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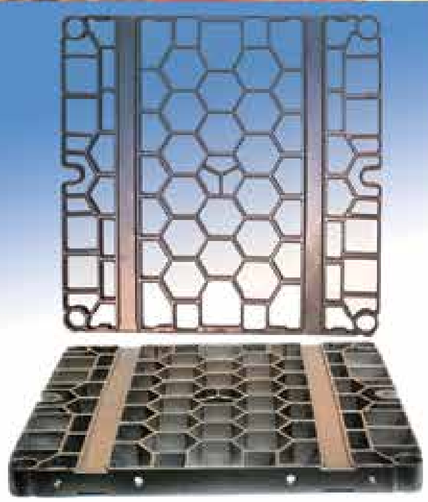
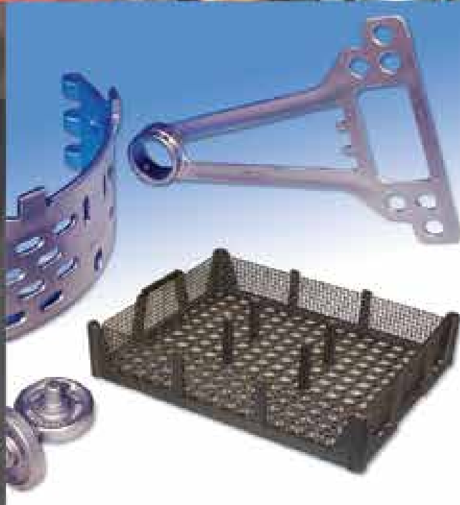
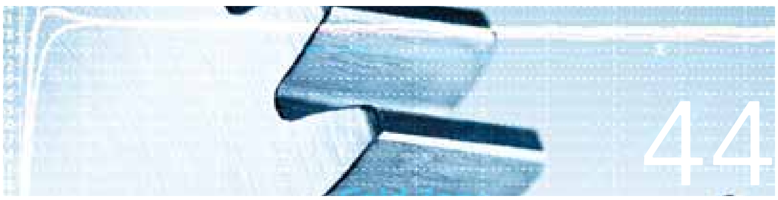
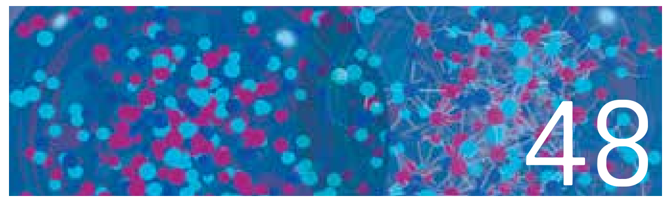


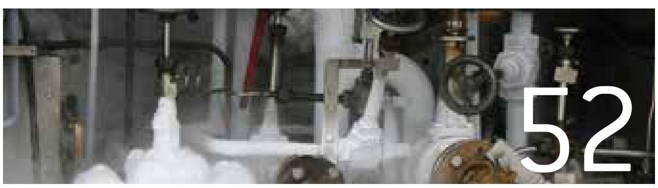


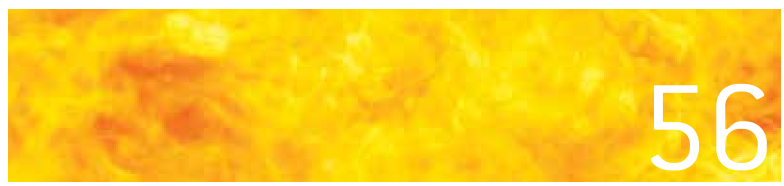
FEATURES

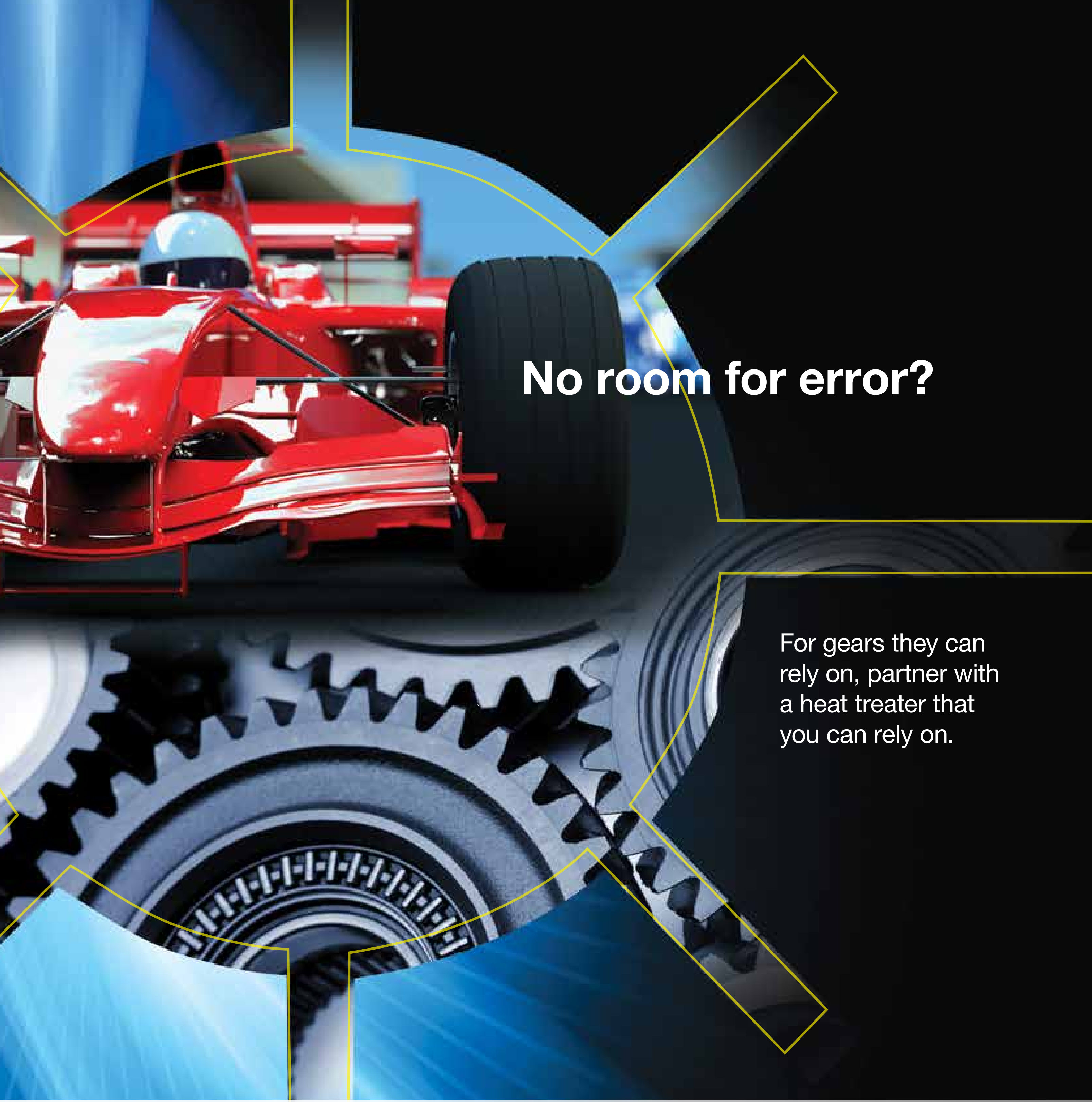
Spring/Summer 2013










No room for error?
For gears they can rely on, partner with a heat treater that you can rely on.

DEPARTMENTS

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Volume 2 / Number 1

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LETTER FROM THE EDITOR

Spring is finally here, but things have been heating up around here for months. We're thrilled to present the second issue of *Thermal Processing for Gear Solutions*, a magazine that takes time to do things right.

We have good reason to take our time—it pays off, as anyone in the heat treat industry will tell you. For example, taking the time to implement the necessary safety procedures and proper process control tactics will pay off in the long run, as our columnists Marty Keylon and Jim Oakes explain in their "Site Safety" and "Quality Counts" articles. Invensys Eurotherm's Steve Miller, similarly, takes a closer look at what temperature uniformity surveys can do for this kind of process control.

Learning how to do something right includes learning how it could go wrong, and the "Heat Treat Doctor" Dan Herring describes how gear failures can directly result from improper heat treatment in "How Gears Fail." Likewise, Charlie Li and B. Lynn Ferguson use the commercial heat treatment software DANTE to investigate three examples of heat treatment defects in their article, "Typical Heat Treatment Defects of Gears Using FEA Modeling."

Other articles in this issue of *Thermal Processing for Gear Solutions* concern the future of heat treatment, and they're not run-of-the-mill. Rick Diekman explores the uncharted waters of deep cryogenic treatment (DCT), arguing that this temperature-controlled hardening process has more possibilities than many people think. He dispels the myths of the "pseudo-science" stigma of cryogenic freezing, and emphasizes how it can greatly improve wear resistance in gears. Inductoheat's Valery Rudnev focuses on recent inventions and innovations in induction hardening of gears—high-frequency, environmentally-friendly work that our company profile, Twinsburg, Ohio's CEIA USA knows about first-hand. CEIA's Cody Kothera and Marilyn Thaxton explore the common thread between induction hardening of gears and the company's lifeblood: metal detection technology. Fred Specht of Ajax-TOCCO-Magnethermic provides an eloquent outline for induction heating, ideal for improving gear performance. And to cool off, Robert Hill, president of Solar Atmospheres of Western PA, takes a look at different quenching methods and asks the question, "If these methods are evolving, why not change how we measure their results?"

Austempered ductile iron (ADI) is becoming a preferred choice for heat treaters, and Jack Titus explains why in "Hot Seat." Jack takes us through the evolution of ADI and how its lighter weight and increased fatigue strength pay off, while Proceq's Tom Ott explains how hardness testing is increasingly relevant to the heat treat industry and shares some new products for hardness testing of heat-treated gears.

Heat treatment is fascinating. Watching the glow of steel, hearing the hiss of a quench, witnessing the strengthened final product—it's a beautiful process. The exercise itself is at once new and old, an ancient art with new possibilities being discovered every day. This extraordinary metallurgical process, just like *Thermal Processing for Gear Solutions* itself, has been a long-time-coming. You are making your product the best it can possibly be. So are we.

Tim Byrd
managing editor
Thermal Processing for Gear Solutions magazine
editor@thermalprocessing.com
(800) 366-2185 x205

Thermal processing for Gear Solutions

David C. Cooper
PUBLISHER

Chad Morrison
ASSOCIATE PUBLISHER

EDITORIAL
Tim Byrd
MANAGING EDITOR
Stephen Sisk
ASSOCIATE EDITOR

SALES
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CONTRIBUTING WRITERS
NICHOLAS BUGLIARELLO
RICK DIEKMAN
B. LYNN FERGUSON
BIJI GEORGE
DON GIESSEL
DANIEL H. HERRING
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Three-Chamber Casemaster Evolution Vacuum Carburizing Furnaces from Seco/Warwick

Seco/Warwick Corp. has received an order for a three-chamber CaseMaster Evolution® Vacuum Carburizing furnace with washers, tempers, and a full data retrieval system. The contract was signed recently and Seco/Warwick Corp. will provide the equipment for a worldwide aerospace manufacturer. Seco/Warwick officials said they expect to have the equipment in place by July.

The CaseMaster Evolution® vacuum T9 furnace is a three-chamber furnace with separate preheating, heating, and oil quenching areas. This furnace design allows for significant increases in flexibility and productivity. The furnace will provide low-pressure carburizing through the use of FineCarb® technology and low-pressure carburizing with pre-nitriding with PreNitLPC® technology.

The Vacuum Team offers vacuum heat treating furnaces for hardening, tempering, annealing, solution heat treating, brazing, sintering, carburizing, carbonitriding, high vacuum, CVD–graphitizing, and degassing. Seco/Warwick has built some of the largest and most technically advanced vacuum furnaces in operation today, developing advanced technologies like Universal HPQ™ (High Pressure Quench), PreNit® & FineCarb® LPC vacuum carburizing, fully-automated control systems, and modeling software. Vacuum furnace configurations are available for vertical, horizontal, and elevator style furnaces. Both cylindrical and rectangular hot zones with metallic or graphite heating elements are available for both new and used equipment. Retech LLC provides vacuum melting equipment.

Seco/Warwick provides heat treating equipment and services worldwide for customers involved with steel manufacturing, primary aluminum, aluminum recycling, steel manufacturing, automotive, aerospace, commercial heat treating, HVAC, electronics, lighting, medical equipment, and nuclear applications. The globally-integrated organization includes Seco/Warwick Corp. (USA), Retech Systems LLC (USA), Seco/Warwick S.A. (Poland), Seco/Warwick Thermal S.A. (Poland), Seco/Warwick Allied Pvt. Ltd. (India), and Seco/Warwick RETECH Thermal Equipment Manufacturing Co. Ltd. (China). Visit www.secowarwick.com for more information.

Super Systems, Inc. Releases SuperCALC,

Super Systems Inc. has released SuperCALC, an advanced calculator app for the heat treating industry available on iPhone, iPad, and iPod and Android smartphones and tablets. These apps are available for free. SuperCALC includes:

- The Furnace Calculator, which calculates %carbon, dew point, and %oxygen based on millivolts and temperature;
- The IR 3-gas Calculator, which calculates %carbon using the furnace temperature and the CO, CO2, and CH4 readings from a 3-gas analyzer; and
- The Generator Calculator, which calculates the required airflow and gas flow based on the capacity of the endothermic generator.

To get the app, you can:

1. Open the appropriate link for iPhone, iPad, iPod, or Android (http://www.supersystems.com/calculators.html) or
2. Search for “SuperCALC” in your device’s app store and install the app created by Super Systems, Inc. For more information, visit www.supersystems.com or call 513-772-0060.

Companies wishing to submit materials for inclusion in Industry News should contact the Tim Byrd at editor@thermalprocesing.com.
Releases accompanied by color images will be given first consideration.

Solar Manufacturing Receives Vacuum Furnace Order From Major Gear Manufacturer

Solar Manufacturing, Inc. recently received an order for a Model HVC-3836-2IQ horizontal, front-loading vacuum carburizing furnace from Aero Gear, Inc., a major gear manufacturer in the United States. This furnace will be used for the carburizing of a variety of gears applicable to both the commercial and military aerospace industry.

The work zone of this furnace will be: 24 inches (610 mm) wide x 24 inches (610 mm) high x 36 inches (914 mm) deep, with a hearth designed to accommodate up to a 1,000-pound workload. The entire hot zone utilizes a Flexshield hot face backed by four layers of ½ inch thick graphite felt insulation and supported by a heavy-duty stainless steel structure. The heating elements will consist of thin, durable, curved graphite allowing for a maximum operating temperature of 2500ºF. The vacuum pumping system will be a Stokes Model 412J 300 CFM mechanical pump backed by a Stokes 615 Booster blower for vacuum operation in the low micron range.

A new Solar proprietary radial fan and gas diffuser/distributer design with internal 100 horse power drive motor is capable of providing rapid quenching of loads to their required hardness if gas quenching is specified. Solar's vacuum carburizing system is included in the furnace control system. To learn more about Solar Manufacturing's diverse product line and services, contact Pete Reh, VP of sales, at 267-384-5040 x 1509 or pkr@solarmfg.com. Additional information can be found at www.solarmfg.com.

United Process Controls Welcomes New North American Sales Manager

United Process Controls (UPC) is pleased to announce the appointment of Paul Torok to the position of North American sales manager. Mr. Torok will be responsible for driving the sales growth for UPC's heat treating controls and instrumentation, as well as Waukee flow controls. Mr. Torok will report to Patrick Torok, vice president of sales and marketing, Heat Treat North America.

With over ten years in the heat treat industry, Paul Torok brings a broad range of experience in the manufacturing and implementation of heat treat controls, working most recently at a controls calibration company. He has also worked with UPC member companies Furnace Control Corp. and Waukee Engineering, before the amalgamation in 2007, in field services, mechanical and electrical engineering, and sales. In addition, Mr. Torok was instrumental in the development of the FurnaceDoctor® gas analyzer, while working at Triadx Manufacturing.

"I was drawn to United Process Controls," Mr. Torok states, "because of my past work history and the company's growth and reputation over the past five years since its inception for offering quality products and services. It is a natural compliment to my background, and I look forward to using my skills and customer relationships to manage established accounts and develop new business." He will be based out of United Process Control's West Chester, OH office. For more information, visit www.group-upc.com.

Continued on pg. 63

Lucifer Furnaces Supplies Box Furnace to Lycian Stage Lighting

Lycian Stage Lighting, a leading American based manufacturer of theatrical followspot lights has updated its heat treating with a Lucifer Furnaces bench style box furnace.

Lycian Stage Lighting's products can be found in high school auditoriums, on Broadway, and in the Olympic Opening and Closing Ceremonies. Model HA7-A9 has chamber dimensions of 6"x6"x9" and heats to 1850°F. Temperature is controlled with a Honeywell microprocessor-based digital time-proportioning controller, with accuracy of 0.25%. A representative for Lycian Stage Lighting notes, "Our process is time sensitive, therefore the optional timer control on the furnace made a big difference in monitoring the temperature, thereby freeing up our technician and increasing our production efficiency."

Built with 5" insulating brick and mineral wool block for lower outside shell temperature and energy efficiency, the insulation is dry fit for better refractory expansion, contraction, and replacement. Seams are overlapped to reduce heat loss and increase thermal storage. Heavy gauge, coiled, low-watt density element wire in easy-to-replace radiant panels provides uniform heat. A 1"-thick hearth plate supports the side heating elements, protects the floor insulation, and provides a flat working surface. The horizontal insulated swing door, constructed of heavy gauge steel to withstand distortion, is insulated with 5" multilayered insulation; a heavy duty hinge-and-cam latch ensures a positive seal, and a safety microswitch automatically disengages power to the heating elements when the door is opened. Lycian Stage Lighting is using the furnace to heat treat a component of their followspot lights that controls the amount of light output on the followspots. The Lycian representative adds, "We'd also like to comment on the excellent service we received from the staff at Lucifer Furnaces. From the initial quote to final production and delivery of our unit, we received a quality product, made in America, by a quality-conscious company."

To find out more, call 1-80-378-0095 or visit www.luciferfurnaces.com.

AN OPEN COMMUNICATION SYSTEM THROUGHOUT YOUR FACILITY

by Marty Keylon

In the last issue of *Thermal Processing,* I wrote a pretty broad and general article about the do's and dont's of safety, using some examples of accidents I knew about. This time, I'd like to pick a specific topic and get into a little more depth.

"LOCK-OUT TAG-OUT"

In my heat treating facilities—I was senior general manager of two—we had very good accident-prevention programs. At one of the facilities, we had an eight-year run of no "lost time" accidents; any accident resulting in a lost day of work for the employee. We had a few close calls with minor cuts and bruises, but overall the programs in place, when followed, worked. One of the incentives implemented was this: For every year without a lost time accident, we would give each employee $100. We ended up capping it at $500, but the savings to the company in lost time wages and insurance premiums far exceeded the cost.

WHAT DOES A LOCK-OUT TAG-OUT SYSTEM DO?

It keeps one person responsible and in control of the power to a piece of equipment that is out of service. Most equipment uses cylinders, valves, mechanical gears, and levers driven by electric or air and hydraulic motors. With this program, you have a way to keep your employees safe while the equipment is locked out and tagged out.

WHEN DO YOU HAVE TO USE IT?

While performing any kind of maintenance, if the piece of equipment needs its guards removed for visual inspection, or in the event of a malfunction. In my last article, I told the tragic story of two men who died in a preventable accident, had the proper lock-out tag-out safety procedures been used.

WHY DO YOU DO IT?

It is invaluable anytime you pose a risk of electrocution, fire or explosion, asphyxiation, burns or spill hazards, or movement of mechanical valves and cylinders resulting in pinching and/or crushing.

WHAT NEEDS TO BE "LOCKED OUT?"

Every piece of equipment that has some type of safety hazard associated with its operation and maintenance, from a simple copy machine (unplug it before servicing any electrical or pinch hazard) to large heat treating furnaces, air compressors, induction machines, vacuum furnaces, car bottom furnaces, open-fire furnaces, transfer carts, and overhead cranes. These all use many different types of power to move the product in, out, and around the shop. In the furnaces, you have fans for circulation of the atmospheres, motors for circulation of oil and water, opening and closing of doors and valves, and very high-pressure hydraulic fluid for cylinders and hydraulic motors. You might also have high-pressure air, nitrogen, argon, endothermic, exothermic, ammonia, hydrogen, helium, hot quench oil, and hot and cold cooling water.

WHAT NEEDS TO BE "TAGGED-OUT"?

When a piece of equipment is properly locked out, the valve or electrical switch is in the "off" position, with a repair tag and a special device that makes it impossible to open or turn back on without removing a lock with a key. You should have some kind of sign out sheet with a description of who signed out the lock, tag, and the equipment number. This person keeps control of the key to the lock.

While this repair is done, there is no way anyone else can turn on the equipment by accident. Most accidents involving crushing or pinching of arms and legs result from accidental activation of quench elevators and furnace doors; the air pressure or hydraulics are activated by someone turning them on while the person is inside the equipment. Electrical shocks occur the same way. When lock-out tag-out is used properly, the operator and maintenance personnel are aware of someone doing repair. While inside the equipment, you are required to have a spotter watching outside. When I was in maintenance, I made it a habit of not only turning off a valve for the different gasses but also disconnecting the service line after the valve, in case it was leaking through. This is a good procedure and should be part of the repair procedures.

ABOUT THE AUTHOR: Past president of the Metal Heat Treaters Association, Marty Keylon is the owner of Keylon Thermal Consulting, a primary rep for North American Cronite, BeaverMatic Industrial Furnaces, and CeraMaterials. You can contact Marty at bgdog756@aol.com or by calling 530-788-8566.

USING PROCESS CONTROL AND SCADA IN HEAT TREAT FOR PROCESS IMPROVEMENT

by Jim Oakes

Heat treaters are always looking for methods to improve productivity without compromising quality. One method that many heat treaters have put in place is to incrementally improve various areas around controls and electronic data to drive costs down, increase throughput, and still deliver a quality product.

In its simplest form, automation is creating a sequence of steps that flow continuously. Basic steps of automation can be broken into different areas of operation, such as operational procedures, preventive maintenance programs, shared data, and smarter controls. Each operation may break these down differently, but all have stakeholders where specific activities related to process automation or data and information is important.

Maintenance is costly and tends to be very reactive. A reactive approach to maintenance bypasses the crucial planning phase of production, risking a reduction in overall equipment utilization as well as any excess capacity, thus leaving opportunities for higher profit margins on the table. Using SCADA (supervisory control and data acquisition) systems and smart process controls can help with this. Rapid access to information that can be used by personnel throughout the facility enables a better decision-making process. By referencing historical data, important questions can be answered more quickly: Did the load take longer to heat than usual? Is the temperature overshooting? Is the carbon percentage oscillating? This information can be valuable when the right person has access to it. Effective planning and use of historical data enhances the heat treater's ability to produce quality parts.

Traditionally, data available on paper charts may not have been used effectively because it was not readily accessible. The "old days" of tracking down a chart to scan or fax it are part of the past. Today, more information is available thanks to the use of open communication standards and plant-wide networks. Access to key data points must be easy so that the right person can analyze the data, compare it to historical data, and determine whether action is necessary. Rework creates significantly more problems because of the substantially longer furnace run times required, additional notification to the customer, longer delivery time, and reduced margins on the job.

Process control is the ability to meet certain parameters over time by using inputs from the process and controlling outputs for desired results. Today's control and sensor technology automates much of this. With technology enhancements come more sophisticated controls, allowing users to make better decisions. These decisions can be on the process itself, productivity, quality, and safety. Traditionally, the inputs for a process were disconnected, but today these are brought together to provide a holistic view of the control decision process. There is even a convergence of modeling software and controls. For example, heat treaters can use diffusion modeling software for carburizing applications where soak time is modified to meet effective case depth requirements.

PLCs, discrete microprocessor controls, or a hybrid of the two are today's standards for most heat treating equipment. Microprocessor controllers typically provide single or multiple PID control loops with expanded features such as event and recipe management. To maximize the benefits of the control technology, the user should design a system for repeatability with a level of flexibility necessary for the equipment. One element of such a design is recipe control. A recipe is made up of the steps of the heat treating process. It can be a simple ramp to temperature and a timed soak; it can also be a more complex process in which multiple temperature inputs, time, atmosphere, pressure, and other variables need to be managed.

Applying incremental steps allows for greater automation and provides better access to information. Using recipe control to automate a nitriding, vacuum, carburizing, or even a simple temperature ramp soak leads to greater chances of running the process correctly and greater opportunity for repeatability. Automation of a process using programmable controls can virtually eliminate variations in a process from shift to shift or operator to

ABOUT THE AUTHOR: Jim Oakes is vice president of business development for SSi SuperSystems, where he oversees marketing and growth in multiple business channels and helps develop product innovation strategies in conjunction with customer feedback. Jim has extensive experience working in the heat treating and software/IT industries. For more information, email him at joakes@supersystems.com or go to www.supersystems.com.

"Automation of a process using programmable control can virtually eliminate variations in a process from shift to shift or operator to operator. Overall productivity benefits from automated process controls as well."

operator. Overall productivity benefits from automated process controls as well. Operators now have an opportunity to contribute to other areas instead of wasting costly time watching the process to ensure accurate metallurgical results.

In today's heat treating environments, controls provide user-defined audible, visual, and electronic alarms, indicating that a cycle is complete or that a deviation from a process has occurred. Recipes can be set up so that, upon completion, the heat is turned off; this eliminates unnecessary costs and ensures parts are heated for the necessary amount of time. Smart alarms capture the attention of operators when a situation needs to be addressed. Such steps in automating a process are relatively simple and positively impact labor and utilization.

With more devices and sensors monitoring the process and a system in place to capture information, data can be accessed remotely. Whether it is a critical job requiring periodic remote monitoring or the ability to tweak a cycle, the technology exists to keep eyes on critical runs at all times. With the right systems in place, technology can be used to refine processes and deliver quality parts more efficiently. The more accessible those data points are, the greater the opportunity for repeatability.

Today's heat treater depends on proven science and state-of-the-art technology to stay competitive. Technology advances continuously. Those who resist change will be left behind, wondering why their business is declining, and will be surpassed by growing global competition. Those who embrace the opportunity that automation and digital documentation provide will continue to grow and prosper.

INDUCTION HARDENING CHOICES FOR GEARS

By Fred R. Specht, District Sales Manager, Ajax-TOCCO-Magnethermic and Daniel H. Herring, THE HERRING GROUP, Inc.

Of the various types of applied energy processing, induction hardening is the most common. Induction heating is a process that uses an alternating electrical current that induces a magnetic field, causing the surface of the gear tooth to heat. The area is then quenched, resulting in an increase in hardness within the heated area. This process is typically accomplished in a relatively short time. The final desired gear performance characteristics are determined not only by the hardness profile and stresses, but also by the steel's composition and prior microstructure.

The hardness pattern produced by induction heating (Fig. 1) is a function of the type and shape of inductor used as well as the heating method. Quenching or rapidly cooling the work-piece can be accomplished by spray or submerged quench. The media typically used for the quench is a water based polymer. The severity of this quenchant can be controlled by the polymers concentration. Cooling rates are usually somewhere in between what would be obtained from pure water and oil. In some unusual situations compressed air is used to quench the work-piece.

External spur and helical gears, bevel and worm gears, racks and sprockets are commonly induction hardened from steels such as 1050, 1144, 4140, 4150, 4350, 5150, and 8650. The most common methods for hardening gears and sprockets are by single shot (Fig. 2) or the tooth-by-tooth method (Fig. 3). Single shot often requires large kW power supplies but results in short heat/quench times and higher production rates. This technique uses a copper inductor (coil) encircling the work-piece. An inductor, which is circumferential, will harden the teeth from the tips downward.

