reflections of Earth* show. The nightly show includes a fireworks and laser display above Epcot's World Showcase Lagoon, where the giant globe takes center stage.

During the show, the globe, which was built atop a custom-manufactured barge, is piloted to the middle of the lagoon. It rotates on its axis and opens up like a flower as color video images flash across the continents. As an added feature, the barge spews flames in all directions as fireworks explode overhead.

Thankfully, the flames were turned off when we visited. But we did get to see the giant sphere in action, and we even got to peek inside. At the base of the sphere is a large, toothed turret bearing, driven by two pinions with redundant 10-hp hydraulic motors. According to Kaplan, there's nothing particularly fancy or high-tech about the gears that drive the video globe. The biggest concern in designing the gear drive was reliability, he says. Because the globe is such a central part of the show, it has to work every night during a single 15-minute show window.

We don't care if the gears are fancy or plain, but the *IllumiNations* video globe proves something we've known all along: *Gears* make the world go around.

Many Disney attractions place high demands on their gears. For example, one of the attractions at Epcot is called Test Track by General Motors Corp. The ride simulates an automotive proving ground, where visitors ride over bumpy terrain, through freezing weather and around steeply banked turns at speeds up to 65 mph.

Test Track has proven to be one of the most demanding rides on its gears. Each car is powered by a rear differential transmission with a fully reversing load, and they are ridden approximately 50,000 miles per year, Kaplan says. "From that perspective, we really work the equipment. It has to be able to take an incredible amount of abuse, because it's in operation 365 days a year, for up to 18 hours a day."

Reliability is one of the most critical aspects of gear engineering for most of the projects Kaplan works on. Some rides, like Test Track, are in constant use while the theme park is open. Others, like the *IllumiNations* globe, are required to perform night after night without a hitch. The globe, for example, was developed with a design life of 10 years. "We're always looking for something that gives us better life or durability," Kaplan says.

However, Kaplan and the engineering team aren't involved in creating all the park's gears. A separate design team usually creates gears used as display elements. Although they aren't functional, those display gears are some of Disney World's most impressive gears. For example, giant gears adorn the outside of the Mouse Gear retail store in Epcot. That building also has large cement planters in the shape of gears outside the entrance. Now that's what we call decorating. ○

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