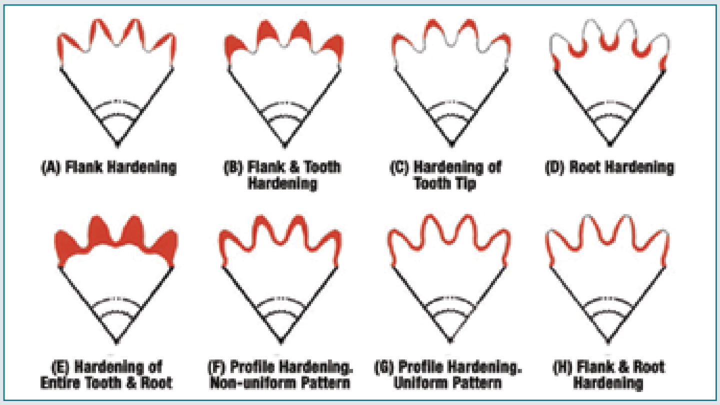

Fig. 1: Patterns Produced by Induction Hardening [2].

Fig. 2: Typical Single Shot Induction Hardening Operation. (Photograph Courtesy of Ajax-Tocco-Magnethermic)

While the single shot method is acceptable for splines and some gearing, the larger heavier loaded gears where pitting, spalling, tooth fatigue, and endurance are an issue need a hardness pattern which is more profiled like those produced with carburizing. This type of induction hardening is called tooth-by-tooth hardening. This method is limited for gear tooth sizes up to 5 or 6 DP using frequencies from 2 to 10 kHz and about 10 DP using a range of 25 to 50 kHz. The lower the frequency; the deeper the case depth. This is a slow process due to the number of teeth and index times, and is usually reserved for gears and sprockets that are too large to single shot due to power constraints. The process involves heating the root area and side flanks simultaneously, while cooling each side of the adjacent tooth to prevent temper-back on the backside of each tooth (Fig. 4). The induction system moves the coil at a pre-programmed rate along the length of the gear. The coil progressively heats the entire length of the gear segment while a quench follower immediately cools the previously heated area. The distance from the coil to the tooth is

ABOUT THE AUTHOR: Fred R. Specht has over 40 years of experience in all aspects of induction heating and melting, and is a specialist in induction heat treating pattern development. A seminar speaker on induction heat-treating at many ASM Heat Treating Conferences, he is presently the chairman of ASM -HTS Applied Energy Committee. He can be reached at (847) 606-9462 or fspecht@ajaxtocco.com. Daniel H. Herring, also known as "The Heat Treat Doctor," is president of THE HERRING GROUP, Inc. He can be reached at (630) 834-3017 or dherring@heat-treat-doctor.com. Go online to [www.heat-treat-doctor.com].

Fig. 3: Tooth-by-Tooth Induction Hardening –Process. (Photograph Courtesy of Ajax-Tocco-Magnethermic)

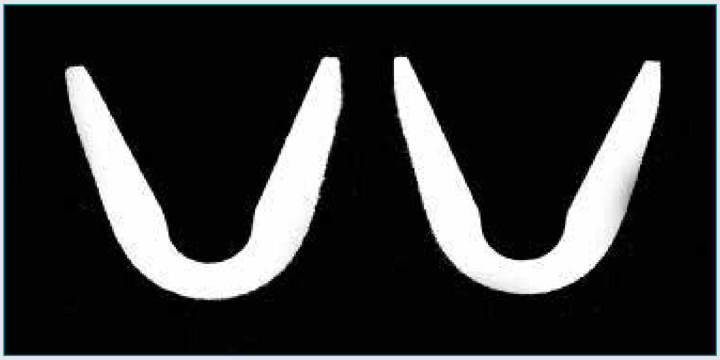

Fig. 4: Tooth-by-Tooth Induction Hardening –Pattern. (Photograph Courtesy of Ajax-Tocco-Magnethermic)

known as coupling or air-gap. Any variation in this distance can yield variation in case depth, hardness, and tooth distortion. The gear is indexed after each tooth has been hardened, often skipping a tooth. This requires at least two full revolutions in the process to complete the hardening of all teeth. Straight, spur, and helical gears up to 210", 15,000 lbs. have been processed with this method. The entire process yields a repeatable soft tip of the tooth with hard root and flank. In other applications, the tip and both flanks can be hardened simultaneously and yield a soft root.

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LIGHTER WEIGHT AND INCREASED FATIGUE STRENGTH WITH ADI

by Jack Titus

Have you ever hit a rock or other hard projectile while cutting your lawn? Have you noticed that the blade is dented, not broken or cracked? How about all of those fasteners used to hold the trim and cosmetic panels on your car? Think about any of the thousands of clips and clamps that exhibit a springing action that you encounter every day. The manufacturing process that enables all of those mower blades and strange-looking fasteners to function without breaking is: Austempering.

I've briefly discussed austempering before—the process of quenching to above the Martensite (Ms) point in molten nitrite/nitrate salts, where bainite in steel and ausferrite in cast irons is the transformation product. Austempering is the process that produces a variation of bainitic microstructures in ferrous alloys that is chemically and isothermally driven.

Most fasteners are stamped and formed from mild low-alloy steels, which contain enough carbon to produce adequate hardenability to facilitate missing the pearlite nose of the TTT curve, the same requirement to create martensite when quenched in oil. Instead of cooling to the temperature [Ms] point, in austempering the component is held just above the Ms point, approximately 500°F to 700°F [260°C to 371°C] and held there to form 100% lower bainite. Upper bainite, a higher-temperature form of bainite, is softer with diminished properties. The temperature range suitable for forming lower bainite depends on the carbon and alloy content of the material. Lower bainite's transformation for steel, cast iron, and more specifically austempered ductile iron [ADI] will always be closer to the Ms point. The higher the alloy and carbon content, the lower the Ms point, thus the lower bainite temperature. As the alloy content increases, the hold time will increase; typically high-alloy materials are required only in large sections requiring more hardenability.

The advantage of austempering in steel is the toughness and ductility improvement over the similarly tempered hardness of quenched steel; tempered martensite is still martensite and, as such, retains its lower impact strength.

Because a finite time for transformation to bainite is required, the quench tanks and part removal systems become a design consideration. Because fastener sections are thinner (usually less than ½" [13 mm]), they are perfectly suited for heat treatment in continuous mesh belt furnaces. Conversely, since austempered ductile iron (ADI) parts are generally larger, having seen applications like transmission cases, drivetrain components, gears, and shafts for example, they are processed in special integral quench batch furnaces. In addition, the higher alloy ADI will require longer soak times in the salt quench, making the heavier-duty continuous cast-link belt furnaces and their associated quench less flexible, thus less suitable.

Austempering is a through-hardening process not requiring carburizing, although increasing the surface carbon can have beneficial effects, which I'll detail later. Just as in martensite hardening, the austempered part's surface must be free from decarburization to provide the expected wear and fatigue resistance.

> *"Austempering is the process that produces a variation of bainitic microstructures in ferrous alloys that is chemically and isothermally driven."*

AFC-Holcroft has long been providing the industry with batch and continuous austempering furnace equipment. Batch systems are coined UBQA—Universal Batch Quench Austemper. Carburizing batch furnaces consist of a hot zone and vestibule/oil quench tank; UBQA's integrate an intermediate chamber between the hot

ABOUT THE AUTHOR: Jack Titus can be reached at (248) 668-4040 or jtitus@afc-holcroft.com. Go online to [www.afc-holcroft.com] or [www.ald-holcroft.com].

Figure 1: An illustration of the physical size difference between the Monster™ UBQA and a standard UBQ integral quench batch furnace with a 3,500 Lb. [1,588 Kg] load size of 36" w x 48" l x 36" h.

zone and the salt vestibule/quench. This chamber isolates the molten salt vapor from the hot zone and contains a mechanism to transfer the load uninterrupted from the hot zone to the quench tank. Being a batch system offers the flexibility of holding the load in the salt for various times, accommodating small and large section sizes. Mesh and cast link belt systems have a continuously-running conveyor lifting quenched parts from the tank; this requires the parts to reach the salt temperature and appropriate soak duration prior to being removed from the salt. Sections too massive will not receive the proper hold time as the conveyor is moving at a constant speed. As in oil quench mesh belt furnaces, parts dropping from the belt into the quench chute must cool fast enough while falling through the salt to miss the pearlite nose and reach the bainite region before settling onto the discharge conveyor. Once cooled to the bainite region, no harm comes to parts soaked longer than required (generally speaking), but holding short of the required time will cause martensite to form when the retained austenite cools to below the Ms point upon removal from the salt and washed.

In the U.S., the general rule for oil quench tank volume is one gallon of oil for one pound of the quenched load. Salt, however, is different and can contain several times the volume; however pounds, not gallons, is the measurement of salt. Salt does not vaporize during quenching as does oil, but adequate agitation is still important to create uniform heat transfer around parts. Water can be added in small amounts to salt to increase the quench speed, but the method of addition is generally a proprietary function since, if not done properly, can cause quench speed variations and safety issues.

The evolution of ADI has led to the adaptation of austempering gear components. It's lighter weight and increased fatigue strength has made the process attractive to automotive and off-road applications. An important advantage of ADI for automotive transmission applications is the sound-deadening effect of ausferrite and graphite[-1]. Another advantage of bainite and ausferrite in gears is what I call "micro-surface ductility," the characteristic of bainite's inherent ductility to mold itself via contact pressure to the mating gear teeth, thereby providing a lower and more uniform transfer force per square millimeter. This unique force transfer technique is achieved in carburized gears by allowing for a high retained-austenite concentration on the gear teeth, resulting in a similar force-spreading affect.

Carbo-Austempering™[-2], an endo-gas carburizing process developed by Applied Process Inc.–Technologies Div. has provided a tier 1 supplier about ten percent of its side-gear production for all-wheel drive cement trucks. The process greatly increases the hardness and fatigue strength of ausferrite and bainite and finds additional application in defense-related applications[-3].

Since reduced noise is a fundamental requirement of any drivetrain design, bainite and ausferrite's isothermal nucleation and growth development results in a uniform and predictable volume change that equals about half that of martensite. Its appropriate gear design principles and sound-absorption qualities make ADI an ideal gear material.

Finally, in collaboration with Applied Process, AFC-Holcroft has built the largest integral salt quench batch furnace trademarked the "Monster-™." It's designed to process 20,000 Lbs. [9.072 Kg] of steel or cast iron components. With a load size of 84" x 96" x 56" [2050 mm x 2438 mm x 1422 mm] it will be able to austemper huge single fabrications and castings or hundreds of racked parts.

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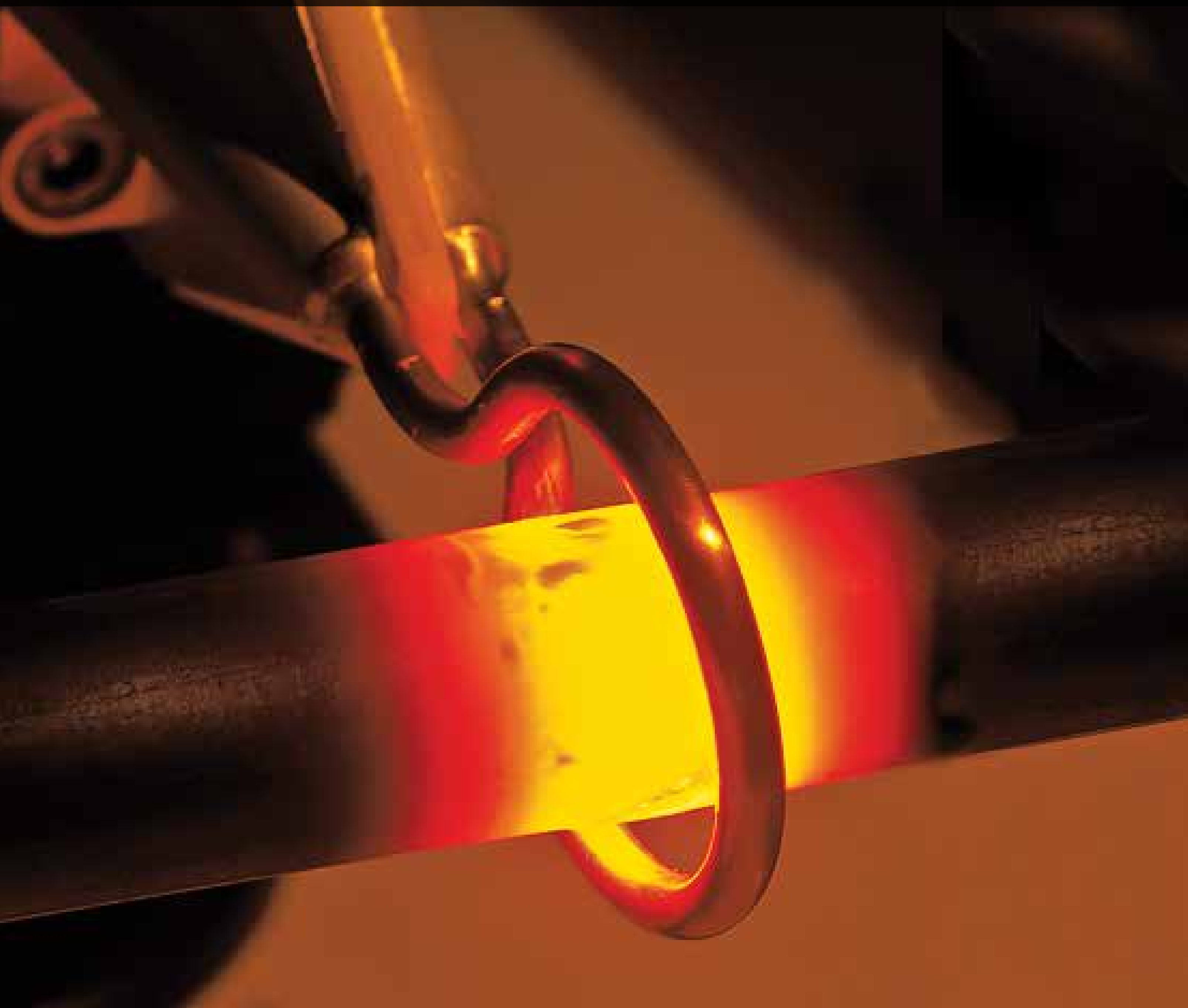
2. Carbo-Austempering is a trade mark of Applied Process Technologies Div, Livonia, MI USA
3. Correspondence from John R. "Chip" Keough, Chairman, Applied Process Technologies Div, Livonia, MI USA

CEIA USA

CEIA USA has created a solid foundation of reliable solid-state generators featuring the highest quality standards and performances.

By Tim Byrd



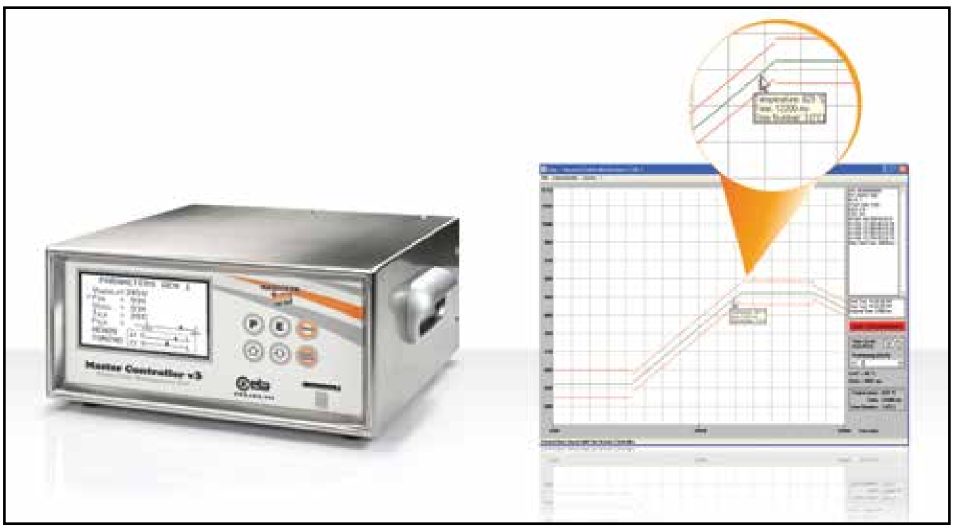
What is the common thread between metal detection and induction heating? CEIA has explored this question for over 20 years and, in the process, created a solid foundation of reliable solid state generators featuring high quality standards and high performances. The answer is that both use electromagnetic field technology.

What is the common thread between metal detection and induction heating? Both use electromagnetic field technology. CEIA has explored this question for over 20 years and, in the process, created a solid foundation of reliable solid state generators featuring high quality standards and high performances. “CEIA was founded through the interest in electromagnetic field technology, which has carried down throughout all aspects of CEIA,” explains Cody Kothera, industrial sales manager for CEIA USA.

CEIA started its induction heating work, oddly enough, for the eyeglass frame industry, making high-frequency induction units for soldering eyeglass frames. “There was a need for high-frequency work,” says Kothera. “Not a lot of people did it. We played a major role in developing that, and expanded it from a 2.8 kW generator that works at 1800kHz, up to a 100kW generator with lower frequencies.

“In induction heating, a high-intensity electromagnetic field is created that induces a current into the metal, which creates heat. It’s the same technological concept we use in the metal detection field of the business; if you walk through a metal detector, there is an electromagnetic field being created through the two sides of the detector. If you introduce metal into that field, the field will change, and the detector will notice this change and alert the operator.”

Today, operating from a 42,000 sq. ft. facility in Twinsburg, Ohio, CEIA USA offers the Power Cube Family, a complete



modular line of equipment. It features reduced dimensions, perfect for the manufacturing operation of heat treatment, brazing, and soldering on all types of metal parts. Next to a wide range of generators (Power Cube), the family includes control units (Master and Power Controllers) for the semi-automatic and automatic management of the heating cycles, a full range of optical sensors (SH Series) equipped with low-intensity LED aiming, wire solder dispensers (WF Series) for low and high temperature applications, and a complete line of accessories.

CEIA S.p.A., located in Arezzo, Italy, has an in-house EMC testing laboratory that is governmentally accredited as a "competent body in the matter of electromagnetic compatibility." Marilyn Thaxton, NA marketing manager, identifies an added benefit to this service: "It helps to test, prove, and research CEIA equipment. Plus, it gives us the benefit of being an authorized testing location. That's why we spend so much of our resources on R&D—20% of CEIA's staff. We're staying ahead of the curve."

Kothera describes CEIA's R&D department as "cutting edge. One of the things we just introduced is a dual-color pyrometer. A lot of infrared pyrometers use single wavelengths of the infrared spectrum, which means you have to set the emissivity. The dual color pyrometer measures two wavelengths, so you don't have to set the emissivity; this allows more functionality and less room for operator error. It makes the operator's life easier. Recently, we also introduced our first 100kW generator, which is now the largest power that we go to. Our generators perfectly adapt to hardening applications, surface hardening, annealing, etc. The area and the heating depth depend, in fact, on the coil geometry and on the exposure time to the electromagnetic field."

For quality control, CEIA also uses a data logger that allows the user to track the historic temperature data and store it for quality control purposes, or to pass it along to the customer. With their control units, customers have the ability to set temperature tolerances. Kothera explains, "If you have a temperature range you need to be in, it will alert you if you are out of that tolerance. It also gives you traceability with the data logger to historically record that info; if there is a problem with your part down the road, you can see if the heating was an issue or not."

CEIA takes a non-traditional approach to induction heating. Aside from just providing the generators, they also provide the control units and optical pyrometers for temperature monitoring. The control units allow the user to program either a time-and-power or a time-power-temperature graph. In other words, if you need to heat a gear to 500 degrees and hold it there for 10 seconds, you can do it with a closed-loop system that gives plug-and-play capabilities throughout the product line. The controllers can be added on to the generators, and the pyrometers can be added on to the controllers, giving it an extra level of functionality. ISO 9001 certified, CEIA prides itself on providing high-quality equipment, good solutions with continued support, and a one-year warranty on all induction equipment.

FOR MORE INFORMATION: For more information, visit www.ceia-usa.com or call 888-532-2342.

How Gears Fail

By Daniel H. Herring

Material issues such as hardenability, grain size, and inclusions can result in various gear failures. This underscores the criticality of steel cleanliness as well as controlling the size, shape, and type of inclusions present.

Heat treatment plays an important—some would say critical—role in gear manufacturing. Therefore, there is a need to better understand, from the perspective of the heat treater, the contribution of heat treatment to gear failures. Aspects such as design, material, heat treatment, and service application all provide examples that serve as an excellent platform on which to discuss different types of failure and what caused them. Furthermore, they provide heat treaters with wisdom to avoid future mistakes.

TYPES OF GEAR FAILURES

Critical failure modes for power transmission gearing include: Wear, scoring, profile pitting, tooth breakage, and spalling. In general, these can be classified into two categories: Fatigue failures and wear failures. Fatigue failures are most often associated with failures related to bending (root fillet cracks), sub-case (sub-surface) fatigue, contact (impact, stress rupture) and thermally-induced failures. By contrast, wear failures are often associated with macropitting (pitch line surface degradation) and abrasive and adhesive wear.

Root fillet cracks and fractured teeth failure are generally the result of cyclic bending stresses exceeding the fatigue strength of the material at the root fillet surface (Figure 1). Improper case depth, non-martensitic transformation products (NMTP) in the root microstructure, and overload conditions can cause surface cracking, followed inevitably by crack propagation to failure.

Fatigue cracking (e.g. sub-case spalling or case/core separation) starts near the case-core

Figure 1: Tooth damage due to bending fatigue.

Figure 2: Gear teeth torn away from the surface of the gear.

Figure 3: Severe pitting from end loading.

Figure 4: Soft spots in the carburized case (Observed After Shot Peening).

interface where, on the applied stress and critical strength curves, the stress exceeds the strength. The contact load induces a fluctuating applied stress gradient opposed by the critical strength gradient developed by heat treatment in the material.

Case crushing (Figure 2) is a related phenomenon; both can be due to improper heat treatment, a high-stress concentration, or both. Case depths that are either too shallow or too deep (not leaving an adequate core to support the case) are common heat treatment-related causes.

Surface or sub-surface pitting (Figure 3) occurs at the intersection of the applied (shear) stress and allowable strength at or extremely close to the surface. When sliding is present and the coefficient of friction is significant (due to poor lubrication, improper lubricant selection, or lubricant breakdown), the stress is maximized at the surface.

Other types of gear failures can be traced to poor heat treatment, such as shallow case depth or soft spots (Figure 4) from improper cleaning, incorrect case hardening

Figure 5: Inadequate hardness leading to gear failure.

process parameters, stop-off paint failures or from improper tempering. Poor quenching methods and improper austenitizing temperatures can also lead to inadequate hardness, with gears prematurely failing due to soft teeth (Figure 5). Material issues such as hardenability, grain size, and inclusions (Figure 6) can result in various gear failures. This underscores the criticality of steel cleanliness as well as controlling the size,

Figure 6: Inclusion initiated pitting in vacuum degassed steel.

Figure 7: Improper hole placement.

shape, and type of inclusions present. Alloy segregation and banding are other issues that one can encounter in a given material, one of the reasons why normalizing is considered a prudent step in the heat treatment of gears.

PREVENTING GEAR FAILURES

It is important to recognize that fatigue strength is influenced by factors such as hardness distribution (case and core hardness, case depth), microstructure (grain size, retained austenite percentage, non-martensitic phases, carbide morphology, and intergranular toughness), and by design (Figure 7) and manufacture (residual compressive stress state, surface finish, and geometry). The objective of heat treatment is to have high hardness and adequate subsurface strength on the active flank and good surface hardness and high residual compressive stress in the root area.

Case depth selection (i.e. the strength gradient) is influenced heavily by core hardness and tempering temperature. From an alloying standpoint, molybdenum and manganese strongly influence core hardness, while chromium has a moderate influence and nickel has only a weak influence. It should also be noted that the case hardness is much more sensitive than the core hardness to the tempering temperature employed (which is why tempering temperatures must be selected based on final case hardness).

Low case hardness can also be due to carburizing with too lean a carbon potential, formation of undesirable microstructural constituents, partial decarburization of the surface, a “slack” quench, or use of the wrong tempering temperature. Variations in process parameters result in undesirable microstructures. Excessive retained austenite (Figure 8a) and excessive carbide formation (Figure 8b) both can lead to premature failure of the gears in service. Large amounts of retained austenite result from too high a carbon potential or direct quenching from carburizing temperature. Possible causes of carbides and carbide necklacing is, again, too high a carbon potential, insufficient diffusion time, too short a soak time, and too low a hardening temperature.

Certain gear failures can also be traced to issues with case leakage—failure of selective carburization masking methods (e.g. copper plating, stop-off paints) to protect the surface from damage. In some cases, surface contamination or improper drying will cause surface blistering. Overly aggressive blasting after plating can also damage the mask. When nital etched, unwanted carburization often appears as an irregular dark gray indication (in an area that should have been light gray).

Variations in quenching, even within the same quench medium, can cause improper core microstructure and hardness. An 8822RH transmission gear was quenched at two different gas pressures (20 bar and 12 bar), resulting in differences in hardness and microstructure (Figure 9).

The condition of a particular heat treat furnace can also play a major role in premature gear life. Air intrusion into the furnace, whether through poor practices or leaks, can affect case hardness and residual stress patterns by creating partial or, in some extreme instances, total surface decarburization (Figure 10). Common reasons for this condition to exist are: Having an atmosphere carbon potential less than the surface carbon within the part, or a loss of protective atmosphere (e.g. when a power failure occurs).

Finally, the choice of carburizing method (atmosphere, vacuum) can result in differences in surface condition, intergranular oxidation (IGO), and surface dealloying due to oxidation.

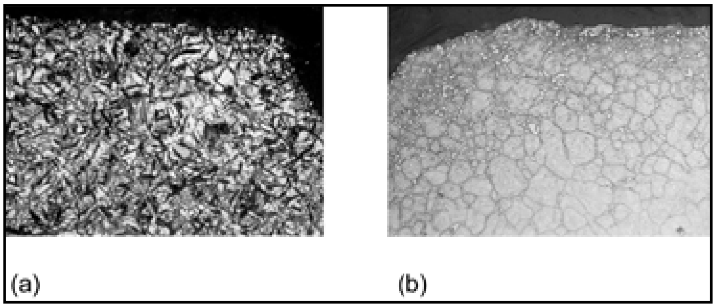


Figure 8: Case microstructure variation due to out of control process parameters.

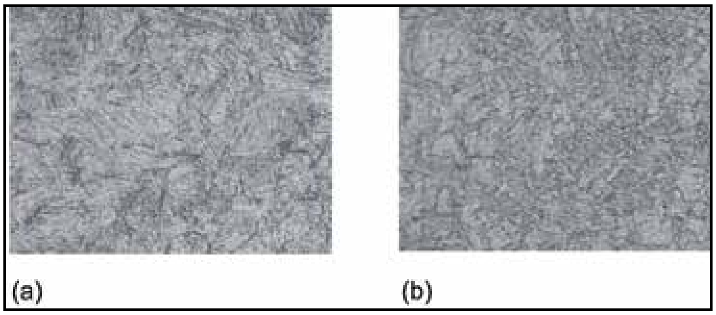


Figure 9: Core microstructure variation due to quenching (a) fully martensitic microstructure, 44 HRC(b) martensite with transformation products (bainite and ferrite) present, 26 HRC.

FINAL THOUGHTS

Gears fail for many reasons, but failures induced by heat treatment are avoidable through good practices and tight control of process and equipment variability.

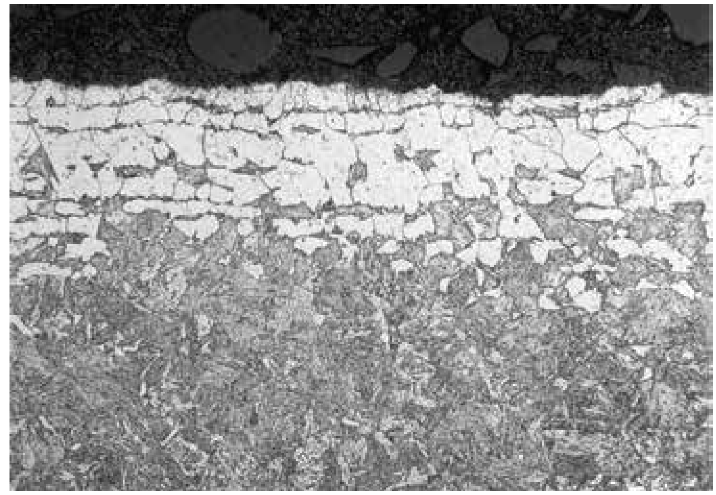


Figure 10: Complete surface decarburization.

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ABOUT THE AUTHOR: Daniel H. Herring is "The Heat Treat Doctor" with THE HERRING GROUP, INC. For more information, call 630-834-3017 or email dherring@heat-treat-doctor.com, or visit www.heat-treat-doctor.com.

Recent Inventions and Innovations in Induction Hardening of Gears and Gear-like Components

By Valery Rudnev

Depending upon the gear size, required hardness pattern, and tooth geometry, gears are induction hardened by encircling the whole gear with a coil (so-called "spin hardening of gears"), or for larger gears, heating them tooth-by-tooth.

This paper focuses on recent inventions and innovations (from the past four-six years) in induction hardening of gears and gear-like components, including, but not limited to:

- "Know-how" in controlling distortion of induction-hardened gears
- Simultaneous dual-frequency induction hardening
- Advanced induction-hardening process recipes when hardening small and medium size gears
- Novel inductor designs to minimize distortion when induction hardening hypoid and spiral bevel gears
- IFP technology for induction gear hardening
- Induction tempering and stress relieving of gear-like components with improved temperature uniformity

This paper also provides a review of basic principles and applications devoted

Figure 1 (left): In tooth-by-tooth hardening, inductors can be designed to selectively harden specific areas of gear teeth where metallurgical changes are required [2]

Figure 2: Induction gear hardening machine for a large bearing ring with teeth located on outside (Courtesy of Inductoheat Inc.)

to induction hardening small, medium, and large gears using tooth-by-tooth techniques and encircling method.

Depending upon the gear size, required hardness pattern, and tooth geometry, gears are induction hardened by encircling the whole gear with a coil (so-called "spin hardening of gears"), or for larger gears, heating them tooth-by-tooth [1-6].

"TOOTH-BY-TOOTH" HARDENING

The tooth-by-tooth method comprises two alternative techniques: "Tip-by-tip" or "gap-by gap" hardening [1-4]. The "tip-by-tip" method can apply a single-shot heating mode or scanning mode; the "gap-by-gap" technique applies the scanning mode exclusively. Inductor scanning rates are typically within 6 mm/sec to 9 mm/sec. Both "tip-by-tip" and "gap-by-gap" techniques are typically not very suitable for small and fine-pitch gears (modules smaller than 6) [1,2].

During "tip-by-tip" hardening, an inductor encircles a body of single tooth. Presently, this technique is not used because the hardening patterns typically do not provide the required fatigue and impact strength. "Gap-by-gap" hardening is a much more popular technique compared to "tip-by-tip" method. This is the reason why the term "tooth-by-tooth" hardening is often associated with the "gap-by-gap" hardening method. "Gap-by-gap" hardening requires the inductor to be symmetrically located between two flanks of adjacent teeth. Inductor geometry depends upon the shape of the teeth and the required hardness pattern. Special locators (probes) or electronic tracing systems are often used to ensure proper inductor positioning in the tooth space.

Two scanning techniques used include one in which the inductor is stationary and the gear is moveable, and the other in which the gear is stationary and the inductor is moveable. The latter technique is more popular when hardening large gears. Inductors can be designed to heat only the root and/or flank of the tooth, leaving the tip and tooth core soft, tough, and ductile (Figure 1). Though this is one of the oldest hardening techniques, recent innovations continue improving quality of gears heat-treated using this method.

Thermal expansion of metal during the heating should be taken into consideration when determining and maintaining the proper inductor-to-tooth air gap. After gear loading and initial inductor positioning, the process runs automatically, based on an application recipe. Figure 2 shows examples of induction using a tooth-by-tooth hardening machine.

When developing tooth-by-tooth gear hardening process, particular attention should be paid to electromagnetic end/edge effects and the ability to provide the required pattern in the gear end areas. Upon scanning gear tooth, the temperature is distributed within gear roots and flanks quite uniformly. At the same time, since the eddy current makes a return path through the flank and, particularly through the tooth tip, proper care should be taken to prevent overheating the tooth tip regions, particularly at the beginning and end of

Figure 3: Inductoheat's STATIPOWER IFPt is a novel IGBT-type power supply specifically designed for induction hardening and tempering applications allowing independently adjustable frequency via CNC-program in a 5-40kHz frequency range and power in the range of 10-360kW

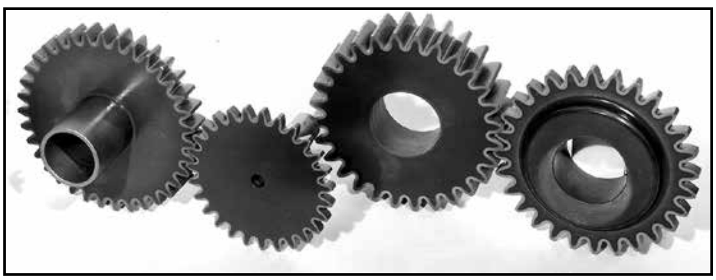

Figure 4: Contour hardened gears. (Courtesy of Inductoheat Inc.)

Figure 5: Inductoheat's simultaneous dual frequency inverter for gear contour hardening. (Courtesy of Inductoheat Inc.)

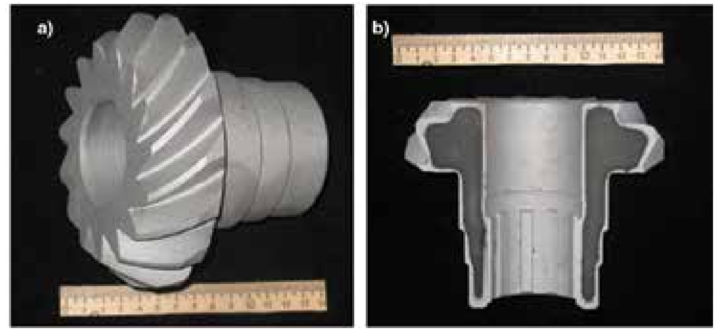

Figure 6: TSH Technology uninterrupted induction hardened pattern is obtained on a spiral bevel gear. (Courtesy of ERS Engineering Corp.)

the scan hardening. Improved system design helps to maintain required hardness uniformity.

Specifics of gear geometry demand a particular process control algorithm. In the past, the process control recipe was limited to an available variation of power and scan rate vs. inductor position. Recent innovations bring the unique ability of Inductoheat's novel inverters to independently control both power and frequency during scanning operation, which optimizes electromagnetic and thermal conditions at initial, intermittent, and final stages of scanning. As an example, Figure 3 shows the STATIPOWER® IFPt (Independent Frequency and Power Control) inverter. The ability to independently change the frequency and power of an induction system during the scanning process represents the long-awaited dream of commercial induction heat treaters, since such type of setup would provide the greatest process flexibility. STATIPOWER® IFPt is a novel IGBT-type power supply specifically designed for hardening and tempering applications, allowing independently adjustable frequency via CNC-program in a 5-40kHz frequency range and power in the range of 10-360kW. This concept substantially expands heat treat equipment capabilities for processing parts by programming power and/or frequency changes on the fly, maximizing heating efficiency and temperature uniformity while heating complex geometry components.

GEAR SPIN HARDENING (ENCIRCLING INDUCTORS)

Spin hardening is the most popular approach for induction hardening gears with fine and medium-size teeth. Gears are rotated during heating to ensure an even distribution of energy. Single-turn or multi-turn inductors that encircle the whole gear can be used [1,3- 6]. When applying encircling coils, it is possible to obtain substantially different hardness patterns by varying process parameters.

As a rule, when it is necessary to harden only the tooth tips, a higher frequency and high power density should be applied; to harden the tooth roots, use a lower frequency. A high power density in combination with the relatively short heat time generally results in a shallow pattern, while a low power density and extended heat time produces a deep pattern with wide transition zones.

Quite often, to prevent problems such as pitting, spalling, tooth fatigue, and endurance and impact limitations, it is required to harden the contour of the gear, or to have gear- contour hardening (Figure 4). This often also maximizes beneficial compressive stresses within the case depth and dramatically minimizes distortion of as-hardened gears keeping it under 80-100 microns (0.003" – 0.004").

Many times, obtaining a true contour-hardened pattern can be a difficult task, due to the difference in current density (heat source) distribution and heat transfer conditions within a gear tooth.

Figure 7: Section of the induction hardened transmission gear. (Courtesy of ERS Engineering Corp.)

Figure 8: Induction hardened automotive journal cross. (Courtesy of ERS Engineering Corp.)

Figure 9: Carrier pin – simultaneous OD and ID hardening. (Courtesy of ERS Engineering Corp.)

SIMULTANEOUS DUAL FREQUENCY GEAR HARDENING

Some induction practitioners have heard about simultaneous dual frequency gear hardening, which utilizes two appreciably different frequencies working on the same coil at the same time [6]. Low frequency helps to austenitize the roots of the teeth and high frequency helps to austenitize the teeth flanks and tips.

However, it is not advantageous have two different frequencies working simultaneously all the time. In some cases, it is preferable to apply lower frequency at the beginning of the heating cycle and after achieving a desirable root pre-heating, the higher frequency can be used instead of or simultaneously with lower frequency, completing a job by working together.

Figure 5 shows Inductoheat's single-coil dual frequency system, comprised of medium- (10kHz) and high-frequency (120 to 400kHz) modules working simultaneously, or in any sequence desirable, to optimize properties of the heat-treated gears [6]. Total power exceeds 1,200kW. As expected, smaller gears will require less power. Heat time usually does not exceed 2 seconds and often is less than 1.5sec.

Inductoheat's simultaneous dual frequency induction gear hardening system (Figure 5) also has some "auto-match" features to simplify tuning. It is rugged and can be used for high-volume single-shot hardening of a variety of powertrain components, dramatically minimizing distortion of heat-treated parts and providing a superior hardness pattern with favorable distribution of residual stresses.

A NOVEL DEVELOPMENT IN INDUCTION GEAR HARDENING: TSH STEELS

There was a belief that not all gears and pinions were well-suited for induction hardening. Hypoid and bevel gears, spiral bevel automotive pinions, and noncircular gears used to be rarely induction hardened. Those gears were typically carburized. This situation has changed. As an example, Figure 6a and Figure 6b show an example of inductively case-hardened components utilizing TSH Technology [7,8].

TSH steels are low-hardenability (LH) low-alloy steels, characterized by limited hardenability and a reduced tendency for grain growth at austenizing temperatures suitable for hardening. They can be substituted for standard steels typically used for conventional induction hardening or carburizing grades. TSH steels have significantly less alloying elements such as manganese,

ABOUT THE AUTHOR: Dr. Valery Rudnev is Fellow of the American Society for Materials, and Group Director, Science and Technology, Inductoheat Inc., An Inductotherm Group Company. He is considered by many as one of the leading global figures in the induction heating industry. Dr. Rudnev has more than 30 years of experience in induction heating and is known within the American Society for Materials (ASM International) and among induction heating professionals as "Professor Induction." His credits include a great deal of "know-how", more than 30 patents, inventions, software registrations and more than 180 engineering/scientific publications. He co-authored the "Handbook of Induction Heating" published by Marcel Dekker, New York, 2003, 800 pages and six) chapters for several handbooks devoted to various aspects of induction heating, induction heat treating, computer modeling, and mathematical simulations. For more information, visit www.inductoheat.com

molybdenum, chromium, and nickel than the majority of conventional low-alloy steels. Their chemical composition is somewhere between micro-alloy steels and plain carbon steels, providing fine-grain martensite with extremely high compressive stresses at the tooth surface.

With TSH technology, components are usually through heated, or partial heated (depth of heating needs to be 2-3x deeper than required harden depth) and then rapidly quenched. The hardened depth is mainly controlled by the steel's chemical composition. Even though components made from TSH steels are often through-heated, their limited hardenability allows for obtaining crisp hardness case depth with a well-controlled hardness pattern having minimum case hardness deviations, even when hardening complex-shaped parts (Figure 7 and Figure 8).

In the past, it was practically impossible to induction harden the components shown in Figures 6, 7, 8 and 9. Now it is possible to get those impressive uninterrupted hardness patterns by using a simple operation: Through heating those parts using low frequency inverters and water quenching. Notice that spiral bevel pinion (Figure 6) was induction hardened on OD, ID, and teeth region using a single operation having a continuous hardness pattern. The carrier pin (Figure 9) was induction hardened on outside surface (1.25" diameter) and two inside diameters (longitudinal and transversal) using a single operation that also produced un-interrupted case hardness pattern. Inside diameter of longitudinal hole was 0.5". The inside diameter of the transverse hole was 0.25" [7,8].

CONCLUSIONS

Induction heat-treating being environmentally friendly, green, and lean technology is an increasingly popular choice for induction hardening of gears and gear-like components. Recently developed inverters and process know-how further expands its capabilities.

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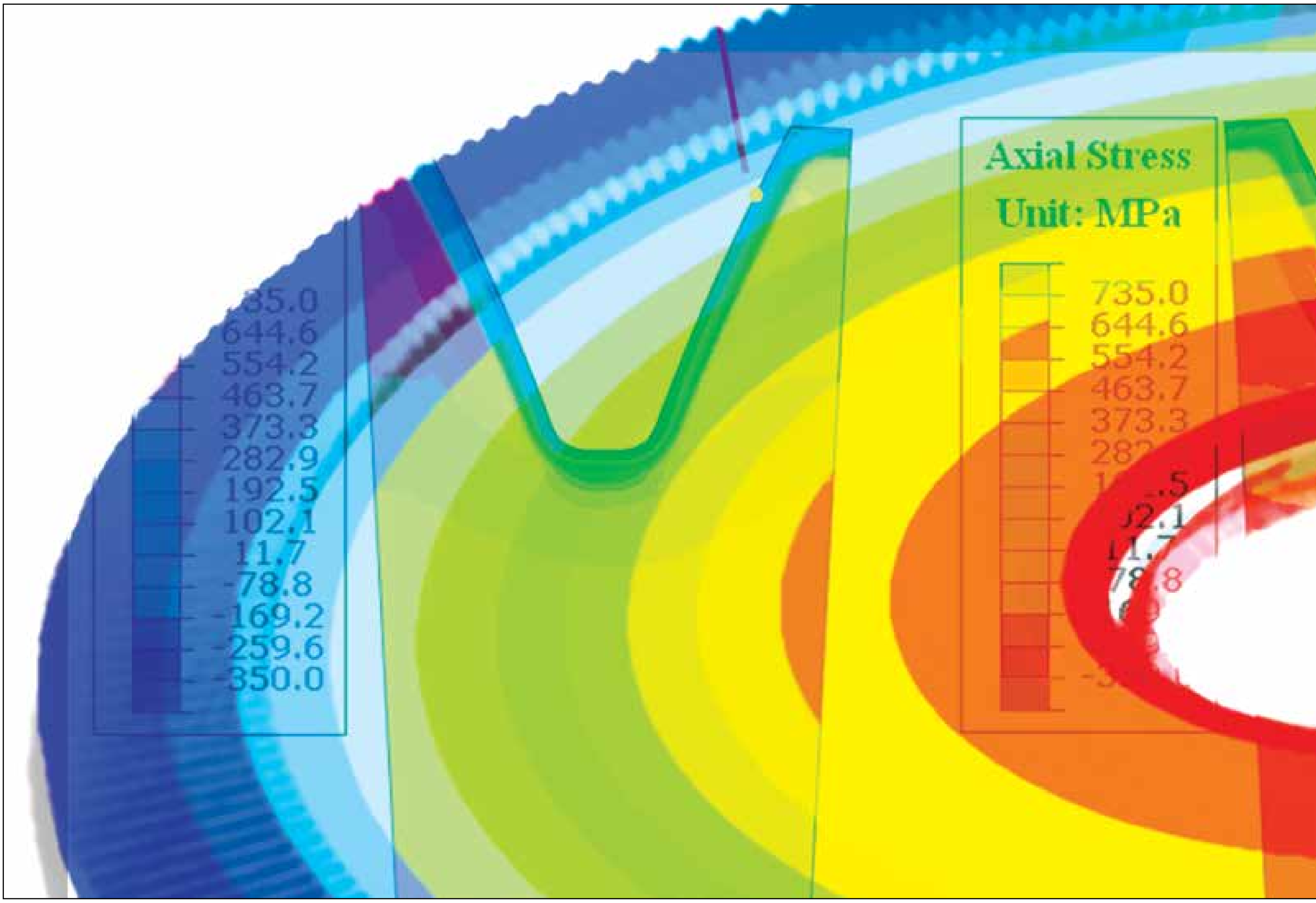
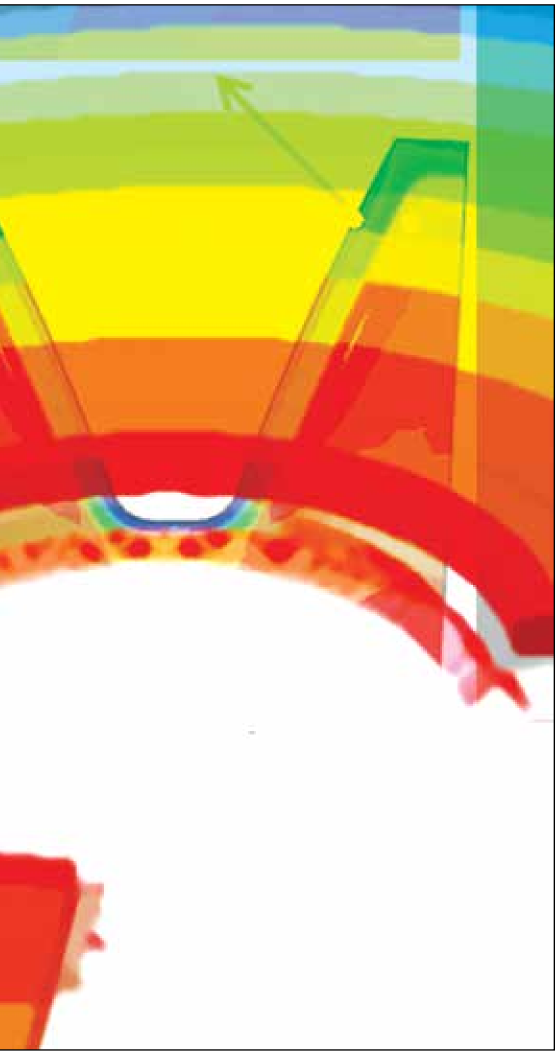


Typical Heat Treatment Defects of Gears and Solutions Using FEA Modeling

By Zhichao Li and B. Lynn Ferguson

In this paper, the commercial heat treatment software DANTE is used to investigate three examples of heat treatment defects. Improved processes are suggested with the help of modeling.

Steel gears are heat treated to obtain enhanced properties and improved service performance. Quench hardening is one of the most important heat treatment processes used to increase the strength and hardness of steel parts. Defects seen in quenched parts are often due to high thermal and phase transformation stresses. Typical defects include excessive distortion, surface decarburization, quench cracks, large grain growth, and unfavorable residual stresses. Gear geometries with large section differences may suffer high stress concentrations and crack during quenching. Surface decarburization before quenching may lead to high surface residual tension and possible post heat treatment cracking. In this paper, the commercial heat treatment software DANTE is used to investigate three examples of heat treatment defects. Improved processes are suggested with the help of modeling. The first example is an oil quench process for a large gear. Peeling cracks were observed on the gear surface during grinding of the quench-hardened gears. Computer modeling showed that surface decarburization was the cause. The second example is a press quench of a large face gear. Unexpected large axial bow distortion was observed in quenched gears, and computer modeling indicated that an incorrect press load and die setup



were the reasons. The third example is an in-process quenching crack caused by high concentrated tensile stress from unbalanced temperature and phase transformations in a spiral bevel pinion gear. The quenching process was modified to solve the problem. This example also emphasizes the need for heat treatment modeling in gear design to reduce the possibility of heat treatment defects. The three examples illustrate how to effectively use heat treatment modeling to improve the quality of the gear products.

INTRODUCTION

During heat treatment of steel gears, thermal gradient, phase transformation, and the resultant internal stress interact with each other to contribute to distortion and residual stress in the quench-hardened parts. Both distortion and internal stress during quenching are complicated and not intuitively understandable in most cases, which make process troubleshooting and improvement difficult. To reduce the machining cost after heat treatment, minimum distortion is preferred. Minimum distortion can be obtained by tuning up the heat treatment process parameters, such as heating and cooling rates, and carburization schedules, etc., although such tune ups are usually costly and time consuming. The increasing demand of gear performance requires the designer to take advantage of the favorable resiudal stresses obtained from carburized and quenching processes. To achieve these goals, computer modeling is being more widely used in the heat treat industry to optimize the heat treatment process [1-3]. DANTE is a commercialized heat treatment software based on the finite element method [4]. It can be used to predict the phase transformations, deformation, residual stresses, hardness, and distortion for heating, carburization, cooling, and tempering processes.

Surface decarburization affects the surface hardness achieved by the quenching process. Many heat treaters believe that the decarburized layer can be ground off to regain higher surface hardness and the effect of decarburization is totally eliminated. Decarburization also affects the surface residual stresses [5]. Favorable residual compression is expected on the surface of steel parts from carburization and quenching processes. Decarburization can shift the surface stress from compression to tension, and the effect on the depth of tensile stress is normally deeper than the depth of the decarburized layer. A grinding process may not able to effectively remove the surface tension and regain favorable residual compression. Computer modeling can be used to understand the relationship between the depth of decarburized layer and its effect on residual stresses.

A press quench is often used to reduce the distortion of gears larger than eight inches in diameter. The press quench is more complicated than the traditional oil quench, and distortion can be affected significantly by the selection of the quench press, die geometry and quenchant channel design, and the process setup.

Excessive distortion and quench cracks are often seen in gears with large section differences. Nonuniform phase transformation between thin and thick sections can lead to stress concentration in a gear during the quenching process, and excessive stress can crack the part at the worst, or distort the part at the least. The quenching process can be modified to reduce the possibility of cracking or to control size and shape change.

Quenching is a highly nonlinear process due to phase transformations and plastic deformation. Effective computer modeling is required to understand the part response during quenching before solutions to problems can be obtained [6]. A gear can rarely be designed with perfectly uniform section, so knowledge of the effects of gear geometry on potential heat treatment defects is critical for the gear designer. Heat treatment models can be used in the gear design process to reduce cost, improve quality, as well as shorten the design cycle.

EFFECT OF DECARBURIZATION ON RESIDUAL STRESSES

A ring gear made of AISI 4320 was carburized, quench hardened, tempered at a relatively low temperature, and then finished by a grinding process. Peeling cracks on the tooth face were observed during the grinding of the hardened gears. The axial height of the ring gear is 650mm, the inner diameter is 950mm, the tip diameter is 1300mm, the root diameter is 1210mm, and the gear has 60 outer straight teeth. Because of the gear geometry and the observed cracking mode, a plane strain FEA model of a single tooth with cyclic boundary conditions was created to investigate the causes of cracking. Figure 1 shows a CAD model of this ring gear and the finite element model created for heat treatment simulations. To model the decarburization effect, very fine elements are required in the shallow surface to ascertain the carbon, temperature, phase, and stress gradients during quenching. Point A in Figure 1 is located right on the tooth surface, and point B is located at a 6mm normal depth from the surface. The material response along the straight line AB is used to investigate the effect of decarburization. The gear face from tip to root cools at different rates during quenching. Contour plots of carbon, temperature, metallurgical phases, and stresses are used to understand the part response. Modeling results indicate that the grinding cracks are caused by high residual tensile stresses in the tooth surface due to decarburization.

The carburization temperature was 950°C, and a boost/diffuse process was used to expedite the carbon diffusion rate. The boost step was 35 hours with a 1.0% carbon potential, and the diffuse step was 15 hours with a 0.85% carbon potential. At the end of the carburization process, the predicted carbon distribution is shown by the curve with solid markers in Figure 2(a). At high temperature when the gear is entirely austenite, its surface may decarburize in an atmosphere containing oxygen. An oxidizing

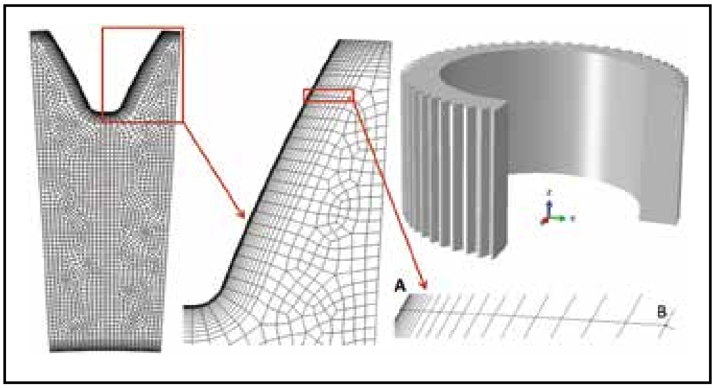


Figure 1: Gear geometry and finite element model.

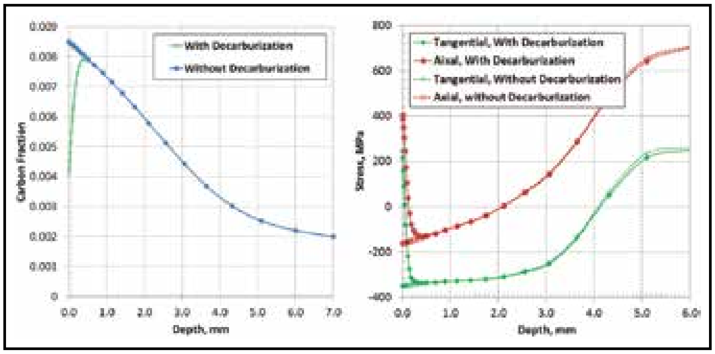


Figure 2: (a) Carbon and (b) residual stress distribution after quench.

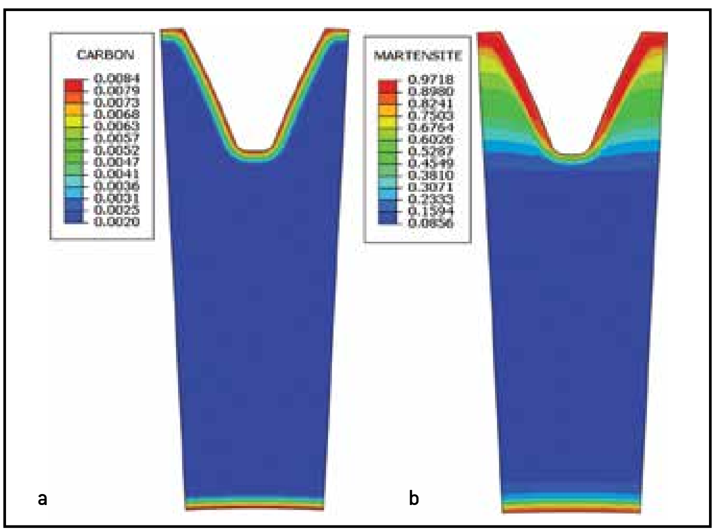


Figure 3: (a) Carbon distribution, and (b) martensite distribution at the end of quenching.

atmosphere can be found in a poorly maintained furnace. During the transfer from furnace to quench tank, gears are exposed to air. For large parts, the transfer time in air is usually longer than for small parts, which makes the decarburization effect more significant due to the reaction time between the oxygen and surface carbon. The transfer time from furnace to the quench tank is 2 minutes. However, an oxygen atmosphere in the furnace can cause surface decarburization. In this study, it is assumed that the ring gear is exposed to an oxygen atmosphere for 10 minutes before being quenched, which is a combined effect of furnace atmosphere and air transfer. The surface carbon is assumed to drop to 0.4% due to the carbon-oxygen reaction. The carbon distribution within the decarburization zone is shown by the curve with hollow diamond markers in Figure 2(a). The depth

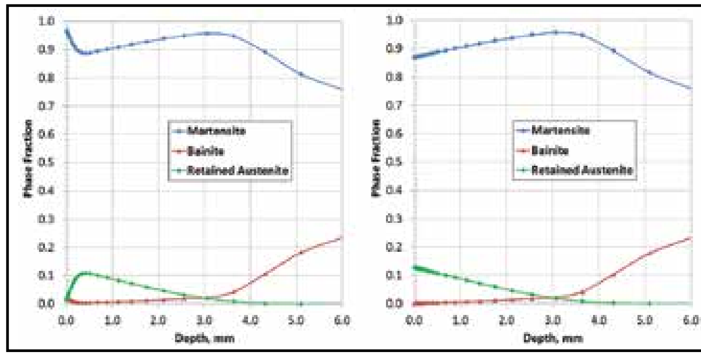


Figure 4: Phase distributions at the end of quenching process. (a) With decarburization effect, (b) Without decarburization effect.

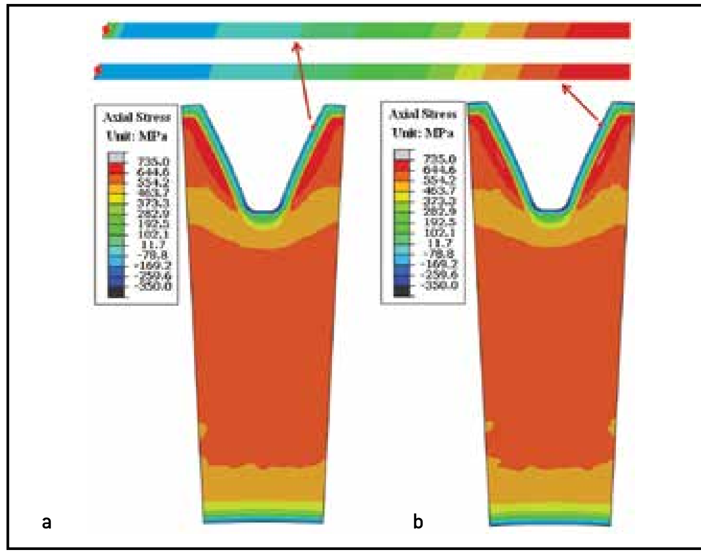


Figure 5: Contour plots of axial residual stresses at the end of quenching process. (a) With decarburization effect, (b) Without decarburization.

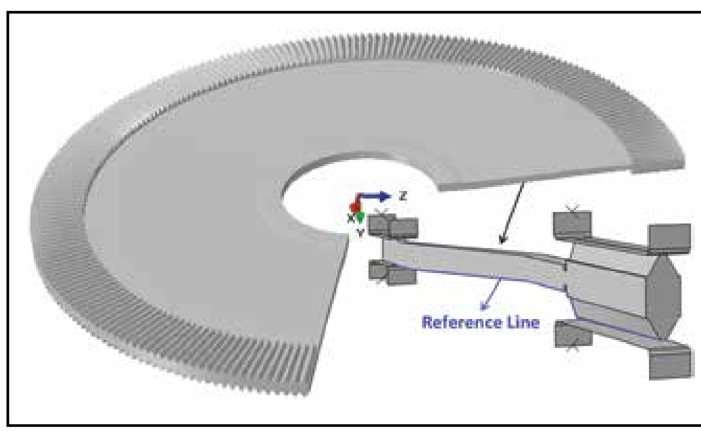


Figure 6: Face gear CAD model and press quench model setup.

of decarburized layer is about 0.10mm using 0.65%C as the initial threshold. Without decarburization, the predicted axial and tangential stresses after quenching are 160 MPa and 350 MPa in compression, respectively. With decarburization, the axial and tangential surface stresses are 400 MPa and 250MPa in tension. The change in axial residual surface stress due to decarburization is 560MPa. The tensile stresses will contribute to the cracking probability during the grinding process.

During quenching, both the thermal gradient and phase transformations contribute to the stress evolution in the part. Contours

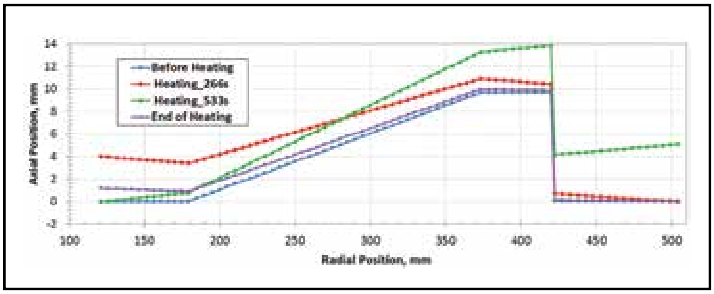


Figure 7: Face gear axial deflection during furnace heating.

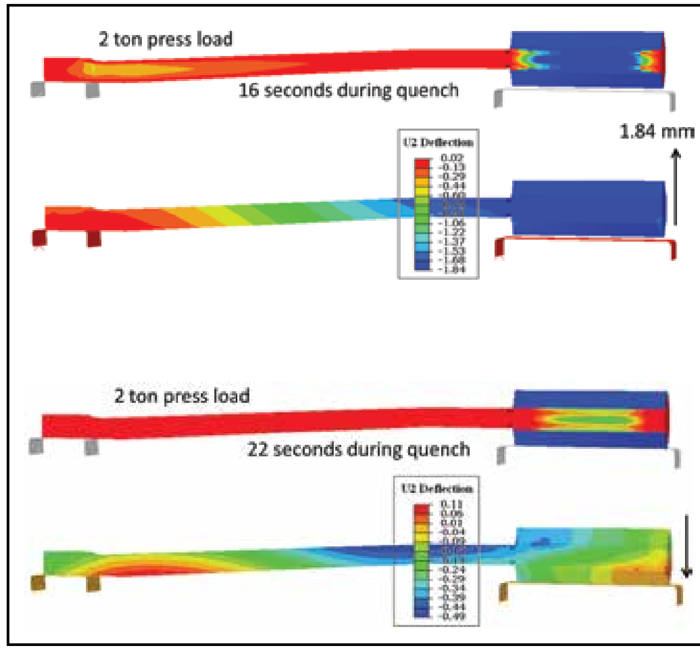


Figure 8: Insufficient press load during quenching process.

of carbon profile and martensite distribution after quenching are shown in Figure 3. The carburized case contains mainly martensite with about 10% retained austenite in the as-quenched condition. The retained austenite will transform to bainite during the tempering process. The depth of the hardened case increases from the root to tip along the tooth face due higher cooling toward the tooth tip and the deeper martensite distribution. The gear body microstructure is about 90% bainite and 10% martensite.

Figure 4 shows the phase distributions along line AB (Figure 1) at the end of the quenching process. With decarburization, 100% martensite is formed right on the surface because the martensite transformation finishing temperature (Mf) is higher than the room temperature for 0.4% carbon of this steel grade. Under the decarburized layer, the carbon content is about 0.8%, and 12% retained austenite is predicted to be present after quenching.

For steel, the starting temperature (Ms) for martensite transformation decreases as the carbon level increases. During a traditional oil quench process, martensite formation is delayed in the carburized case due to its high carbon content. There is a volume expansion with martensite formation. In a carburized gear, the surface transforms to martensite after the case-core location has formed martensite during a traditional oil quench. The delayed surface expansion leads to residual compression in the carburized case. If decarburization occurs before

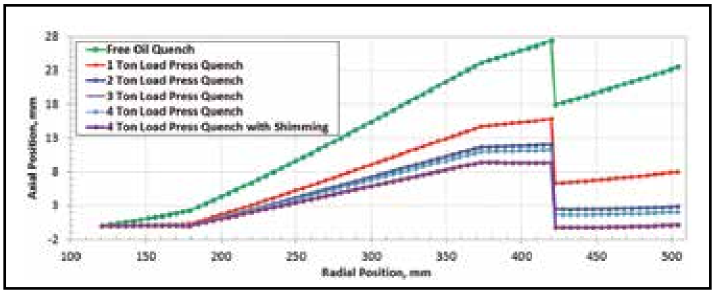


Figure 9: Effect of press load on axial bow distortion.

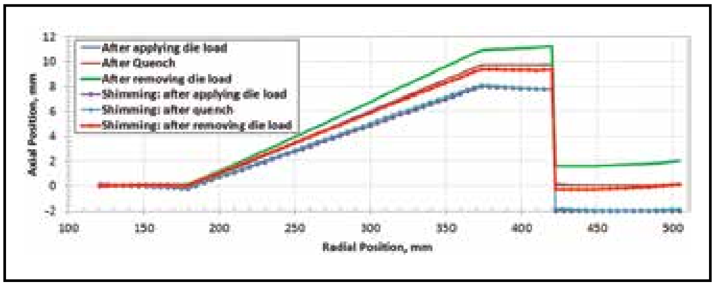


Figure 10: Gear shapes at different stages during quenching.

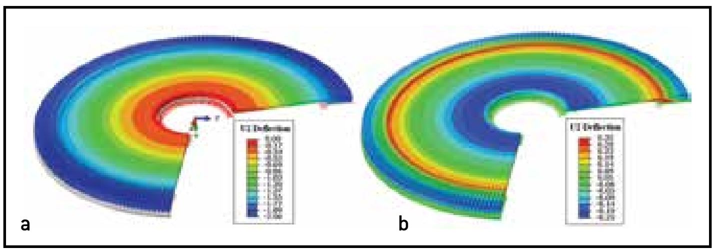


Figure 11: Bow distortion in the axial direction. (a) 4 tons press load without shimming, and (b) 4 tons load with 2mm shimming.

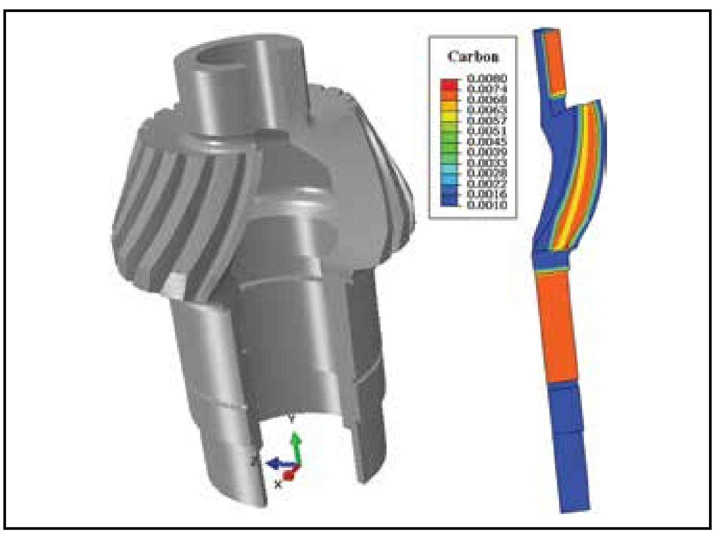


Figure 12: CAD model and FEA model of the spiral bevel pinion gear.

quenching, martensite formation starts in the shallow decarburized layer earlier than in the subsurface layers, and the delayed volume expansion of the sub-surface under the decarburized case will convert the stresses in the shallow decarburized case from compression to tension. Low temperature tempering does not have a significant effect on the residual stress distribution. Both axial and tangential residual stresses contribution to the cracking possibility during grinding, but axial stress usually dominates because of its higher magnitude. The contour plots of the axial residual stress are shown in Figure 5.

DISTORTION ANALYSIS OF LARGE FACE GEAR DURING PRESS QUENCH

Large gears are often quenched in a press in order to meet the dimensional requirements. The gear distortion can be significantly affected by the quench press equipment, the die design, the quenchant flow and the process sequence. In this section, a press quenching process for a large face gear about one meter in diameter is modeled using DANTE. The causes of distortion are examined, and an improved process is suggested.

A simplified CAD model of the face gear is shown in Figure 6. The face gear has a large ratio of diameter to thickness. The web of this face gear is not planar, and it behaves like a washer inside the die during quenching. The main distortion mode is bow deflection in the axial direction, and a single tooth model with cyclic boundary conditions is effective for predicting this type of distortion. The quenching dies are assumed to be rigid in the model. The bottom dies are fixed during quenching. The same load is applied to the hub die and the tooth die. Both hub and tooth dies on the top can move freely in a vertical direction during the quenching process. Quench oil is assumed to flow over the part on the top and bottom surfaces in a general inward to outward direction. A friction coefficient of 0.15 is assumed between the dies and gear surfaces. The press quench model setup is shown in Figure 6. The reference line shown in Figure 6 is used to represent the gear shape during both heating and quenching processes.

The gear tooth section is thicker than that of gear hub. During the heating process, the hub heats faster than the tooth section, and it will reach the furnace set temperature earlier. This means that the phase transformation to austenite starts and finishes earlier in the hub section. Material volume shrinks with transformation to austenite. The timing difference for volume shrinkage between gear tooth and hub creates internal stresses and axial displacement. Assuming that the gear sits on a support surface with the bottom surfaces of gear hub and tooth sections contacting the supporter, the shape change of the gear during heating is shown in Figure 7. The reference line in Figure 6 is used to represent the gear shape. At different furnace heating times, the model results show that it may have only hub or tooth section contacting the support. Significant axial bow deflection will occur during a free furnace heating process. However, the predicted axial deflection at the end of heating is only 1mm with the hub displaced upward.

During the press quench, an excessive press load can cause distortion of the gear tooth due to TRIP effect, or may even damage the tooth profile by plastic deformation. In general, an applied load is used to hold the gear in the dies instead of totally constraining the gear using displacement control. A minimum load is preferred to effectively hold the gear in the dies. An insufficient load means that the reaction force from the gear exceeds the applied press load, as shown in Figure 8, and a section of the part may separate from the die. At 16 seconds during quenching, martensite formation in the hub and web is almost completed, so the gear web has high strength. A press load of two tons is insufficient to hold the gear at this point. The top die is pushed up about 1.84mm, and the gear tooth section is separated from the bottom die. With further martensite formation in the tooth section, the gear tooth moves down against the bottom die. A load of two tons is sufficient to hold the gear once the phase transformation is completed.

The effect of applied press load on axial bow distortion was investigated using finite element models by applying different loads during the press quench. A free oil quench process was modeled to compare with the press quench results. Due to the washer shape of this face gear, the distortion experienced in the free quench is extremely

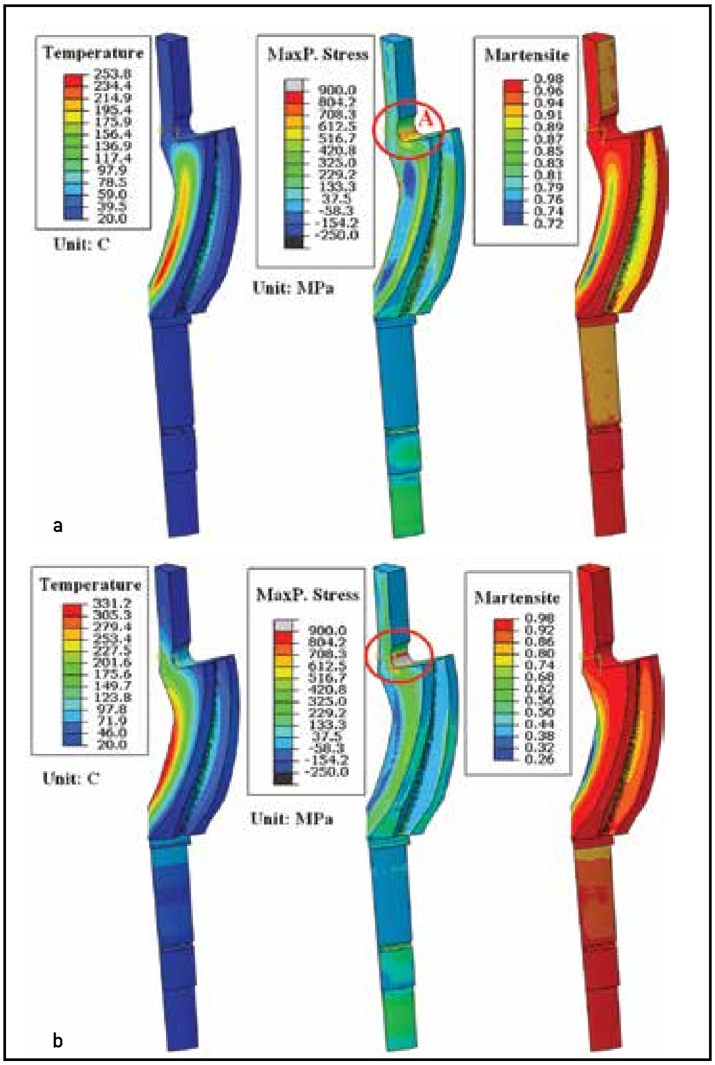


Figure 13: Temperature, Maximum Principal Stress, and Martensite Distributions. (a) At 11.4 seconds during fast quench on both OD and ID. (b) At 27.2 seconds during slow quench on OD only.

large. The predicted axial bow distortion is about 24mm upward at the tooth section, as shown in Figure 9. With a 1-ton press load, the predicted axial distortion is about 8mm. Increasing the load to 2 tons, the predicted distortion is reduced to 3mm. There is no noticeable difference on distortion between 3 and 4 tons load, and the distortion is about 2mm. A minimum of 3 tons load is required for press quench. A load of 4 tons has no negative effective on the gear tooth profile, and 4 tons load is suggested.

With sufficient press load (4 tons), the gear is hold inside the dies consistently during the entire press quench process. Due to the thermal gradients and phase transformations during quenching, residual stresses exist in the gear at the end of press quench. A 2.0mm springback is predicted after removing the press load, and the spring back is basically the final distortion amount, as shown in Figure 10. By applying a 2.0mm shim to raise the hub section in the initial die setup, the axial bow distortion caused by the spring back can be compensated. With the shimming, the gear is deformed with the tooth section moving downward 2.0mm after closing the die and applying the press load. There is no significant difference of residual stresses between the cases with and without shimming, and both cases have a similar spring back amount, meaning the shim is predicted to accomplish the desired improvement in final dimensions.

Small amount of distortion exists in the press quenched gear with shimming. Figure 11 compares the axial bow deflections in the final part between the two cases with and without shimming. The distortion can be effectively controlled by applying the shim.

QUENCH CRACK OF PINION GEAR DURING QUENCHING PROCESS

The intensive quenching process was used to improve the residual stress state of a pinion gear with spiral bevel teeth. The axial height of the gear is about 150mm, and the largest outer diameter of the tooth is about 100mm. The gear has 22 teeth as shown by the CAD model in Figure 12. The gear is made of AISI 9310. Only a portion of the gear surface is carburized, and the uncarburized surface is copper plated prior to carburization. The pinion gear has a high cracking possibility during intensive quenching process, especially if the process deviates from the designed process. Finite element models were used to understand the effects of process parameters on stress state and possible causes of cracking. Based on the modeling results, an improved intensive quenching process has been suggested to reduce the cracking possibility. A single tooth model with cyclic boundary condition was used in this study.

A single-chamber system is modeled to intensively quench the pinion gear. The quenching system and fixture are designed to flexibly control the water flow rates along the OD and ID surfaces. Three different quenching processes are modeled to investigate the effect of quenching process and cracking possibility. The first model has a high cooling rate on both the OD and ID surfaces. As shown in Figure 13(a), the highest stress of 570 MPa is observed at the fillet region A at 11.4 seconds during the quench; this stress is judged to not be high enough to cause cracking. However, a high quench rate on the ID surface tends to reduce the favorable residual stresses in the carburized gear tooth surface. To maximize the compressive residual stress in the gear tooth surface, a model the ID surface is insulated, and a low quench rate (low for IQ but high for conventional quenching) is applied on the OD surface. At 27.2 seconds during the quench, a high tensile stress of 1000 MPa is predicted at location A as shown in Figure 13(b); this stress indicates a high cracking possibility. The delayed martensite transformation in the tooth ID surface tends to expand the whole tooth section, which creates a bending effect on the region A. Contrary to the traditional thinking, the tensile stress in fillet region A is reduced by applying a high quench rate on the OD while keeping the ID surface insulated.

During quenching, the highest maximum principal stresses at point A are the tangential stress, as shown in Figure 14. A local cylindrical coordinate system is used to convert the stress tensor to the tangential stresses at point A during quenching. The temperature, martensite, and tangential stress at point A are plotted in terms of quenching time for all the three cases.

The transferring time between opening heating furnace and staring quenching is 10 seconds. The heat loss during air transfer will affect the gear response during quenching, so it is modeled. Figure 10 compares the tangential stresses at point A for all the three cases. Fast quenching on both ID and OD surfaces has the lowest peak stress about 570 MPa. With slow quenching on OD surface only, the stress peak is as high as 1000 MPa. By fast quenching on OD surface only, the stress peak is 700 MPa, which indicates a small cracking possibility. All the three cases end up with residual tension at the fillet region A, and lowest residual tension is predicted from the case of fast quenching OD surface only.

SUMMARY

Accurate modeling of heat treat process provides a method for examining heat treat process steps and the complex relationships between part geometry, steel hardenability and phase transformations, stress state and part dimensional change. Specific cases were reported as examples of modeling application for real problems.

- Decarburization was shown to produce tensile surface stresses that can be sufficiently high to cause surface cracking during finish grinding.
- Press quenching imposes residual stress states that differ from residual stress and distortion from free quenching. Springback due to the final residual stress state can be an issue and can be overcome.
- Control of local quench rate offers a way to achieve enhanced residual stress states for performance improvement. Improper local quench rates not only can degrade part performance, they can produce defective parts.

By using modeling tools such as DANTE, it is possible to predict the evolution of both stress and metallurgical phases throughout the carburizing and quench hardening process. Highly nonlinear processes such as steel heat treatment do not obey simple rule sets

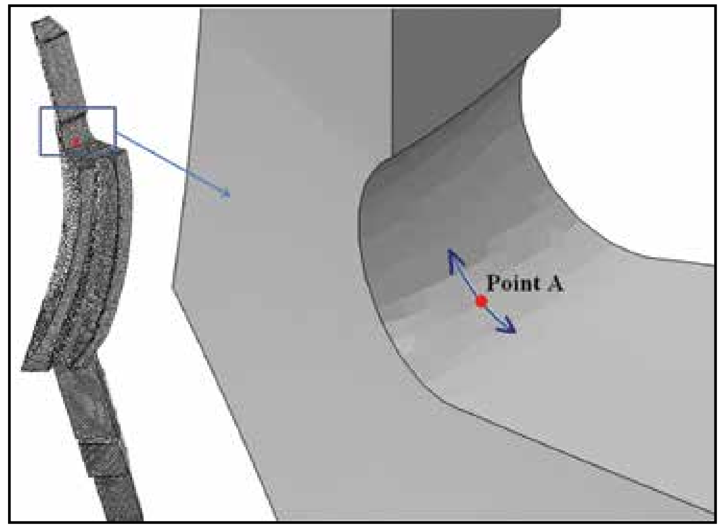


Figure 14: Critical point selected to investigate cracking possibility.

and nonlinear finite element analysis allows for greater depth of understanding of process effects.

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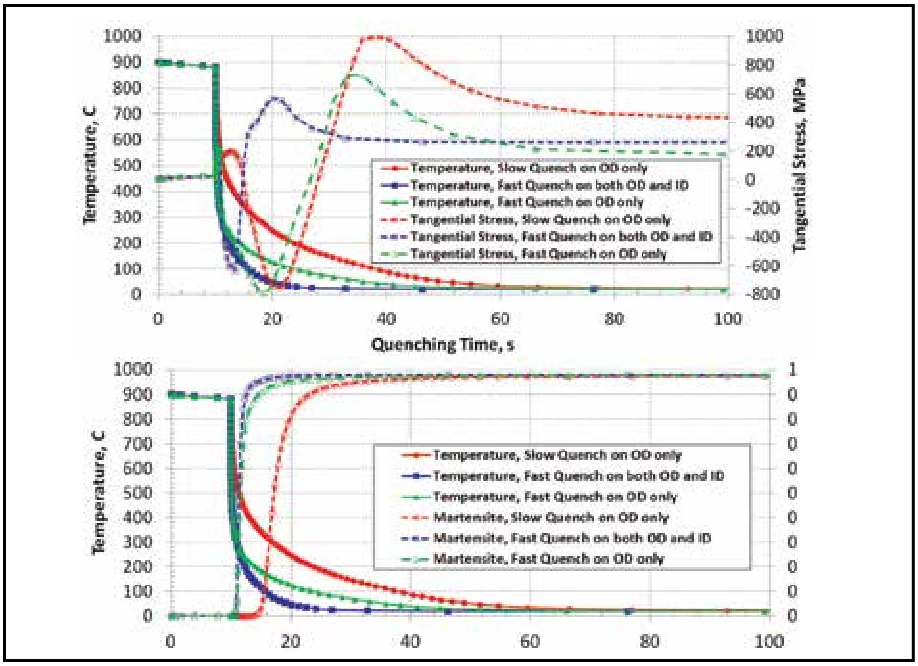

Figure 15: Temperature, phase, and tangential stress evolution at point A during quenching.

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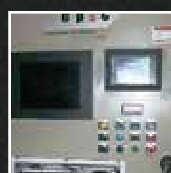
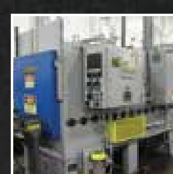
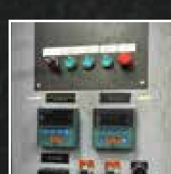
ABOUT THE AUTHORS: Dr. Zhichao Li is a graduate of the Harbin Institute of Technology in Harbin, China, where he earned both Bachelor and Master Degrees in Metalforming, and Wright State University, where he earned a Ph.D. in Mechanical Engineering. At DCT, Dr. Li is in charge of DANTE software development, enhancement, and support. Lynn Ferguson is founder and President of DCT. He is a graduate of Drexel University where he earned a B.S. in Metallurgical Engineering and M.S. and Ph.D. in Materials Engineering. Over the past decade he has been extensively involved in simulation of mechanical and thermal processes using computer-based tools such as the finite element analysis.

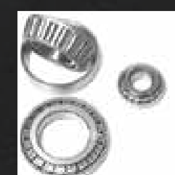
Complete Induction & Die Quench System for Bearings and Gears







This machine is currently being used to heat and die quench spiral bevel ring gears up to 500mm in diameter.



This machine is designed with an automatic conveyor and loading system to continuously heat, die quench, and temper 500mm rings. This unit has an EFD 400kW output supply with a 1.7-3.0 kHz frequency designed for deep and fast heat penetration which allows rings to be heated and die quenched in just minutes. This system is setup to convey quenched parts to and through a continuous Apar IPSEN tempering and preheat electric furnace with a 36" x 48" opening with a 3,000 lb load capacity. This unit also comes complete with its own outside cooling system and monitoring to ensure flow, min/max pressure, and min/max temperature. Conversion available to make this unit a Heat and Quench station with variable high frequency independant of the Die Quench. Call for special pricing and details!

MACHINE SPECIFICATIONS:

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- Max Diameter 500mm (800mm optional)
- EFD Power Supply
- Power Requirements 3 x 480v - 60Hz - 570KVA
- Dimensions (L x W x H) 1790mm x 1200mm x 1730mm
- Weight 15500 kg

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Tighter Control Through Understanding What Your TUS Reports Are Telling You

By Steve Miller

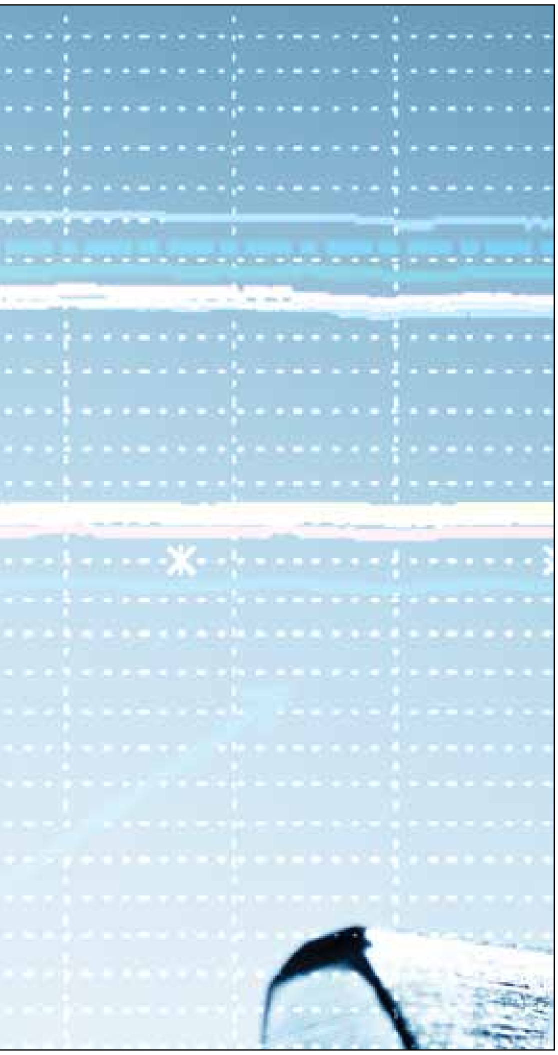
Furnaces may have multiple operating ranges, meaning they may need to have TUS's performed more frequently.

Temperature uniformity is the temperature variation (usually expressed as ± degrees) within the qualified furnace work zone (Figure 1) with respect to a set point temperature. A TUS (temperature uniformity survey) is a test or series of tests where calibrated field test instrumentation and sensors are used to measure temperature variation within the qualified furnace work zone before and after thermal stabilization. Prior to the first use of a furnace, an initial TUS should be performed. After this, periodic tests should be run based on the furnace class and type. Furnaces may have multiple operating ranges, meaning they may need to have TUS's performed more frequently.

AMS2750E now allows a second thermocouple within 0.38" of the control thermocouple to be logged onto the chart recorder; this is an alternative to digitally transmitting the actual control sensor. The digital transmission method is still the most accurate, and helps with conformance to the SAT (system accuracy test).

For work zones with volumes less than 3 ft^3:

- Box: Four TUS sensors should be located at the four corners and one in the center (Figure 2)



- Cylinder: TUS sensors should be located 90 degrees apart, one in the center.

For work zones with volumes greater than 3 ft³:

- Box: Eight TUS sensors should be located at the corners and one in the center.
- Cylinder: Three TUS sensors should be located on the periphery of each end, 120 degrees apart—one in the center and two in the qualified work zone.

Performing a TUS is relatively straightforward. Typically, you will start a survey prior to the first sensor reaching the lower tolerance level. Doing so will show that the furnace is coming up to temperature, not exceeding the high threshold and, most importantly, stabilizing for at least 30 minutes. It's important to note when collecting data that the data acquisition device is recording at least once every two minutes.

Once the furnace has stabilized, no sensor can go above or below the threshold limit for that furnace class.

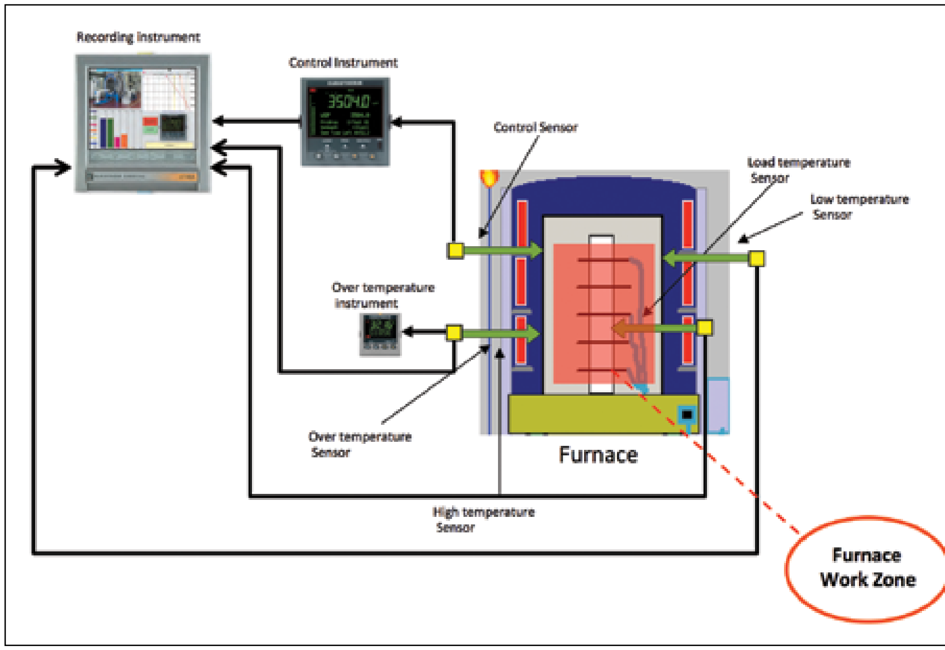


Figure 1: Furnace work zone applicable to TUS.

One thing to keep in mind is that stability is identified in different ways. According to AMS2750E specification.

For unloaded furnaces: If temperature readings of any TUS sensor exhibit an upward or downward trend (continuously higher highs or lower lows), the test period should be extended as necessary until the trend is no longer evident.

For loaded furnaces: If a survey load is used during the TUS, some survey thermocouples may continue to rise in temperature and slowly approach the set temperature. This rise in temperature of survey TC toward the SP temperature meets the requirement for stabilization. In other words, a loaded furnace may exhibit a continual increase/decrease in temperature during its 30-minute cycle.

Remember, you need a separate recording device capable of meeting AMS2750E Field Test Instrument standards of +/- 1°F or .6 °C.

The report needs to style the following:

1. Furnace ID name and number
2. Survey date and time start
3. Survey date and time stop
4. Name of technician performing survey
5. Survey result
6. Testing company detail
7. Testing company signature

The report needs to show the following data:

1. Summary of readings
2. Quality organization approval
3. Survey temperatures
4. Correction factors
5. List survey test instrumentation (Figure 3)

The report needs to identify the following:

1. Sensor & location identification
2. Time and temperature profile

Once you gather the required data and are ready to look at the results, it's time to examine what exactly you are looking for, and what it's going to tell you. The TUS results can tell us a lot. Here are a few questions to ask:

1. Did any test, control, or recording sensors exceed upper temperature uniformity tolerance?
2. Were all temperatures held until stabilized?
3. Did data collection continue for a minimum of 30 minutes?
4. Did all surveyed thermocouples remain within the desired temperature range and not drift above or below max/min temperature?

If any of these conditions were not met, it is imperative to look at the data to see why they weren't met, then correct the problem and run the survey again.

The report tables and the profile give a good overview of the heating rate in each part of the work zone, including the time to stabilize, ultimate hot and cold spots, and variation from the setpoint (Figure 4). One way to compare electronic records is to utilize the conditional formatting within Excel. This will show the pattern of heating and stabilization, and it's

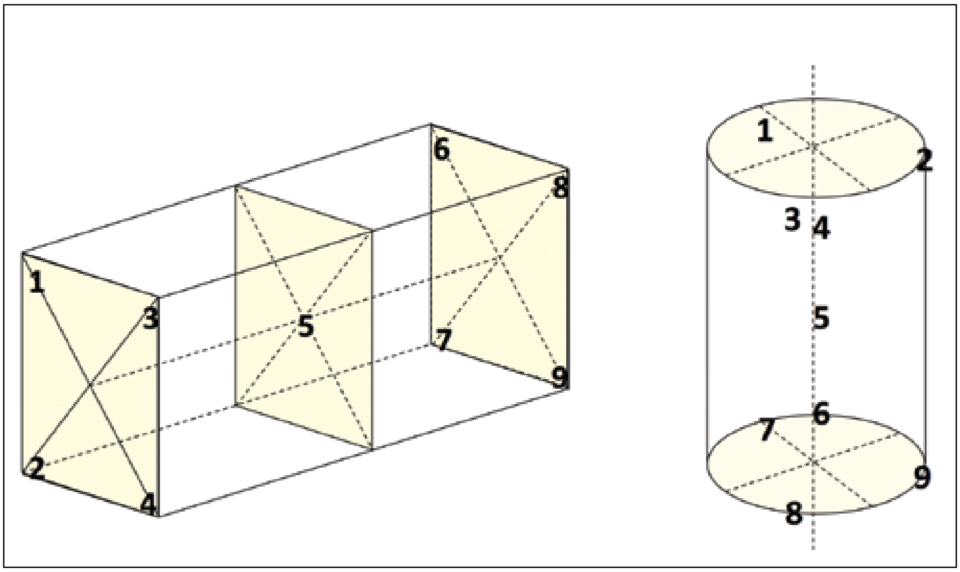


Figure 2: Necessary TUS sensor locations.

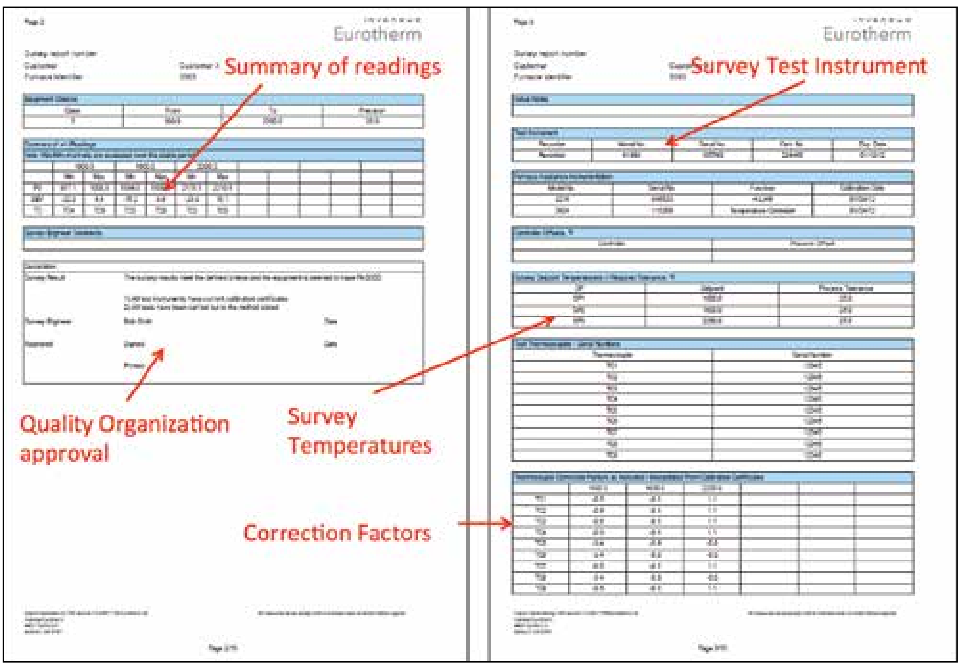


Figure 3: Various report requirements for TUS.

easy to compare with prior reports to see if any major changes are occurring or if there is a pattern of degradation. This method requires a working knowledge of Excel and the ability to export a csv file from your data recorder.

An alternative method is to use reporting software. One example is Dream Reports from Invensys Eurotherm. The tamperproof files can be read directly into the reporting software, and individual reports can be customized to show conditional formatting or compared with a set "golden batch" (ideal TUS trace).

Once the report is setup, it may run for different surveys and the information can be compared.

The purpose of this test on the Invensys Eurotherm Nanodac is to estimate the maximum error when reading the thermocouple types listed in the AMS2750D standard, type T,R,B,E,J,K,N, and S. This is then tested with the worst case calculated drift for the K-type thermocouple. The temperature profile of the environmental chamber is then cycled as below with a programmer. The time for each section is 12 hours and cycles from 25°C to 35°C then to 15°C. The overall worst case drift at was at 15°C and was equal to 1200.6°C (highest reading) - 0.14°C (mv source drift) = 1200.46°C. The worst case from the table below is (0.035*1200°C)/100)+0.29°C=0.7 1°C. The nanodac reads less than the worst case estimated error.

The nanodac thermocouple inputs meet the requirement of the AMS2750D requirements of not drifting by more than 1.1°C over a period of three months, with the condition that the retest temperature is within the specified range of 25°C ±10°C. This has been supported by worst-case experimental results that have drifted less than the worst case calculation.

To enable more accurate TUS results, use cutback to minimise overshoots. This also can be automatically set by running an autotune on the process. Cutback high 'CBH' and cutback low 'CBL' are values that modify the amount of overshoot or undershoot that occur during large step changes in PV (for example, under startup conditions). They are independent of the PID terms, which means that the PID terms can be set for optimal steady state response and the cutback parameters used to modify any overshoot that may be present.

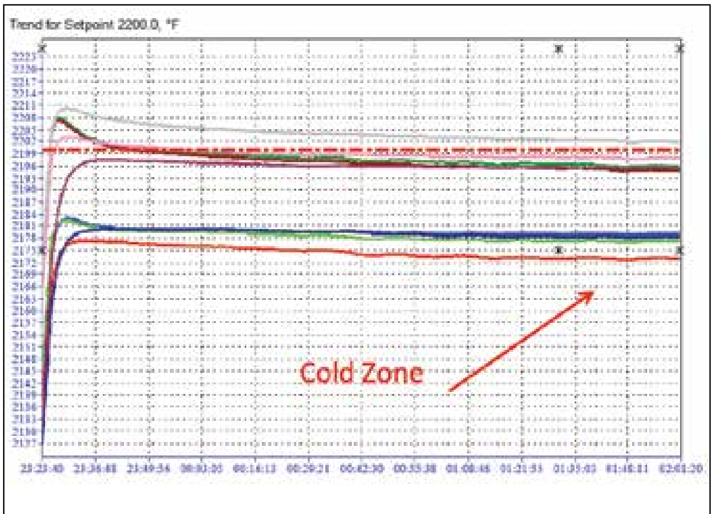
Cutback involves moving the proportional band towards the cutback point nearest the measured value whenever the latter is outside the proportional band and the power is saturated (at 0 or 100% for a heat only controller). The proportional band moves downscale to lower the cutback point and waits for the measured value to enter it. It then escorts the measured value with full PID control to the setpoint. In some cases it can cause a "dip" in the measured value as it approaches setpoint as shown, but generally decreases the time needed to bring the process into operation.

If cutback is set to "auto" the cutback values are automatically configured to 3*PB.

Cut back can be used for furnaces that have a large temperature difference between loading and the desired setpoint – it takes into account some of the inertia of the heating system and protects from overshoot

Gain Scheduling – In some processes the tuned PID set may be very different at low temperatures from that at high temperatures from that at high temperatures from that at high temperatures particularly in control systems where the response to the cooling power is significantly different from that of the heating power. Gain scheduling allows a number of PID sets to be stored and provides automatic transfer of control between one set of PID values and another.

Gain scheduling is basically a look-up table that can be selected using different strategies or types; Auto-tune will tune to the active scheduled PID set. Different PID's can also be set dependant on programmer segment (you may want to have a different control methodology when soaking at



Summary of +/- Readings						
Note: Max/Min channels are evaluated over the stable period						
	1000.0		1600.0		2200.0	
	Min	Max	Min	Max	Min	Max
PV	987.8	1010.1	1583.3	1608.5	2172.6	2202.4
DEV	-12.2	10.1	-16.7	8.5	-27.4	2.4
TC	TC1	TC8	TC3	TC8	TC3	TC8

Figure 4: The report tables and profile give a good overview of the heating rate in each part of the work zone.

temperature to ensure stability to the ramp segment when you want to minimize the time to temperature without overshoot).

Failure of TC1 auto transfer to TC2 – particularly useful if you have a system with a resident SAT sensor or 2nd control sensor linked to the recorder (and linked back to control) – AMS2750E. When controlling the time cycle for a heat treatment load:

1. Manually, the operator uses a clock and time load and must check charts to see when furnace achieved temperatures
2. Semi-automatic, furnace has cycle timer that sounds an alarm, time-triggered when close or at setpoint
3. Automatic (providing redundant backup to the operator), timer built into controller and triggered as desired. This can be triggered from a load or in-situ sensor that actually takes part temperature and starts soaking when this is within a set deviation of the setpoint. Alarms can be added in case the furnace heating system malfunctions and the temperature is not reached – a maximum time to reach temperature is programmed and if exceeded then will alarm and take action if necessary.

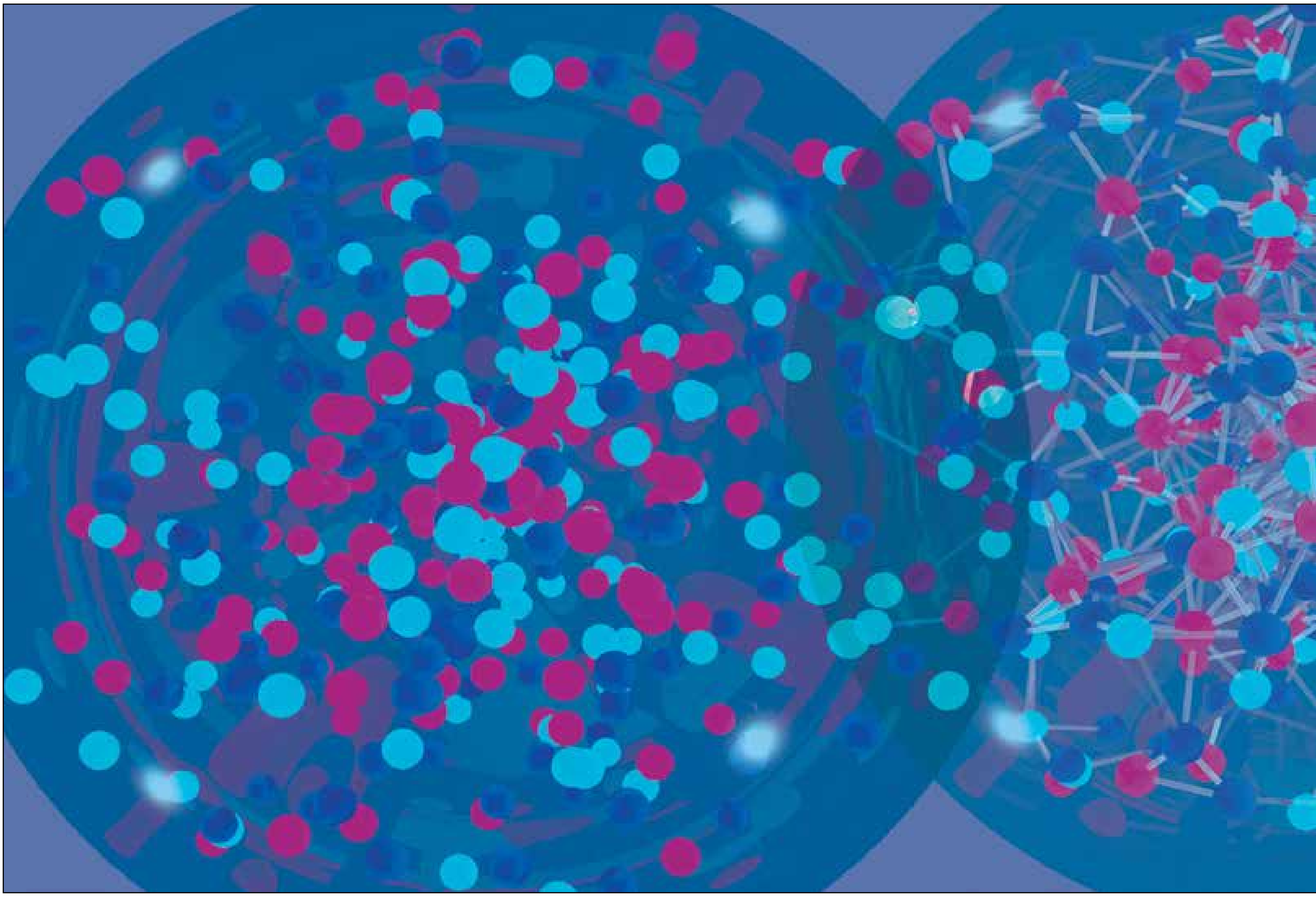
REDUNDANT CONTROL

Atmosphere control for carburizing typically uses a carbon sensor or oxygen probe, although Lambda Probes are now being used for certain applications. This architecture could be used to satisfy CQI-9 requirements for logging and checking carbon levels.

ADDITIONAL INPUTS

With multiple inputs, you can monitor control and load TC's not only for monitoring purposes but for such applications like a "segment wait" function where the setpoint program will wait to advance to the next segment until the part TC has reached SP.

ABOUT THE AUTHOR: Steve Miller has been the national sales manager for Invensys Eurotherm since 2009 and has over 20 years of experience in the heat treat industry ranging from engineering, marketing, and sales. For more information about Invensys Eurotherm, visit www.eurotherm.com.



Gas vs. Liquid Quenching: A Direct Comparison in Hardenability to Reduce Distortion

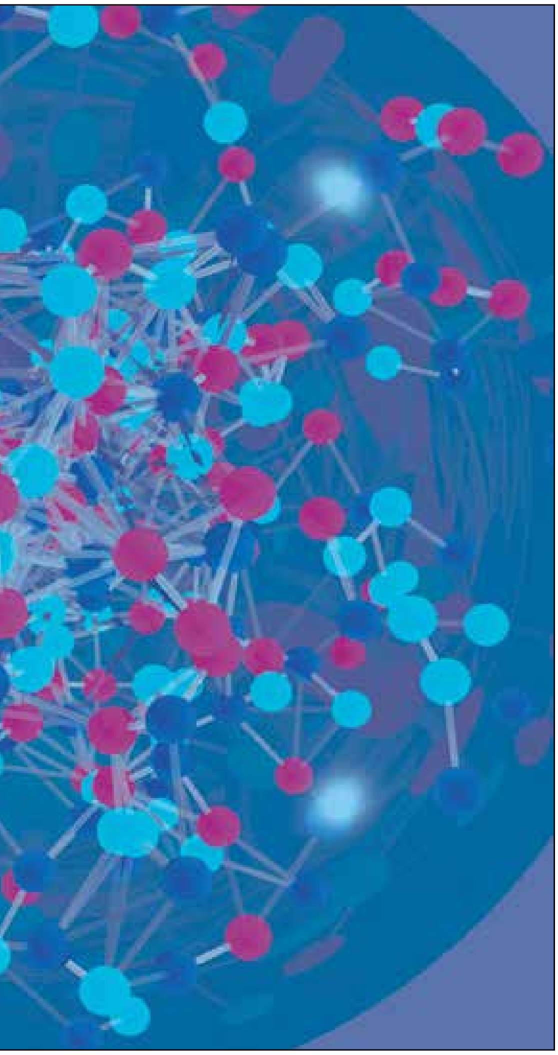
By Robert Hill

High hardness occurs where high volume fractions of martensite develop—always nearer the quenched site. Lower hardness indicates transformation to be incomplete.

INTRODUCTION

Hardenability is the ability of steel to partially or completely transform from austenite to some fraction of martensite at a given depth below the surface when cooled under a certain condition. The "gold standard" test for all hardenability results has always been the Jominy End Quench Test. The information gained from this test is necessary for metallurgists in selecting the proper combination of alloy steel and heat treatment parameters, in order to minimize their thermal stresses and distortion in the manufacture of components of various sizes.

The Jominy End Quench Test involves a normalized cylinder specimen that measures 1" in diameter by 4" in length, heated to the austenitizing temperature for that given material. Once thoroughly heated, the specimen is quickly transferred to a test stand that holds the specimen vertically. One end of the sample is then sprayed with a controlled flow of water. This cooling spray of one end of the sample simulates the effect of quenching a larger steel component in water. Once at room temperature, the specimen is ground to a depth of .015" on parallel surfaces. The hardness is then measured at 1/16"



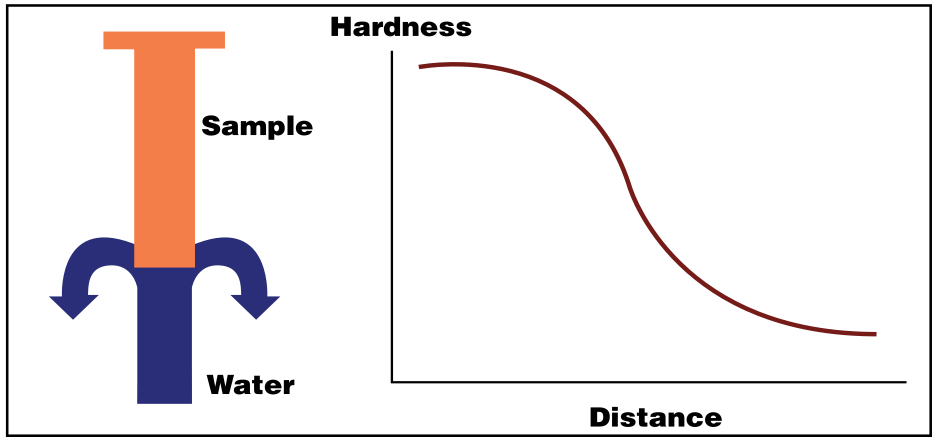


Figure 1: Structures with bainite or ferrite/pearlite microstructure usually develop farthest from the quench site.

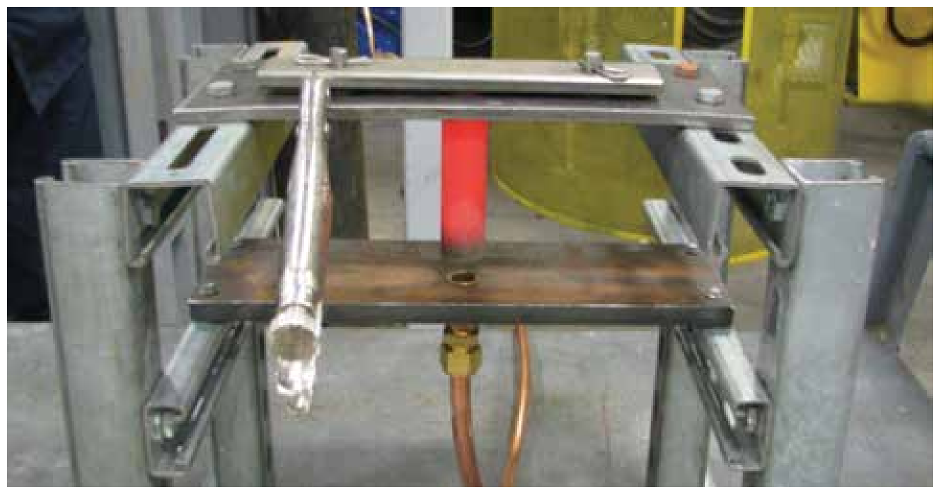


Figure 2: New air quench test stand.

increments from the quenched end of the bar.

High hardness occurs where high volume fractions of martensite develop—always nearer the quenched site. The lower hardness indicates transformation to be incomplete. Structures such as a bainite or ferrite/pearlite microstructure usually develop farthest from the quench site (see Figure 1). With this valuable information, the metallurgist can make critical design decisions. Steels with higher hardenabilities are needed for larger, higher-strength components, whereas steels with lower hardenabilities may be selected for smaller components.

PROBLEM

In the gear industry, it is well known that the medium used for quenching a material influences the cooling rate due to varying thermal conductivities and specific heats. Liquid quenchants such as brine, water, or oil cool much more quickly than air quenching. Today, it is also well-understood that eliminating two of the three phases of liquid quenching (vapor and vapor transport phases) and cooling via conduction only can dramatically reduce distortion. With the unique geometries and critical dimensions of gearing, the preferred method to achieve near net shapes with minimal distortion is to quench with inert gas within vacuum furnaces. As the cooling parameters within vacuum furnaces continue to increase, due to such factors as increased gas velocities, increased pressures, various pedigrees of gases, and better fan designs, why would the Jominy End Quench Test not also adapt to changing times?

DESCRIPTION OF THE TEST

In order to differentiate the hardenability of materials when gas-quenched, a new Jominy Test method is necessary. That new test for this experiment will be a Jominy AIR End Quench Test.

The first phase of this experiment will examine how various gas velocities affect hardenability on various alloy steels. The three alloy steels chosen for this test were 4130, 4140, and 4340. All specimens were normalized at 1700°F ± 10°F for one hour. The respective austenitizing temperatures and times for the test specimens were as follows:

4130 per AMS6370N:
1600°F ±10°F for one hour

4140 per AMS 6349C:
1550°F ±10°F for one hour

4340 per AMS 6415S:
1525°F ±10°F for one hour

A total of four tests were performed utilizing all three materials. Each respective material was cut from the same bar, maintaining heat lot integrity. The baseline was established by a typical Jominy End Quench Test performed with water. For the next three tests, an air quench test stand was built (see Figure 2). All dimensions

Distance from End of Quench (in.)	Water	Gas 50mph	Gas 100mph	Gas 200mph
1/16	51	26	37	44
2/16	51	26	35	39
3/16	51	26	34	38
4/16	51	25	32	36
5/16	49	25	32	34
6/16	44	25	31	33
7/16	40	25	30	32
8/16	37	25	30	31
9/16	35	24	30	31
10/16	33	25	29	30
11/16	32	24	29	30
12/16	31	24	29	29
13/16	31	24	28	29
14/16	31	24	29	29
15/16	30	24	28	29
16/16	29	24	28	28
18/16	29	24	28	28
20/16	28	24	27	28
22/16	27	23	27	28
24/16	27	24	27	28
26/16	26	23	27	29
28/16	26	23	27	29
30/16	26	24	25	30
32/16	25	24	27	32
36/16	24	25	26	34
40/16	23	23	26	35

Table 1: HRC readings, 4130 jominy bars.

Distance from End of Quench (in.)	Water	Gas 50mph	Gas 100mph	Gas 200mph
1/16	59	39	56	59
2/16	59	39	55	58
3/16	59	39	55	58
4/16	59	39	53	57
5/16	59	39	53	57
6/16	59	38	51	57
7/16	58	38	50	57
8/16	58	38	49	57
9/16	57	37	48	57
10/16	57	37	46	57
11/16	56	36	43	57
12/16	56	36	42	56
13/16	55	36	43	56
14/16	54	36	42	56
15/16	54	36	40	55
16/16	52	36	40	54
18/16	51	36	39	51
20/16	49	35	39	51
22/16	48	36	37	48
24/16	45	36	37	47
26/16	45	35	37	45
28/16	43	36	36	43
30/16	43	36	36	41
32/16	42	35	36	41
36/16	41	35	35	41
40/16	41	35	35	41

Table 2: HRC readings, 4140 jominy bars.

for the test stand were identical to the standard Jominy stand, including matching the orifice size for the gas jet while maintaining the identical distance to the end of the test specimen.

GAS VELOCITIES

To better understand the gas velocities that needed to be examined, three vacuum furnaces were selected. All furnaces had identical internal hot zones measuring 36"w x 36"h x 48"d. All gas velocities were measured by an anemometer capable of measuring wind speed up to 300mph (see Figure 3). The internally quenched (IQ) vacuum furnaces represented three distinct vintage furnaces with varying fan designs, nozzle configurations, and hot zone designs. Furnace Number One, a 2-bar vacuum furnace manufactured in the 1990s, produced a gas velocity of approximately 50mph. Furnace Number Two, a 10-bar vacuum furnace manufactured circa 2000, measured gas speeds at approximately 100mph. Furnace Number Three, a brand new, state-of-the-art 20-bar vacuum furnace, measured gas velocities approaching 200mph. These same gas velocities, supplied by banks of 2500psi nitrogen cylinders, were then measured at the Air Quench Test Stand. The three alloys were then heated to their corresponding austenitizing temperatures and quenched at gas speeds of 50, 100, and 200 mph.

ADDITIONAL WORK

A special end-quench vacuum furnace was built by Solar Manufacturing in 2012 (see Figure 4). This vacuum furnace was equipped to heat the same sized Jominy bar within a fixture and immediately end quench with a stream of pressurized nitrogen. After multiple tests, we discovered that we could not successfully control the velocity of gas impinging upon the end of the test bar within the furnace. Additionally, the gas flow could not be maintained due to the restrictions of the gas inherent to the small chamber. We could not vent the chamber fast enough to achieve and maintain 200mph. Thus, the Jominy hardness results were not comparable.

CONCLUSIONS

The results of the "open air" Jominy end quench tests exemplify

Distance from End of Quench (in.)	Water	Gas 50mph	Gas 100mph	Gas 200mph
1/16	60	54	56	60
2/16	60	54	56	58
3/16	59	54	56	58
4/16	58	54	56	57
5/16	58	54	56	57
6/16	58	55	56	57
7/16	58	55	56	57
8/16	58	55	56	57
9/16	58	55	56	57
10/16	58	55	56	57
11/16	57	55	56	57
12/16	57	55	56	57
13/16	57	55	56	57
14/16	57	55	56	57
15/16	57	55	56	58
16/16	57	55	56	57
18/16	57	55	55	57
20/16	57	56	55	58
22/16	56	56	55	58
24/16	56	56	56	58
26/16	56	56	55	58
28/16	56	55	55	59
30/16	56	55	56	59
32/16	56	55	55	59
36/16	55	55	55	58
40/16	55	55	55	58

Table 3: HRC readings, 4340 jominy bars.

Figure 3: Test Anemometer .

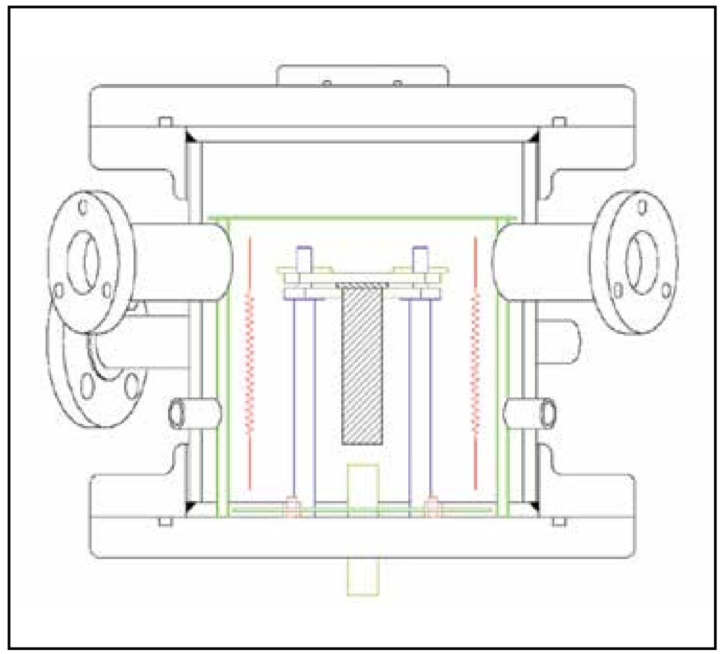


Figure 4: New solar jominy AIR End quench test chamber.

how 200mph-gas velocities are a necessity when quenching 4340 and 4140 materials. Less hardenable water-hardening alloys such as 4130 did not display the same end quench hardness when compared to the traditional Jominy Water Test.

Building a small-scale vacuum chamber to simulate the "open air" testing while adding pressure was unsuccessful. However, a large chamber, the newly designed Solar Super Quench 20-Bar vacuum furnace (see Figure 5), will be able to maintain 200mph-gas speeds internally at higher pressures.

Test loads will be quenched at full gas velocity (200mph) coupled with 20-bar pressure. The data collected will undoubtedly uncover revolutionary information for the metallurgical world. For the gear industry, traditional heat treatment distortion will be dramatically minimized with the utilization of high-pressure gas quenching.

Figure 5: Solar 20 Bar Vacuum Furnace.

ABOUT THE AUTHOR: Robert Hill, president of Solar Atmospheres of Western PA, has over 30 years of metallurgical experience involving a wide range of heat treating methodologies. During the past ten years, Bob has specialized in the development of large vacuum furnace technology and titanium processing capabilities for Solar Atmospheres. He has published numerous articles on vacuum technologies and vacuum heat treating applications. Bob has publicly presented these papers at several National ASM Heat Treating Conferences, SME events, and at various local chapters throughout the country. For more information about Solar Atmospheres, log on to www.solar-atm.com

Deep Cryogenic Treatment

By Rick Diekman

DCT is a very important process to the gear making industry. If done correctly, it can increase product durability and reduce tooling costs.

What is deep cryogenic treatment? Deep cryogenic treatment (DCT) of steels and other materials is a distinct process that uses the application of extreme cold applied with distinct time/temperature profiles to modify the performance of materials. This process is also referred to as cryogenic processing, cryogenic tempering, deep cryogenic treatment, deep cryogenic tempering, and deep cryogenic processing. What are cryogenic temperatures? The scientific community generally defines cryogenic temperatures as temperatures below -150°C (-238°F or 123°K). This is, admittedly, an artificial upper limit; temperatures used presently in cryogenic treatment are generally -185°C (-300°F or 89°K). DCT is often confused with cold treating, a process used on hardened steel to reduce retained austenite. DCT is differentiated from cold treatment by the use of cryogenic temperatures, having distinct time/temperature profiles, and by its applicability to materials other than steel.

Go to a metallurgical conference and start talking about cryogenic processing and you will get some very interesting conversations. Amid cries of "Snake oil!" and "Get the tar and feathers!" you will have some quiet voices telling you that they use DCT to vanquish their competitors. Indeed, during the writing of this paper, disparaging remarks about DCT were made on a conference call of metallurgists who were planning a metal treating conference. And this was the same group that was told

earlier that a webinar about DCT scored the biggest number of participants and the most questions in this organization's webinar history. So what is it about this process that creates such differing opinions? Are those that swear by the process alchemists, sorcerers, wizards, shamans, and enchanters? Are dark forces called into play to get the reported results? Are those who specify DCT delusional victims of placebo effects hoping to find some meager advantage that will show the world that they too can be smart? And what of those who disparage DCT? Are they intelligent scientists who know a con when they see it? How can reducing the temperature of a solid change it? Why does this process polarize the materials science community?

There are many reasons for the above behavior. Until recently, DCT was an empirically developed process. It is common wisdom that heat changes things, but cold frozen things are, well, frozen. Humans have been using heat to modify metals for over 7,000 years. We've only had cryogenic temperatures in useful quantities for a little over 100 years, so our cultural and scientific knowledge of cryogenic cold is limited. DCT has only been around since the late 1930s, where it was developed for use on aircraft engines in Germany, and independently in the United States for use on knives. There was generally a lack of research about the process; what research existed centered on the validity of the process's results. Even with the careful research of Dr. Randall Barron, the metallurgical community did not recognize the process.

Another reason for the problems was inflated claims of what could be done with DCT. Early practitioners advertised that treated engines would get 120 miles per gallon, that nobody had ever had a treated engine fail, and that the process increased the tensile strength of steel ten times. These claims did terrible damage to the process's reputation. A corollary to the inflated claim problem was that DCT actually does give results that seem inflated. A study of five metals by Dr. Barron showed that, while cold treating increased wear resistance by factors of 1.2 to 2.0, DCT increased wear resistance on the same metal/heat treat combination by factors ranging from 2.0 to 6.6 (Barron, 1984). Also, the use of DCT on metals other than heat-treated steel drew scorn even though research showed good results with most metals, cemented carbides, and some plastics (Kalia, 2010) (Stewart, 2004) (Yong, 2006). Brake rotors do show a two to seven times increase in life when tested in the laboratory even though their microstructure is pearlitic and they have no austenite. In real life use, they consistently last three times longer than untreated rotors even under racing conditions.

The assumption that DCT is the same as cold treatment has also skewed some of the research. Cold treatment involves inserting the component to be treated into the cold temperature. This has led researchers to immerse components to be DCT treated directly into liquid nitrogen. However, DCT involves lowering the temperature of the component slowly, holding it there for a period of time, and then warming it slowly to ambient temperature. One or more tempering cycles may follow.

Immersion has been shown to be mostly useless. It does not allow time for the changes in the crystal structure to occur and can cause severe stress in the part being treated. The timing is critical. Some research is being done to optimize the profiles for individual steels. For instance, some research indicates the holding time for AISI T42 steel should not be longer than eight hours (C. L. Gogte, 2010). In contrast, research indicates that the hold time should be 36 hours for AISI D2 (D. Das, 2009). The point is this: Like heat treating, the process must be done correctly for good results.

WHAT DOES DCT DO TO METALS?

There are several theories concerning reasons for the effects of cryogenic treatment. One theory involves the more nearly-complete transformation of retained austenite into martensite. This theory has been verified by x-ray diffraction measurements. Another theory is based on the strengthening of the material brought about by precipitation of submicroscopic carbides as a result of the cryogenic treatment (Collins, 1998) (Fanju Meng, 1994). Allied with this is the reduction in internal stresses in the martensite that happens when the submicroscopic carbide precipitation occurs. A reduction in micro cracking tendencies resulting from reduced internal stresses is also suggested as a reason for improved properties. Studies also show reduction in residual stresses.

Another area to consider is the basic effect of cold on the crystal structure of metals. Point defects in the crystal structure are temperature-dependent. Lowering the temperature of the crystal structure will cause the number of point defects in the crystal structure to change according to the equation:

$$N_d = N \exp(-E_d/kT)$$

N_d is the number of defects present, N is the total number of atomic sites, E_d is the activation energy needed to form the defect, k is the Boltzmann constant, and T is the absolute temperature. Reducing the temperature at a suitably slow rate drives the point defects out of the structure to the grain boundaries. In other words, the solubility of vacancies and other point defects in the matrix drops. Note that the rate of descent of the temperature needs to be suitably slow for this to happen.

Another theory is that there is a discreet distance between atoms in a crystal structure that is associated with the lowest energy state in the metallic bond. Crystals that have all the atoms at this exact distance are stronger and therefore more wear-resistant. By reducing the temperature slowly, we take the extra energy out of the atom-to-atom bond and, when gently warmed up, more of the atoms are at the ideal distance from each other.

It is likely that the results achieved with DCT are due to a combination of all of the above factors. More research is needed to determine how much each factor contributes. Knowing how much each factor contributes to the results of DCT would be of great help in optimizing it for any given situation. That being said, the results of DCT are so significant that using it can give huge competitive advantages.

WHAT DOES THIS MEAN TO GEAR MAKERS?

DCT is valuable to the gear industry in two major areas: product and tooling. A study conducted by the Illinois Institute of Technology Research Institute for the US Army Aviation and Missile Command concluded that DCT created 50% more pitting resistance life and 5% more load-carrying capacity on 9310 steel than cold treating. It also noted that DCT raised the tempering temperature of the metal (Swiglo, 2000).

Further studies conclude that the wear resistance of cold-treated EN353 is increased 85% over conventionally heat-treated steel; but DCT showed an increase of 372% (Bensely, 2005). Studies of the impact strength of the same material show that it is increased by DCT to a similar extent as with cold treatment (A. Prabhakaran, 2004). Of note in studies of EN353 is that the samples were subjected to DCT directly after quench with no snap temper. It would be interesting to see what a safety temper *after* quenching but *before* DCT would accomplish on the same steel.

Most work performed on gears until now has been done in the racing industry, where OEM gears and shafts are treated long after they were manufactured. Although racing is not a good means of scientific testing since every race is different, our customers consistently report about a three times life increase on treated transmissions. We've found that one must take the type of race into account, as drag racing imparts very sudden shock loads, whereas track racing creates more wear. Tempering temperatures must therefore be adjusted. Although this is not scientific, considering all variables are controlled, real-world experience shows that the reliable final result is one of major life increase. The ability to withstand the vagaries of actual use is a testament to the value of DCT. We treat transmission components for racing transmission manufacturers who use them in their standard products.

TOOLING

Perishable tooling is a major cost in manufacturing. DCT has been used for years on both HSS and carbide cutting tools. Many studies are available that show the value of DCT in making tool steels more wear-resistant and tough, resulting in reduced costs. One study on both M2 steel and H13 steel predicts a 50% decrease in tooling costs (Molinari, 2001). Industrial tests have shown tremendous increases in life. Like racing, the ability to control all parameters is limited, but again, the world outside the laboratory is the world we live in.

Carbide has been shown to undergo a phase change when DCT is applied, which makes it more wear-resistant. It was noted that if the tool is allowed to become hot while cutting, the phase would change back to "normal." This is a good indication as to why interrupted cuts with DCT-treated carbide tooling were always successful (Yong, 2006).

Grinding wheels also show particular increases in life. We are only now getting into laboratory tests as to why diamond wheels and CBN wheels show increases in life up to ten times. Grinding is an important field of study, in that the variables of grinding have to be very carefully controlled in order to avoid inducing tensile residual stresses into the part being ground. Increasing the wheel life without affecting the other parameters could lead to significant cost reductions along with maintaining the integrity of the part being ground.

EQUIPMENT

All cryogenic processing equipment is comprised of a thermally insulated container and some means of extracting the latent heat of the payload to reach the desired low temperature. In most cases the insulation is a solid material that contains small closed cells of trapped still air. The thermal conductivity of such insulation is essentially that of still, non-convecting air, assuming that the solid material that encloses the air pockets is of thin cross-section and low conductivity. Examples are polyurethane foam, aerogel, and expanded glass foam. Six inches of any of these will conduct approximately 15 BTU/hr.ft^2 across a temperature differential of 400°F, which exists between the interior of a refrigerator at –320°F and an ambient temperature of +80°F.

These solid insulating materials are relatively inexpensive and, in the case of foamed in place polyurethane, can readily fill irregularly-shaped cavities. They all suffer from one important drawback. Temperature cycling establishes a temperature gradient across the insulating slab, which results in differential contraction in the material. Repeated temperature cycles ultimately result in fatigue cracking of the insulation. Energy expenditure to sustain the temperature difference goes up, and temperature uniformity within the refrigerator may deteriorate.

The use of vacuum insulation in cryoprocessor design avoids these problems. A vacuum insulated container consists of two concentric shells, usually cylindrical, separated by a small distance relative to their diameters, which are joined around the perimeter of one end of the shells. The space between the shells contains reflective insulation and is evacuated to a pressure of about 10^{-6} torr. This essentially eliminates heat flow by conduction and convection because most of the conducting or convecting gas has been removed. Heat gain via infrared radiation is minimized by multiple reflective layers placed in the vacuum space. Heat flow across a vacuum insulated space, given a temperature difference across the walls of 400°F, is 0.008 BTU/hr.ft^2, a factor of 1900 better than solid insulation of 6" thickness (Jeffrey Levine, 2001). The principal mode of heat transmission into the interior of a vacuum insulated container is metallic conduction through the perimeter that joins the inner and outer shells.

In addition to providing a barrier to flow relative to solid insulation, the vacuum insulated vessel is immune to thermal cycling fatigue. Additionally, the vacuum insulated vessel can sustain elevated operating temperatures far in excess of that permissible with the use of polyurethane. This permits the post-refrigeration tempering of components in one device, eliminating the need for a separate tempering oven.

Heat extraction from the payload is affected by the phase change of a low boiling-point fluid. If mechanical refrigeration is used, a high-pressure fluid is allowed to expand and become a gas within an evaporator coil inside the insulated space. The evaporator coil is a heat exchanger, which absorbs heat from the payload via convection, natural or forced, within the chamber. This ensures the relatively slow cooling of the payload and avoids thermal shock resulting from a too rapid cooling. Rapid cooling can cause shrinkage of the outside of the cooled component while the relatively warm interior is not shrinking. Tensile stress induced this way can lead to cracking or the initiation of residual stress, especially at sharp edges. Reaching cryogenic temperatures by mechanical refrigeration for industrial size payloads requires multistage refrigeration. These are very expensive machines to build and maintain.

Fortunately, liquid nitrogen is abundant, readily available, and relatively inexpensive. It has a boiling point of -321° F, and a heat of vaporization of about 150 BTU/liter. It is produced in huge industrial gas production facilities and delivered to your facility where the expansion and phase change occurs free of the capital and maintenance expense demanded by in-house mechanical refrigerators.

Two other approaches have been tried and have presented difficulties:

1. A hybrid of mechanical refrigeration and LN_2 cooling
2. A controlled immersion of components into LN_2.

The hybrid approach uses mechanical refrigeration to do an initial cooling of the payload to some sub-atmospheric temperature that is well above the desired cryogenic range. At that point, a spray of LN_2 droplets is showered onto the payload to bring the temperature down to the desired point. Unless the mechanical refrigeration has a sufficient BTU removal rate, the payload will be substantially warmer than indicated by the thermocouple that monitors chamber temperature. This will cause the LN_2 spray to come on prematurely with the resultant rapid cooling of parts and the increased possibility of cracking.

The controlled immersion of components into LN_2 has been tried in two versions:

1. The payload is lowered slowly into a pool of LN_2.
2. A chamber is slowly flooded with LN_2 so that the liquid level rises to and eventually covers the payload.

Both suffer from a serious weakness arising from fundamental physics. First, the temperature gradient above a pool of LN_2 is very steep. Second, the rate of heat transport between a warm solid and a cold gas at -320°F is much slower than the rate between the same warm solid and a liquid at -320°F. Therefore, in either of the above methods, a slow decrease in the distance separating the part and the liquid does not ensure a slow cooling rate of the part. The steep temperature gradient above the liquid, and the sudden increase in the heat transfer rate when liquid contact is made, increases the risk of thermal shock. Thermal shock can negate the benefits of DCT.

CONCLUSIONS

DCT is a very important process to the gear making industry. If done correctly, it can increase product durability and reduce tooling costs. It has been proven in the laboratory and in the real world. It remains to be seen how much the processing parameters can be optimized for both performance and for cost. This is starting to be done with good effect.

ABOUT THE AUTHOR: Frederick J. (Rick) Diekman has over 30 years of experience in the field of wear resistance. He is President of Controlled Thermal Processing, Inc. and has over 20 years of experience with Deep Cryogenic Treatment. He is founder and co-chair of the ASM International Cryogenic Processing Sub Committee, has taught an ASM course on DCT. He works closely with the Cryogenic Society of America, and was instrumental in the CSA's establishment of its data base of research articles on DCT.

Heat Treat Process For Gears

By Nicholas Bugliarello, Biji George, Don Giessel, Dan McCurdy, Ron Perkins, Steve Richardson, and Craig Zimmerman

Different heat treating processes—as well as the materials being treated—impart particular qualities in your gears. Allow Bodycote to provide a deeper understanding of your options.

Heat treatment is a critical and complex element in the manufacturing of gears that greatly impacts how each will perform in transmitting power or carrying motion to other components in an assembly. Heat treatments optimize the performance and extend the life of gears in service by altering their chemical, metallurgical, and physical properties. These properties are determined by considering the gear's geometry, power transmission requirements, stresses at different points within a gear under load, load cycling rates, material type, mating part designs, and other operating conditions. Heat treatments improve physical properties such as surface hardness, which imparts wear resistance to prevent tooth and bearing surfaces from simply wearing out. Heat treatments also improve a gear's fatigue life by generating subsurface compressive stresses to prevent pitting and deformation from high contact stresses on gear teeth. These same compressive stresses prevent fatigue failures in gear roots from cyclic tooth bending. Physical properties such as surface hardness, core hardness, case depth, ductility, strength, wear resistance and compressive stress profiles can vary greatly depending on the type of heat treatment applied. For any given type of heat treatment the results can be tailored by modifying process parameters such as heating source, temperatures, cycle times, atmospheres, quench media, and tempering cycles to meet specific application requirements.

Besides selecting heat treatments that will produce a set of desired physical properties, manufacturing engineers want to minimize distortion of dimensions from treatment such that

final proper fit into a gearbox can be achieved. Many gears are machined into an oversized condition prior to heat treatment so that a planned amount of grind stock may be removed after the process in order to meet dimensional requirements. By selecting heat treatment processes where distortion is reduced, the amount of grind stock needed may be reduced to minimize machining on hardened surfaces after heat treatment and thereby reduce the overall costs of manufacturing. Removing too much of the outermost portion of a case hardened gear that distorted excessively will also negatively impact the fatigue properties and wear life performance. Some heat treatment processes are designed to treat the entire surface of a gear, while others are selective in nature. Induction hardening or selective heating may be employed to harden just the gear teeth only, which can be an effective method of reducing the distortion in a gear. Masking of journals and keyways may be employed in case hardening processes to keep them soft and allow for easier grind stock removal after heat treatment. Reduction of distortion by intelligent heat treatment process design allows manufacturing engineers to improve the performance and/or reduce the overall costs of manufacturing a gear.

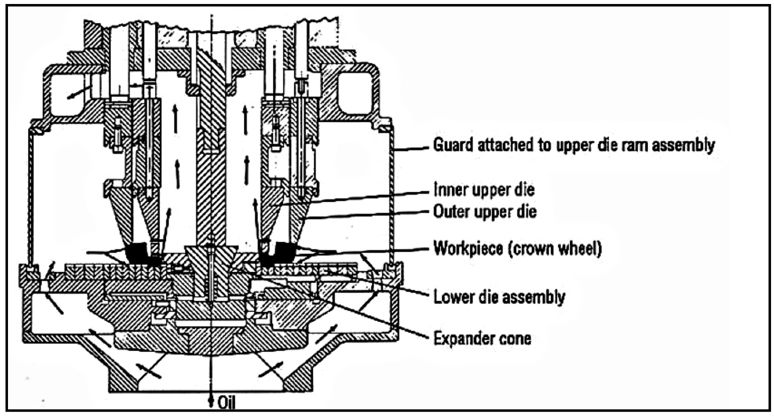


Fig. 1: Typical press quench equipment and tooling design (Source: The Heat Treat Doctor: Fundamentals of Press Quenching by Dan Herring, Industrial Heating April, 1995).

In all cases, gear design engineers understand that heat treatments play a complex and vital role in both the ease of manufacturing and the performance of the gears they make. Today, many options exist for the heat treatment of gears. Proper selection and design of the heat treatment process can greatly affect performance, ease of manufacture, and economics of a component. This paper will focus on a variety of different processes and highlight some benefits and disadvantages of each.

HEAT TREATING BASICS

To understand heat treating, a basic knowledge of metallurgy is needed. Iron, when combined with small percentages of carbon, forms steel. Plain carbon steels typically contain 1 percent or less carbon in combination with iron. The maximum hardness that any plain carbon steel can achieve during heat treatment is primarily a function of its carbon content. Higher carbon content steels are capable of being hardened to higher hardness values than lower carbon content steels. To make alloy steels, small percentages of other elements such as Cr, Ni, Mo, Si, B, V, Ti, Al, N, Nb, W, and Cu (to name the most common) are added to steel. These alloying elements are added in order to increase hardenability or enhance specific properties such as toughness or resistance to softening from heat build-up. For heat treaters the higher hardenability allows for slower quenching, which means distortion can be kept to lower levels in more highly alloyed steels. Steels can be annealed by thermally processing at a high temperature and slow cooling to soften it. In this soft and malleable state it can be machined, formed, hobbed, and ground easily into a desired shape. What makes steel industrially important is that it can be hardened after the material has been formed or shaped in the soft state to a desired geometry. By use of a thermal processing cycle where steel is

Fig. 2: Two fully automated low pressure carburizing furnace lines (Bodycote-Livonia, Michigan).

heated to austenitizing temperatures and rapidly quenched, the near-finished components can be hardened to improve wear resistance, strength, and hardness. After quenching to the maximum hardness achievable, which is determined by the steel's carbon content, the steel may then be tempered down to a lower hardness to improve ductility and toughness at the expense of slightly reducing the strength, hardness, and wear characteristics of the material.

What actually occurs in steel during heat treating are phase transformations as atoms rearrange themselves into different crystal structures. The starting point of most heat treated parts is an annealed material. In fact, when purchasing steel it is generally in the annealed condition. An annealed structure is a combination of primarily ferrite (Fe, pure iron) and iron carbide (Fe_3C, cementite). These will be in the form of alternating layers of ferrite and Fe_3C (pearlitic structure), or ferrite with dispersed Fe_3C spheres or spheroids (spherodized structure). When steel is heated above its austenitizing temperature, it transforms into the austenite structure. An approximate austenitizing temperature for most plain carbon steels is around 1330ºF and varies by exact grade of steel. Once full transformation of the steel to an austenite structure has occurred the austenite may be quenched (cooled rapidly), and that austentite structure will transform to a martensite structure. This transformation of

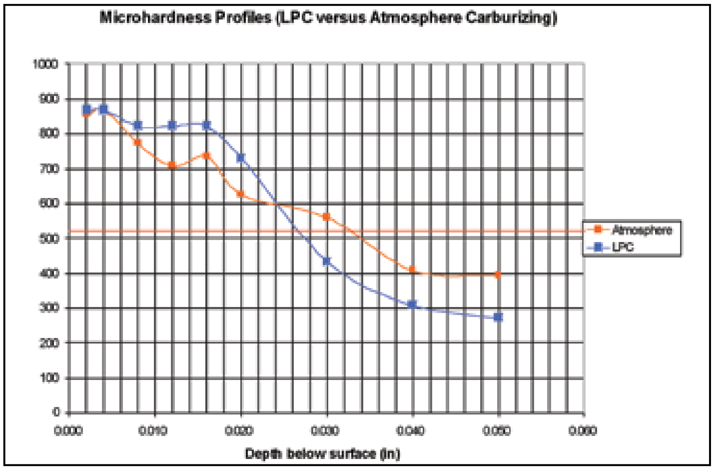


Fig. 3: Hardness and compressive stress profiles generated by LPC (compare to Fig. 4).

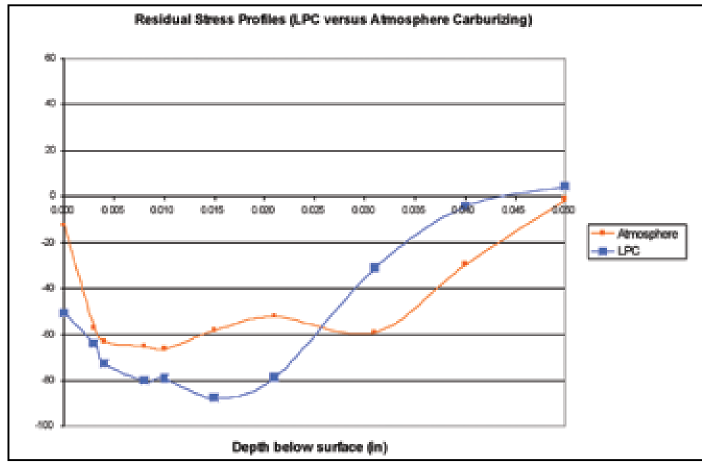


Fig. 4: Hardness and compressive stress profiles generated by atmosphere carburizing (compare to Fig. 3).

austenite to martensite is the hardening process. The martensite structure yields the highest hardness and tensile strength properties of any structure for that steel. Producing a martensitic structure from austenite is the goal in hardening heat treatment of steels. One critical aspect of this hardening process is the cooling rate employed during quenching. Each grade of steel requires that a certain minimum cooling rate be achieved during quenching or the transformation from austenite to martensite will not occur. Austenitized steels held at high temperature and quenched too slowly down to ambient temperature will not transform from austenite to a martensitic structure. They will instead revert back a softer mix of ferrite and cementite again.

Table 1 summarizes the methods in common use today for heat treatment of gears. Each method has its place; some are perfect for high volumes, while others are practical only on a piece-by-piece basis. Some improve all metallurgical properties, while others improve only one or two.

NEUTRAL HARDENING

There are two general classifications of heat treatments used for hardening steels: neutral hardening, and case hardening. Neutral hardening refers to maintaining the carbon potential of the atmosphere at the same percentage as the carbon in the steel during the hardening cycle. This means that carbon is entering and leaving the surface of the steel at the same rate, and no net gain or net loss of carbon atoms inside the surface of the steel occurs. Many gears are neutral hardened, but for the most demanding applications case hardening processes, such as carburizing and nitriding, are the preferred methods due to their improved wear characteristics and mechanical properties.

ATMOSPHERE CARBURIZING

Carburizing, the most widely used form of surface hardening, is the process of diffusing carbon into the surface of low carbon steel at elevated temperatures. This results in a high carbon case forming just inside the surface of a low carbon component. During quenching from austenitizing temperatures the austenite will transform to martensite, and the higher carbon case will have a high hardness while the lower carbon core material will have a lower hardness. The goal of this process is to produce a hard, strong, wear resistant outer surface while retaining a softer, ductile tough core.

When austenite transforms to martensite during quenching, a volume expansion occurs in the material and it grows. The volumetric expansion in the case is greater than the volume expansion in the lower carbon, lower hardness core structure. This difference in size changes puts the carburized surface of the part into a state of compression, which makes it stronger. For example, when a force is applied to a gear tooth, it first has to overcome these compressive forces before beginning to put the surface of the tooth in tension. In order to deform this material, it requires a force that exceeds the combination of overcoming the compressive stresses present in addition to the normal yield strength of the material. These compressive stresses caused by differences in volume expansion rates between the case and core improves the overall tensile and yield strength of the carburized case inside a gear tooth. It is these compressive stresses that resist deformation from high contact stresses present as gear teeth press and roll against each other. These compressive stresses also increase fatigue life by helping to prevent cracking in tooth roots as the teeth are cyclically loaded and unloaded with bending stresses. The high carbon, high hardness surface of the carburized case also resists wear and scoring caused by friction as gear teeth rub and wear against each other.

One can't discuss heat treating gears without discussing distortion, which occurs for a variety of reasons. One source is pre-existing residual stresses present in the material caused by prior operations such as steelmaking, rolling, forming, forging, casting, machining, and grinding. As the material begins to heat up during carburizing, these residual stresses present in the material relieve and cause the gears to distort if these stresses were large or non-uniform.

A second source of distortion is high temperature creep during processing. Gravity is the enemy of many gear designs during thermal processing, especially in carburising, where high temperatures and long processing times are the norm. At high temperatures, steel has little strength and can sag and bend under gravity's force if sections of a part are not properly supported or components not stood up or hung perfectly straight. Spending the extra time to fixture parts correctly and designing customized fixtures to properly support a gear during exposure to high temperatures can save many hours of straightening and machining afterwards. Some part shapes such as long shafts are best racked in vertical orientations to maintain straightness while other shapes such as rings are better if laid flat horizontally to maintain roundness. Selection and experience in designing heat treatment fixtures can dramatically affect the results.

A third source of distortion is quenching, which is typically the main offender in distorting parts during heat treatment. The ideal quench is the slowest quench that will uniformly pull heat out of the part, while still fully transforming the surface to martensite and achieving the desired case and core properties. This sounds easy enough, but in practice it can be quite difficult given the design and complex shape of many gears. Due to variations in customers' part geometries, limitations in fixture designs, non-uniform quench tank agitation, and part-to-part or part-to-fixture interactions, it is

	Relative Distortion	Load Carrying Capability	Wear Resistance	Fatigue Resistance	Quality Risk	Capital Cost	Relative Piece Cost
Heat Treatment Method	1=low, 5=high	1=high, 5=low	1=high, 5=low	1=high, 5=low	1=low, 5=high	1=low, 5=high	1=low, 5=high
Atmos Neutral Harden & Oil Q	4	4	5	4	1	2	3
Atmos Neutral Harden & Hot Oil or Salt Q	2	4	5	4	1	2	3
Atmos Neutral Harden & Press Q	2	4	5	4	2	3	5
Atmos Carburize & Direct Oil Q	3	2	2	2	3	3	4
Atmos Carburize & Direct Hot Oil or Salt Q	2	2	2	2	3	3	4
Atmos Carburize, Cool, Reheat, & Oil Q	3	2	2	2	3	3	4
Atmos Carburize, Cool, Reheat, & Hot Oil or Salt Q	2	2	2	2	3	3	4
Atmos Carburize, Cool, Reheat, & Press Q	2	2	2	2	4	4	5
Low Pressure Carburize & Direct Oil Q	2	1	2	1	2	5	5
Low Pressure Carburize & Direct Gas Q	1	2	2	1	2	5	5
Nitride	1	5	2	3	3	3	5
Ferritic Nitrocarburize	1	5	3	4	3	3	2
Ferritic Nitrocarburize & Oil Q	1	5	3	4	3	3	2
Carburize, Cool, & Induction Harden & Q	2	2	2	2	4	2	5
Induction harden (single shot low frequency) & Q	2	2	5	4	3	3	4
Induction harden (single shot mid frequency) & Q	2	3	5	3	3	3	4
Induction harden (single shot high frequency) & Q	1	4	5	3	3	3	4
Induction harden (single shot dual frequency) & Q	1	4	5	3	3	4	4
Induction harden (tooth by tooth) & Q	1	2	5	2	5	3	5
Flame harden (spin) & Q	5	4	5	4	5	1	1
Flame harden (tooth by tooth) & Q	1	5	5	5	5	1	4

Table 1: Common heat-treating methods for gears.

the most difficult distortion mechanism to resolve and predict. Even within a single part it's possible to have some thinner sections of a component cool faster than thicker sections causing one area to transform earlier than another and warp dimensions as the transformations with their associated volume expansions occur at different times during a quench.

When distortion occurs to an unacceptable degree, solutions need to be found. After exhausting all the variations of processing parameters, fixturing methods, quench modifications, and ensuring parts are free from stress prior to heat treatment, other options need to be considered. This can be as simple as a straightening step, or as difficult as re-engineering the part. Some other methods of heat treating may provide more effective solutions to reducing distortion as well. Processes such as press quenching, tooth to tooth induction hardening, vacuum carburizing with gas quenching, and nitriding are employed when excessive distortion results during conventional carburizing of specific gear geometries.

PRESS QUENCHING OF GEARS

The art of press quenching while being around for decades remains

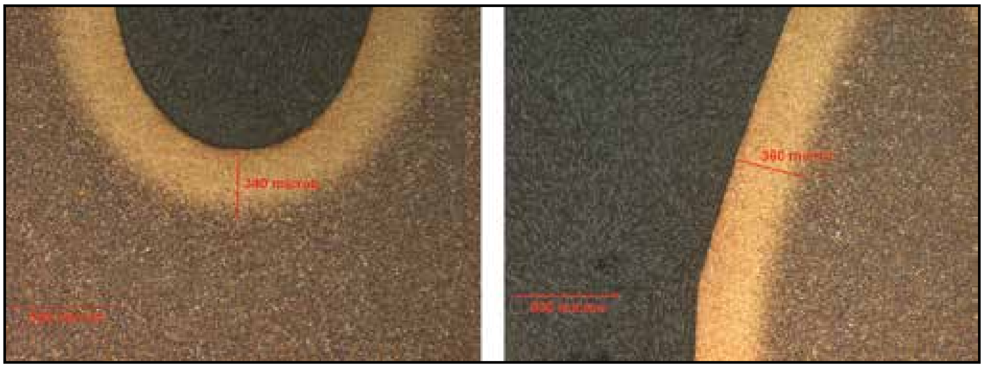


Fig. 5: LPC process: carburized case in gear root (left), carburized case in gear tooth (right).

Fig. 6: No presence of intergranular oxidation after LPC process.

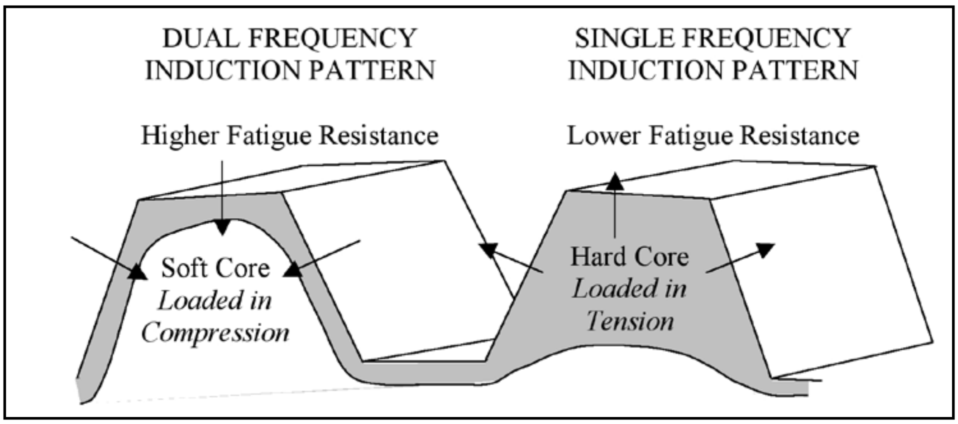


Fig. 7: Dual frequency induction patter (left), single frequency induction patter (right).

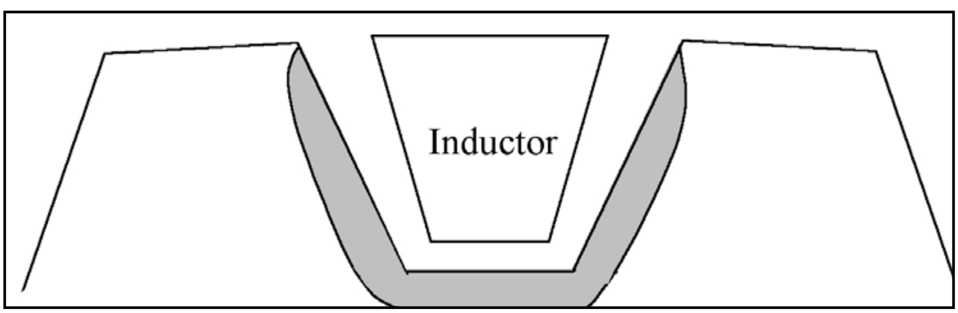


Fig. 8: Single-tooth hardening.

somewhat of a mystery to the engineering world, and even our own heat treating industry. In basic form, gears are carburized in large batches, slow cooled, reheated individually, and then quenched rapidly under some form of restraint to minimize distortion. The main dimensions that are restrained during press quenching are the flatness of the gear and the roundness of the bore in relation to the hub.

The quenching equipment utilized is referred to as a press. They are either pneumatic or hydraulic in design, depending on the individual piece of equipment. The press has a lower die assembly that floats in nature and becomes stationary during the quench process. The upper die uses a primary and secondary upper pressure system that has two levels of controls through an outer and inner cylinder assembly. Depending on the press being used the maximum die pressure is different.

When the gear is transferred to the press and placed on the die for quenching, it is restrained through the use of tooling designed specially for the gear being quenched. Oil flow becomes critical to the success of the pressing operation to minimize any distortion. The oil flow comes up from the oil reservoir through the chambers or holes within the lower die assembly, then circulating up and around the table to the oil flow rings based on the lower die table. The oil flow can be controlled through the manipulation of oil flow rings, which are located underneath the support rings. The oil flow can be restricted or wide open depending on the gear being quenched. This flow is regulated through timer controlled valves. The inner cylinder force is exerted against the rim of the gear to address flatness while the outer cylinder can be used to apply pressure to the face of the hub or to apply pressure to expand out an expander mandrel in the attempt to control the spline or bore sizing.

Whether a plug or an expander is used in a bore depends upon what is trying to be accomplished. An expander is employed when the heat treater is trying to expand the tooling out to meet an intended bore diameter prior to the actually quenching the part. The intent is to minimize any "out of round" conditions that may occur. Larger bore diameter gears with thin wall thicknesses are prime candidates for the use of an expander to prevent any out of round conditions. A plug is used for holding a bore dimension. The plug is ground to a size close to the intended bore diameter. The heat treater is trying to have the bore cool or shrink uniformly to a certain dimension. A finish grinding operation of the bore is usually performed after plug quenching.

The focus on gear press quenching should not be on the use of tooling. It has been taught that the best gear starts with the gear blank. Addressing the forging operation for the gear blank is important. In the forging operation, the direction of the grain pattern is critical such that the part will not have non-uniform residual stresses present. It is important that the blank also be normalized or annealed at temperatures that exceed the planned carburizing temperature by 50ºF. It is also important to ensure that the cycle time at temperature is held for a proper length of time. Insufficient time or temperature during normalizing or annealing will result in greater distortion being present during subsequent heat treatment steps. It is often recommended to perform a subcritical stress relieving operation after the rough machining of the gear blank to help minimize distortion in the final heat treating operation. While not considered absolutely necessary, it does help reduce distortion and improve the final quality of the part.

Another concern that comes up in gear hardening is the tapering of the bore diameter through the length of the bore. This arises due the sectional changes present in some gears along their axis. The use of an expander and using various pressures on the inner cylinder will result in minimizing tapering. Tapering cannot be eliminated in some gear designs, but it can be minimized.

When designing gears where press quenching is planned, it is recommended to have the heat treater involved from the design stage to understand how it will affect the final product. Press quenching is not the lowest-cost hardening process available, but it is a competitive process among today's gear hardening processes. In many cases press quenching is the only option, as distortion from conventional carburizing and quenching processes can be too excessive on some sensitive gear geometries.

LCP/HIGH PRESSURE GAS QUENCH

Low Pressure Carburizing (LPC) with high pressure gas quench is a relatively new carburizing technology that has become more widely used during the last decade. It has become the popular choice of carburizing treatment for automotive transmission gears over the last 10 years with General Motors, Ford, Chrysler, and many foreign automakers now adopting this process. Many fuel injectors are currently carburized using this technology. Some aerospace components are also being low pressure carburized, with rotorcraft transmission gearing being another early adopter of LPC.

LPC equipment comes in a variety of forms from different furnace manufacturers that all have different concepts and designs. In general, the equipment consists of vacuum chambers capable of heating parts to carburizing temperatures and capable of injecting small amounts of hydrocarbon gases at low pressure that act as a carbon source. In addition to the carburizing cells there are quenching cells where carburized hot loads may be cooled using high pressures of inert gases to rapidly cool the parts allowing hardening to occur by transforming austenite to martensite in the case and core structure. The gas quench cells are equipped with powerful fans and are capable of injecting gases typically up to 20 bar positive pressure in conjunction with heat-exchangers using chilled water to quickly remove heat from the quenching gases. The most common quenching media is high pressure nitrogen gas, and the more common carburizing gases are propane and acetylene. Many furnace manufacturers are using different gases, however, and blends of gases as carbon sources and quench gases.

High hardenability alloys are required for LPC and high pressure gas quench. Typical grades of materials used are 8620, 5120, 4118, 17CrNiMo6, 9310, 3310, 8822H, 4822, and 8630. Lower hardenability plain carbon steels that can be carburized and oil quenched simply cannot be hardened using a gas quench because they will not properly transform as cooling rates are too slow. Even with high hardenability grades some consideration must be given to core hardness, as the gas quench will produce lower core hardness compared to oil quenched parts.

A major advantage of LPC is that these same slow cooling rates during gas quenching translate into low distortion from quenching. Many parts that cannot be successfully oil quenched and maintain required dimensional tolerances are able to be LPC processed with a gas quench and yield acceptable dimensions. By eliminating the non-uniform cooling of parts associated with liquid quenches that have vapor, boiling, and convective cooling all taking place simultaneously and replacing it with gas quenches that have slower cooling rates and are more uniform and purely convective, distortion can be greatly reduced as gear surfaces are more uniformly cooled at slower rates. LPC with gas quenching can sometimes eliminate post-heat treatment straightening or clamp tempering operations, reduce grind stock allowances and hard machining, or replace more costly processes such as press quenching of individual gears.

A second advantage of LPC is cleanliness of the parts after processing. The finished parts emerge from the furnace very clean. At times it is almost difficult to identify the heat-treated and non heat-treated parts. For this reason the heat-treated parts are slightly discolored, using the discoloration process to identify the heat-treated parts. In comparison, conventional carburizing uses oil quenching where the oil will burn onto the surfaces and finished parts are often dark, sooty, and have oil residue left on the surfaces.

Another advantage of the LPC process is that it has the capability to utilize a higher carbon potential atmosphere during the boost thus obtaining higher hardness values deeper into the case in comparison to the conventional carburizing. This higher hardness deeper into the surface before transitioning to the core imparts greater compressive stresses to the surface case material and improves the fatigue properties and resistance to deformation by high single point rolling contact stresses on gear teeth.

Another advantage of LPC processing over conventional carburizing is the depth of case attainable in gear tooth roots. The pitch to root ratio of the effective case depth after LPC is remarkably uniform. Oftentimes in conventional carburizing of gears, the case depth in the roots of teeth may only amount to half the case depth present at the mid-pitch tooth location. With LPC processing, the effective case depth present in the gear roots is nearly equivalent to the case depth present at the gear tooth midpitch location. This deeper case depth present in the gear tooth roots enhances fatigue life under tooth bending conditions and will outperform conventional carburized parts in this aspect.

Another advantage of LPC is the absence of any inter-granular oxidation (IGO) on the surface of the part. This saves the gear manufacturer from grinding off the case to remove the IGO and saves valuable time and manufacturing costs. Typically .0003" to .0007" deep IGO will be present on any gears carburized in conventional endothermic atmosphere furnaces.

The LPC process produces excellent metallurgical and dimensional results which are required for high performance transmission gears. There are many types of gears and products well-suited for the LPC process and the advantages of this process have been outlined above. The main disadvantages of this process are that LPC equipment is capital intensive and the consumables are expensive. Process engineering, operation, and maintenance require higher skill levels than traditional carburizing. There is also a limitation of load sizes that can be processed as the gas quenching requires that lighter loads be processed in order to cool them rapidly enough.

GAS NITRIDING

The gas nitriding process for case hardening of alloy steels allows complex configurations to be treated with minimal distortion. This process is performed at low subcritical temperatures and completely avoids the problems of structural transformations associated with high temperature austenitizing and quenching of steel during carburizing. Earlier in this article we detailed the three causes for distortion in carburizing which included stress relieving of pre-existing residual stresses, high temperature creep distortion, and phase transformations upon quenching. Since there are no phase transformations at low nitriding temperatures, there is no distortion from phase changes. There is little concern for distortion due to high temperature creep at the low subcritical nitriding temperatures. That leaves only stress relief of residual stresses as a possible cause of distortion during nitriding. In order to eliminate this source of distortion a typical manufacturing sequence for nitrided gears would be to rough machine, stress relieve at 50 ºF above the nitriding temperature, final machine putting as little stress into the parts as possible, and then nitride. Nitriding is often performed on finish-machined components with little distortion and usually requires no post-heat treatment machining to clean up the tolerances. The nitriding process basically consists of placing steel surfaces at nitriding temperatures in contact with ammonia gas (NH3). The ammonia dissociates at the steel surface providing atomic nitrogen which can then diffuse into the gear, react with specific alloying elements in the steel, and form alloy nitrides which creates a hardened wear resistant case below the gear's surface.

There are many benefits of the gas nitriding process. Its purpose is to produce a very hard, wear resistant, load bearing case in relatively inexpensive alloy steels. The low treatment temperatures keep distortion and growth to a minimum and it is typically performed on finish-machined parts. This process is very simple to run and has fewer variables to control than the other case hardening processes discussed earlier. The lack of quenching which is a major source of variation in carburizing results is not present in nitriding and allows for better control and greater repeatability. The nitrided case also is not softened or tempered like carburized gears, which start to lose hardness at temperatures as low as 300ºF. Nitrided cases will not soften until exposed to temperatures above 1000ºF and can withstand high service temperatures. Isolated surfaces can be masked from nitriding and left soft for ease of machining, welding, or other purposes. The corrosion resistance of some low alloy steels is also slightly improved by nitriding.

Some limitations of gas nitriding include only being able to achieve shallow case depths (0.030" max for some materials) due to the low diffusion temperatures. The nitriding alloy selections are limited to materials that contain Cr, Mo, V, Ti, W, and Al alone or in combination. There are occasional problems with spalling of the case if nitriding networks form, but this can be minimized with proper controls. Nitrided stainless steels lose much of their corrosion resistance by nitriding as chromium becomes bonded to nitrogen, which breaks down the protective chromium oxide layer normally present on stainless surfaces. The gas nitriding process is a readily available heat treatment process that creates an extremely hard, load bearing wear resistant surface with depths ranging from .005" to .025" depth. It can be performed on many commonly available alloy steels with minimal size change and high retention of core mechanical properties.

INDUCTION HARDENING GEAR TEETH

Induction heat treating is localized heat treatment used to increase the fatigue life, strength, and wear resistance of a component. Induction hardening is accomplished by placing the part inside an alternating magnetic field causing an electrical current to form at the surface. Heat is generated as a result of the I2R losses in the material and allows heat treaters to selectively austenitize only the surface material of a component while leaving the core material untransformed. Not only is the surface only selectively heated, but induction allows only those desired surfaces to be heated while other surfaces may be left cold. In the case of gears it is possible to only austenitize the near surface of a single tooth leaving the balance of the part cold during processing. The heated gear surface is subsequently quenched in either water, oil, or a polymer based quench to transform the austenite into martensite thereby increasing hardness in the required area while leaving the remainder of the component virtually undisturbed.

Gear Hardening: There are numerous factors that determine the appropriate induction hardening process to choose. Items such as geometry, permeability of the material, and desired mechanical properties will dictate processing variables such as frequency, power density, and heat time.

There are many frequency selections to choose from when hardening gears. The relationship between frequency and current penetration depth are inversely proportional. Such that lower frequencies cause the current to form at deeper depths while higher frequencies generate heat immediately adjacent to the surface. Tooth form is a significant factor when selecting the correct frequency, as high frequencies will heat the tooth tips first and low frequencies will heat the roots first.

Power density and heat time are crucial to achieving the desired mechanical properties with the least amount of dimensional movement and associated risk of cracking. When calculating power densities a target value of 12 KW/in2 should be used to minimize total heat penetration into the component core. Heat time should always be optimized to achieve full transformation to austenite at the desired hardening depth.

Profile Induction Hardening: Profile induction hardening produces a tough core with associated tensile stresses and a hardened surface layer that exhibits compressive stress in the tips, flanks, and roots. Extensive product validation testing has determined that this combination of stresses best extend the component's fatigue life and wear resistance over other types of induction hardening while also producing the least amount of dimensional movement.

The most common method of obtaining a profile hardening pattern is to use a "blend" of frequencies to actually heat the tips, flanks, and roots concurrently. This is accomplished by simultaneously generating high and low frequencies and passing them through the inductor at the same time. This type of power supply is relatively new to the market and is referred to as a "simultaneous dual frequency" generator. Most of these units allow the technician to individually adjust the intensity of the various frequencies seen by the part. This provides them the flexibility to customize or sculpt the shape of the pattern to the specific geometry of the tooth.

Single Tooth Hardening: Single tooth hardening is primarily used to induction heat treat gear teeth to improve strength and wear characteristics. The process is accomplished by hardening one tooth root at a time. After each root has been hardened the system indexes the part to the next position and the process begins again. This process is time consuming as a 55 tooth gear will take 55 hardening cycles to complete. However, it is primarily used to harden very large, low volume parts that could not be done using conventional equipment due to the massive power requirements associated with heating the entire part at the same time or very large diameter gears that will not fit inside any existing carburizing furnaces.

To harden a tooth root the coil rests in between to adjacent teeth. This configuration hardens the tooth root and the flank of each adjacent tooth as shown in fig. 8. This method of hardening provides strength and wear resistance on the contact areas of the gear while minimizing dimensional movement by leaving the tooth tips unhardened.

CONCLUSION

A variety of heat treatment techniques exist for case hardening gears. Heat treatment processes can be tailored to maximize the life and optimize the performance of a gear in its service application by tailoring the heat treatment to produce specific desired properties. Distortion is always a factor in heat treatment processes, but it can be controlled and minimized by selecting specific processing parameters, being knowledgeable about fixturing, using different types of case hardening processes, and taking extra steps to ensure the gears have minimal stresses present in them prior to heat treatment that could be relieved. No one heat treat process is superior to the other, but ultimately they all compliment each other. Having an understanding of the processes available will help you choose which process is appropriate for your gear.

ABOUT THE AUTHORS: Nicholas Bugliarello, Biji George, Don Giessel, Dan McCurdy, and Ron Perkins are with Bodycote. Steve Richardson and Craig Zimmerman were formerly with Bodycote. To learn more, visit www.bodycote.com.

Applied Process, Inc. Hosts First AP University

More than 30 designers and engineers went "back to college" to learn how austempered ductile iron (ADI) could work in their manufacturing operations. The first ever AP University, hosted by Applied Process, Inc. was held in January at Eastern Michigan University on the Livonia Campus and Joyworks Studio in Ann Arbor, MI. The program was so successful that plans are in the works for another session. The three-day event was created to educate those who design engineered components on how to best utilize the opportunities provided by ductile iron and ADI. Curriculum covered a range of topics and was taught by industry professionals.

Classes covered the following subject:

- The casting process,
- castability studies,
- casting issues and resolutions,
- successful weldment-to-casting conversions,
- an introduction to ADI,
-austempering 101,
- ADI applications in gearing, and
- applications of casting conversions.

Attendees toured the Applied Process plant and visited Joyworks, a metalworking studio focused on research and education owned by John R. Keough, chairman of Applied Process.

"We are passionate about our products and processes," explained Vasko Popovski, director of sales and marketing for Applied Process. "In this economy, companies are facing the problem of cutting costs while still providing a quality product. We believe casting and ADI are the solution, and brought industry leaders together to show them the added value—not only for them, but for their customers as well."

Companies that choose to create products through castings can often cut down on production time and cost while offering their customers a product designed specifically for their needs. These products are often stronger than those modified through welding.

"The event was much more than we expected," explained Tim Covert, senior material engineer at Ford Motor Company. "We deal with ADI, but I was new to casting design. I was impressed, not only by the process, but by the knowledge and professionalism shown by the Applied Process staff."

Austempering is an isothermal heat treatment that produces a structure that is stronger than those created by conventional heat treatments. Austempered ductile iron (ADI) is a specialty heat-treated material that creates a lighter, stronger, quieter, and more wear-resistant part.

Bill Maenle, engineer and product designer at Unverferth Mfg., has dealt with ADI in the past. "Moving from welding to casting has allowed us more flexibility, which means we can best cater to the needs of specific soil conditions. In my experience, ADI provides a better product with more reliability."

Maenle was one of many in attendance whose company had previous experience and current applications in ADI. Other companies that were new to casting conversions sent representatives to gain a general knowledge. Many attendees who were new to ductile iron—specifically ADI—left AP University with a knowledge base that will allow them to convert and improve current and future projects.

"I am a chemist by degree and knew little about heat treatments and metals three days ago," admitted Michael Schmidt, business manager at Pennsy. "As we move into metals, I am confident we will find applications for ADI."

Due to high demand, Applied Process already has plans to hold its second AP University. Visit www.appliedprocess.com for information about attending the next AP University.

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Presenting the eldec MIND-M

The eldec MIND-M is the compact, "smaller sibling" of the full-featured MIND hardening machine series from eldec; it is a complete, integrated system for your induction hardening application, eldec MIND-M Flexible Integrated System, or any other induction heat treating of small parts. The energy source with active coolant and quench system (if needed) is integrated into the machine base. The MIND-M can be transported "as is," featuring the smallest footprint of any complete system up to 30kW, medium or high frequency (MF or HF). The spacious working area allows for different modules and work holding devices to be freely positioned. This creates flexibility for different parts and applications. It is effective for low, medium, and high volume production for hardening, tempering, brazing, fitting, or melting in the smallest possible space.

As a globally active company, eldec develops, produces, and sells highly-efficient inductive heating technology for a wide variety of industrial applications. Eldec develops complete system solutions with select technologies. The centerpieces and key areas of expertise are the MF, HF, and SDF® generators and inductors specially customized to the tasks at hand. For more information, visit www.eldec-usa.com.

Heat Treat Equipment – REF #101

Phone: 734-331-3939 • Fax: 734-331-3915
Email: john@heattreatequip.com
Website: www.heattreatequip.com

Summit Products, Inc. – REF #102

65 Greenside Drive, Grand Island, NY 14072
Phone: 716-867-4312 • Fax: 716-867-4312
Email: summit@roadrunner.com

The W.H. Kay Company – REF #103

30925 Aurora Road, Cleveland, OH 44139
Phone: 440-519-3800 • Fax: 440-519-1455
Email: sales@whkay.com
Website: www.whkay.com

Furnaces, Ovens & Baths, Inc. – REF #104

4790 White Lake Road Clarkston, MI 48346
Phone: 248-625-7400 • Fax: 248-625-4030
Email: sales@fobinc.com
Website: www.fobinc.com

BATCH OVENS & BOX TEMPERING FURNACES

8" 18" 8" Lucifer Elec. 1250 F. **REF #103**
12" 16" 18" Lindberg Elec. 1200 F. **REF #103**
12" 16" 18" Lindberg (3) Elec. 1250 F. **REF #103**
12" 18" 12" Lucifer Elec 1250 F. **REF #103**
14" 14" 14" Gruenberg -Solvent Elec. 450 F. **REF #103**
15" 24" 12" Sunbeam (N2) Elec. 1200 F. **REF #103**
19" 19" 19" Prec.Scientific Elec. 617 F. **REF #103**
20" 18" 20" Blue-M (2) Elec. 400 F. **REF #103**
20" 18" 20" Blue-M (2) Elec. 400 F. **REF #103**
20" 18" 20" Blue-M (Inert) Elec. 600 F. **REF #103**
20" 18" 20" Despatch (Solvent) - 2 Avail Elec. 650 F. **REF #103**
20" 18" 20" Blue-M Elec. 800 F. **REF #103**
20" 18" 20" Blue-M Elec. 1200 F. **REF #103**
20" 20" 20" Grieve Elec. 500 F. **REF #103**
20" 20" 20" Michigan/Grieve Elec. 1000 F. **REF #103**
20" 20" 20" Grieve Elec. 1250 F **REF #103**
24" 24" 36" New England Elec. 800 F. **REF #103**
24" 26" 24" Grieve Gas 500 F. **REF #103**
24" 36" 24" Demtec (N2) Elec. 500 F. **REF #103**
24" 36" 24" Grieve Elec. 850 F. **REF #103**
24" 36" 24" Paulo Gas 1250 F. **REF #103**
25" 20" 20" Blue-M Elec. 650 F. **REF #103**
25" 20" 20" Blue-M Elec. 650 F. **REF #103**
25" 20" 20" Blue-M - Inert Elec. 1100 F. **REF #103**
25" 20" 25" Gruenberg Elec. 500 F. **REF #103**
26" 26" 38" Grieve (2) Elec. 850 F. **REF #103**
28" 24" 18" Grieve Elec. 350 F. **REF #103**
28" 48" 28" Wisconsin (3) Elec. 800 F. **REF #103**
30" 30" 30" Hevi-Duty Elec. 1500 F. **REF #103**
30" 38" 48" Gruenberg (2) M21 Elec. 450 F. **REF #103**
30" 48" 22" Dow Elec. 1250 F. **REF #103**
34" 19" 33" Poll.Ctrls Burnoff Gas 900 F. **REF #103**
36" 36" 35" Despatch Elec. 400 F. **REF #103**
36" 36" 120" Steelman Elec. 450 F. **REF #103**
36" 48" 36" Grieve Elec. 350 F. **REF #103**
36" 60" 36" CEC (2) Elec. 650 F. **REF #103**
37" 19" 25" Despatch Elec. 500 F. **REF #103**
37" 25" 37" Despatch Elec. 850 F. **REF #103**
37" 25" 50" Despatch Elec. 500 F. **REF #103**
38" 20" 24" Blue-M Elec. 1200 F. **REF #103**
38" 26" 38" Grieve Elec. 1000 F. **REF #103**
48" 24" 48" Blue-M Elec. 600 F. **REF #103**
48" 30" 42" Despatch Gas 850 F. **REF #103**
48" 48" 48" CEC (N2) Elec. 1000 F. **REF #103**
48" 48" 60" Gasmac Burnoff (2) Gas 850 F. **REF #103**
48" 48" 72" Despatch (2) Elec. 500 F. **REF #103**
48" 48" 72" Lydon Elec. 500 F. **REF #103**
54" 68" 66" Despatch Elec. 500 F. **REF #103**
54" 108" 72" Despatch Elec. 500 F. **REF #103**
56" 30" 60" Gruenberg Elec. 450 F. **REF #103**
60" 60" 72" ACE Burnoff Gas 850 F. **REF #103**
72" 72" 72" Michigan Gas 500 F. **REF #103**
120" 168" 120" Wisconsin Oven Gas 500 F. **REF #103**

BOX FURNACES

J.L. Becker Slot Forge Furnace, 1986, Brand New, Never Used **REF #101**
L & L Special Furnace Electrically Heated Box Furnace, 1991 **REF #101**
J.L. Becker Box Temper Furnace, 1989 **REF #101**
Sunbeam Electric Box Furnace, good running condition **REF #101**
Surface 30-48-30 Electric Temper Furnace, good/ very good condition **REF #101**
Atmosphere Furnace Co. 36-48-30 Electric Temper Furnace, good/ very good condition **REF #101**
Atmosphere Furnace Co. 36-48-30 Electric Temper Furnace, good/ very good condition **REF #101**
Atmosphere Furnace Co. 36-48-30 Electric Temper Furnace, good/ very good condition **REF #101**
Surface Combustion 30-48-30 Gas Fired Temper Furnace, good/ very good condition **REF #101**
Surface 30-48-30 Gas Fired Temper Furnace, good/ very good condition **REF #101**
8" 18" 8" Blue-M Elec. 2000 F. **REF #103**
12" 24" 8" Lucifer-Up/Down (Retort) Elec. 2150/1400 F. **REF #103**
12" 24" 8" C.I. Hayes (Atmos) Elec. 1800 F. **REF #103**
12" 24" 12" Hevi-Duty (2) Elec. 1950 F. **REF #103**
12" 24" 12" Lucifer-Up/Down Elec. 2400/1400 F. **REF #103**
3" 24" 12" Electra-Up/Down Elec. 2000/1200 F. **REF #103**
15" 30" 12" Lindberg (Atmos) - Retort Elec. 2000 F. **REF #103**
17" 14.5" 12" L & L (New) Elec. 2350 F. **REF #103**
22" 36" 17.5" Lindberg (Atmos) Elec. 2050 F. **REF #103**
24" 36" 18" Thermnlyne (2) - Unused Elec. 1800 F. **REF #103**
36" 48" 24" Sunbeam (N2) Elec. 1950 F. **REF #103**
36" 72" 42" Eisenmann Kiln (Car) Gas 3100 F. **REF #103**
60" 48" 48" Recco (1998) Gas 2000 F. **REF #103**
60" 96" 60" Park Thermal Elec. 1850/2200 F. **REF #103**
126" 420" 72" Drever "Lift Off"-Atmos (2 Avail) Gas 1450 F. **REF #103**
Lindberg, 20"W x 18"H x 24"L, Recirculating Box Furnace, 1250°F, Electric **REF #104**
Despatch, 20"W x 18"H x 36"L, Recirculating Box Furnace, 1350°F, Electric **REF #104**
Electra, 8"W x 6"H x 30"L, High Temperature Box Furnace, 3000°F, Electric **REF #104**
Sunbeam, 24"W x 18"H x 36"L, Atmosphere Box Furnace, 1950°F, Electric **REF #104**
CM Furnace, 15"W x 12"H x 18"L, Atmosphere (H2) Box Furnace, 2100°F, Electric **REF #104**
Sunbeam, 48"W x 48"H x 54"L High Heat/48'W x 48"H x 54"L Low Heat, Titanium Quench Line, 2200°F/1200°F, Electric **REF #104**
Lindberg, 12"W x 10"H x 24"L, Atmosphere Box Furnace, 2000°F, Electric **REF #104**
Lindberg, 15"W x 12"H x 30"L, High Temp Box Furnace, 2500°F, Electric **REF #104**
Lindberg, 15"W x 12"H x 30"L, High Temp Box Furnace, 2500°F, Electric **REF #104**
Accutherm, 18"W x 18"H x 36"L, Box Furnace, 2000°F, Electric **REF #104**
Sunbeam, 24"W x 18"H x 42"L, Atmosphere Box Furnace, 1950°F, Electric **REF #104**
K.H. Huppert, 8"W x 10"H x 12"L, Atmosphere High Temp Box Furnace, 1649°C/3000°F, Electric **REF #104**
Harper, 9"W x 9"H x 20"L, High Temp Box Furnace, 3000°F, Electric **REF #104**
McEnglevan/MIFCO, 18"W x 18"H x 24"L, Recirculating Box Furnace, 1200°F, Gas - Radiant Tube **REF #104**
Johnson, 9-1/2"W x 7"H x 16"L, High Temp Box Furnace, 2300°F, Gas - 180,000 BTU's Natural Gas **REF #104**
Grieve, 12"W x 8"H x 24"L, Atmosphere Box Furnace, 2000°F, Electric **REF #104**
Lindberg, 15"W x 12"H x 30"L, Atmosphere Box Furnace, 2000°F, Electric **REF #104**
Trent, 18"W x 18"H x 24"L, Recirculating Box Furnace, 1750°F, Electric **REF #104**
Wisconsin Oven, 36"W x 36"H x 72"L, Recirculating Box Furnace, 1250°F, Electric **REF #104**

CAR BOTTOM FURNACES

Holcroft 48-144-48 Car Bottom Furnace **REF #101**
Sauder 48-144-48 Car Bottom Furnace **REF #101**
72x84x108 CIM 1000F Gas **REF #104**
48x84x84 KMI 1000F Gas **REF #104**

CHARGE CARS

Surface Combustion 30-48 Charge Car (Double Ended), fairly good condition **REF #101**
Atmosphere Furnace Company 36-48 Charge Car (Double Ended) **REF #101**
Surface Combustion 30-48 Charge Car (Double Ended) **REF #101**

CONTINUOUS ANNEALING FURNACES

Wellman Continuous Mesh Belt Annealing Furnace **REF #101**
Aichelin-Stahl Continuous Roller Hearth Furnace & Conveying System, 1996 **REF #101**
Park Thermal Continuous Mesh Belt Furnace, 2005, Excellent Condition – New – Never been used **REF #101**

CONTINUOUS HQT FURNACES

Tokyo Gasden Ro Continuous Mesh Belt HQWT Furnace Line, 1989 **REF #101**

CONTINUOUS TEMPERING FURNACES

Surface Combustion Mesh Belt Temper Furnace **REF #101**
J.L. Becker Conveyor-Type Temper Furnace with Ambient Air Cool Continuous Belt, 1997 IQ Furnaces **REF #101**
Surface Combustion 30-48-30 Pro-Electric IQ Furnace **REF #101**
AFC 36-48-30 IQ Furnace with Top Cool **REF #101**
AFC 36-48-30 IQ Furnace **REF #101**
Surface Combustion 30-48-30 IQ with Top Cool, Excellent Condition, 2000 **REF #101**
Surface Combustion 30-48-30 IQ Furnace, Excellent Condition **REF #101**

ENDOTHERMIC GAS GENERATORS

Lindberg 1500 CFH Endothermic Gas Generator, 1992, good condition **REF #101**
Lindberg 1500 CFH Endothermic Gas Generator, 1996, excellent condition **REF #101**
Surface Combustion 5600 CFH Endo. Gas Generator **REF #101**

Surface Combustion 5600 CFH Endo. Gas Generator **REF #101**
Surface Combustion 5600 CFH Endo. Gas Generator **REF #101**
Surface Combustion 5600 CFH Endo. Gas Generator **REF #101**

EXOTHERMIC GAS GENERATORS

J.L. Becker 12,000 CFH Exothermic Gas Generator w/ Dryer, w **REF #101**
Thermal Transfer 30,000 CFH Exothermic Gas Generator, 1994, excellent condition **REF #101**

FREEZERS

Webber 36-48-36 Chamber Freezer, 1980 **REF #101**
Cincinnati Sub Zero 36-48-36 Chamber Freezer, 1995 **REF #101**

MESH BELT BRAZING FURNACES

Lindberg Continuous Mesh Belt Brazing Furnace **REF #101**
J.L. Becker 26" Mesh Belt Brazing Annealing Furnace, 2007 **REF #101**
10" J.L. Becker Mesh Belt Furnace with Muffle, 1988 **REF #101**
24" J.L. Becker Mesh Belt Furnace **REF #101**

MISC. EQUIPMENT

Atmosphere Furnace Co. 36-48 Stationary Holding Stations, 1987, 36"W x 48"L work area **REF #101**
Atmosphere Furnace Co. 36-48 Stationary Holding Stations, 1987, 36"W x 48"L work area **REF #101**
Atmosphere Furnace Co. 36-48 Stationary Holding Stations, 1987, 36"W x 48"L work area **REF #101**
Atmosphere Furnace Co. 36-48 Scissors Lift Holding Stations, 1987, 36"W x 48"L work area **REF #101**
Atmosphere Furnace Co. 36-48 Scissors Lift Holding Stations, 1987, 36"W x 48"L work area **REF #101**
Surface Combustion 30-96 Stationary Load Tables, 96-inch rail length, 15-inch rail centers **REF #101**
Surface Combustion 30-96 Stationary Load Tables, 96-inch rail length, 15-inch rail centers **REF #101**
Surface Combustion 30-96 Stationary Load Tables, 96-inch rail length, 15-inch rail centers **REF #101**
Surface Combustion 30-48 Scissors Lift Table, 48-inch rail length **REF #101**
8xxx 2.400 CFH 12 oz (2) North American 1/3HP **REF #103**
8xxx 3.000 CFH 12 oz (3) North American 1/2HP **REF #103**
8xxx 5.400 CFH 4 oz North American 1/3HP **REF #103**
8236 12.000 CFH 12oz (3) North American 1/2HP **REF #103**
8712 15.600 CFH 37 oz, North American 5HP **REF #103**
8193 19.500 CFH 32 oz, Spencer 5HP **REF #103**
8245 23.400 CFH 8 oz. North American 1,5HP **REF #103**
8185 24.000 CFH 24 oz. Buffalo Forge 7.5HP **REF #103**
8251 45.600 CFH 16 oz. Spencer 5HP **REF #103**
8252 66.000 CFH 24 oz . Snencer(New) 10HP **REF #103**
8253 66.000 CFH 24 oz. Spencer 10HP **REF #103**
8250 150.000 CFH 16 oz. Hauck 15HP **REF #103**

PARTS WASHERS

J.L.Becker Gas-Fired Tub Washer **REF #101**
48-72-48 Gas Fired Spray Washer **REF #101**
Dow Furnace Co. 30-48-30 Electrically Heated Spray, Dunk & Agitate Washer **REF #101**
Atmosphere Furnace Co. 36-48-30 Spray/Dunk Washer **REF #101**
Atmosphere Furnace Co. 36-48-30 Spray/Dunk Washer **REF #101**
Surface Combustion 30-48-30 Electrically Heated Spray Dunk/ Dunk Washer **REF #101**
Surface Combustion 30-48-30 Electrically Heated Washer **REF #101**
Proceco/Taylor Gaskin, 26" Diameter x 36"H, Table Washer, N/A, Electric **REF #104**
Surface Combustion, 30"W x 30"H x 48"L, Spray Only Batch Washer, N/A, Steam - Can be converted **REF #104**
Holcroft, 24"W x 24"H x 36"L, Dunk & Spray Washer, UNKNOWN, Electric **REF #104**
FMT - Findlay Machine & Tool, 23" Diameter Drums x 15'L (2), Stainless Steel Rotary Drum Washer, 180-F Wash & Rinse, 180-F Blow Off, Wash & Rinse: Steam, Blow Off: Electric **REF #104**
Midbrook, Inc., 24" Diameter Drum x 8'L Wash x 6'L Rinse x 8'L Blow Off, Stainless Steel Rotary Drum Washer, N/A, Wash & Rinse: Gas, Blow Off: Electric **REF #104**

PIT FURNACES

Lindberg 28" x 28" Pit-Type Temper Furnace **REF #101**
14" 60" Procedyne - Fluidised Bed Elec. 1850 F. **REF #103**
16" 20" Lindberg Elec. 1250 F. **REF #103**
22" 26" L & N Elec. 1200 F. **REF #103**
28" 48" Lindberg Elec. 1400 F. **REF #103**
38" 48" Lindberg Elec. 1400 F. **REF #103**
40" 60" L & N -Steam/N2 Elec. 1400 F. **REF #103**
40" 60" Wellman-Steam/N2 Elec. 1400 F. **REF #103**
48" 48" Lindberg (Atmos) - Fan Elec. 1850 F. **REF #103**
Lindberg, 25" Diameter x 20" Deep, Pit Temper, 1250°F, Electric **REF #104**
Leeds & Northrup, 22" Diameter x 26" Deep, Pit Steam, 1250°F, Electric **REF #104**
Leeds & Lorthrup, 22" Diameter x 26" Dp., Pit Temper, 1400°F, Electric **REF #104**
Lindberg, 33" Diameter x 36" Deep, Pit Carburizer, 1750°F, Gas **REF #104**
Lindberg, 33" Diameter x 36" Deep, Pit Carburizer, 1750°F, Gas **REF #104**
Lindberg, 33" Diameter x 36" Deep, Pit Carburizer, 1750°F, Gas **REF #104**
Lindberg, 33" Diameter x 36" Deep, Pit Carburizer, 1750°F, Gas **REF #104**
Surface Combustion, 36" Diameter x 72" Deep, Pit Carburizer, 1750°F, Gas **REF #104**
Leeds & Northrup/Lindberg, 40" Diameter x 60" Deep, Pit Steam, 1250°F, Electric **REF #104**
Leeds & Northrup/Lindberg, 40" Diameter x 60" Deep, Pit Steam, 1250°F, Electric **REF #104**
Lindberg, 28" Diameter x 72" Deep, Pit Carburizer, 2000°F, Electric **REF #104**
Lindberg, 38" Diameter x 84" Deep, Recirculating Pit Furnace w/ Atmosphere & Cooling, 1250°F, Electric **REF #104**
Lindberg, 38" Diameter x 36" Deep, Pit Temper, 1400°F, Gas - 495,000 BTU's **REF #104**

VACUUM FURNACES

Brew/Thermal Technology Vacuum Furnace **REF #101**
Abar Ipsen 2-Bar Vacuum Furnace, 1986, good condition **REF #101**
24"W x 36"D x 18"H Hayes (Oil Quench) Elec. 2400 F. **REF #103**
48" Dia 60" High Ipsen (Bottom Load) Elec. 2400 F. **REF #103**
Lindberg, 24"W x 18"H x 36"L, Vacuum Furnace, 2400°F, Electric **REF #104**
Abar Ipsen, 30"W x 30"H x 48"L, Horizontal Front Loading Vacuum Furnace, 2400°F, Electric **REF #104**

ENDOTHERMIC GAS GENERATORS

Surface Combustion, 5600 CFH, 1950°F, Gas **REF #104**
Lindberg, 750 CFH, 1850°F, Gas **REF #104**
Lindberg, 1000 CFH, 2000°F, Gas - 390,000 BTU's **REF #104**
Lindberg, 1500 CFH, 2050°F, Electric **REF #104**
AFC/Holcroft, 2500 CFH, 1950°F, Gas Fired **REF #104**
Gasbarre/Sinterite Furnace Division, 3000 CFH, 1950°F, Electric **REF #104**
Surface Combustion, 3600 CFH, 1950°F, Natural Gas **REF #104**
Lindberg, 3000 CFH, 2000°F, Gas Fired **REF #104**
Surface Combustion, 3600 CFH, 1950°F, Gas Fired **REF #104**

INDUCTION HEATING

American Induction, 750 kW/6 kHz, Induction Heating, N/A, Electric **REF #104**
Ajax Magnathermic/Pachydyne, 25 kW/3-10 kHz, Induction Heating, N/A, Electric **REF #104**
Pillar Industries, 500 kW, 10 kHz, Induction Heating, N/A, Electric **REF #104**
American Induction, 75 kW, 10 kHz, Induction Heating/Mono Forge, N/A, Electric **REF #104**
Lepel/Inducto-Heat, 20 kW/450 kHz, RF Induction Heating, N/A, Electric **REF #104**
I.P.E./Inducto-Heat, 200 kW, 450 kHz, RF Induction Heating, N/A, Electric **REF #104**
Tocco, 300 kW, 9.6 kHz, Induction Heating, N/A, Electric
Raydyne, 40 kW, 40 to 50 kHz, Induction Heating/Brazing System, N/A, Electric **REF #104**
Bone Frontier, 50 kW, 10 kHz, Induction Heating, N/A, Electric **REF #104**
Raydyne, 7.5 kW, 410 kHz, RF Induction Heating, N/A, Electric **REF #104**
Lepel/Inducto-Heat, 7.5 kW, 450 kHz, RF Induction Heating, N/A, Electric **REF #104**
Lepel/Inducto-Heat, 7.5 kW, 100 kHz to 400 kHz, RF Induction Heating, N/A, Electric **REF #104**
Lepel/Inducto-Heat, 7.5 kW, 100 kHz to 400 kHz, RF Induction Heating, N/A, Electric **REF #104**
Ajax Magnathermic/Tocco, 30 kW/50 kHz, Induction Heating, N/A, Electric **REF #104**
Inducto-Heat/Lepel, 40 kW, 3 to 10 kHz, Induction Heating, N/A, N/A **REF #104**
Welduction, 100 kW, 450 kHz, RF Generator, N/A, N/A **REF #104**
Pillar Industries, 200 kW, 3 kHz, Induction Heating for Tube/Pipe, N/A, Electric **REF #104**

ATOMOSPHERE GENERATORS

750 CFH Endothermic Dow Elec. **REF #103**
750 CFH Endothermic Insen Gas **REF #103**
1000 CFH Exothermic Gas Atmosphere **REF #103**
1000 CFH Ammonia Dissociator Lindberg Elec. **REF #103**
1000 CFH Ammonia Dissociator Drever Elec. **REF #103**
1500 CFH Endothermic (Air Cooled) Ipsen Elec. **REF #103**
1500 CFH Endothermic Ipsen Gas **REF #103**
3000 CFH Endothermic air Cooled) Lindberg Gas **REF #103**
3000 CFH Endothermic (Air Cooled) Lindberg (2) Gas **REF #103**
3000 CFH Endothermic (Air Cooled) Lindhera Gas **REF #103**
3600 CFH Fnclothermic (Air Cooled) Surface (2) Gas **REF #103**
3600 CFH Endothermic Surface Gas **REF #103**
5600 CFH Endothermic Surface (3) Gas **REF #103**
6000 CFH Nitrogen Generator (2000) Gas Atmospheres Gas **REF #103**
10 000 CFH Exothermic Seco-Warwick Gas **REF #103**

INTERNAL QUENCH FURNACES

24"W 36"D 18"H Dow (Slow Cool) Line Elec. 2000 F. **REF #103**
24"W 36"D 1 8"H Ispen T-4 - Air Cooled Gas 1850 F. **REF #103**
24"W 36"D 18"H Ispen T-4 - Air Cooled Gas 1850 F. **REF #103**
24"W 36"D 18"H Isoen T-4 - Air Cooled Gas 1850 F. **REF #103**
24"W 36"D 18"H Ispen T-4 - Air Cooled Gas 1850 F **REF #103**
30"W 48"D 30"H Surface Allcase Elec. 1750 F. **REF #103**

CONTINUOUS/BELT FURNACES + OVENS

5"W 36"D 2"H BTU Systems (Inert Gas) Rec. 1922ºF **REF #103**
12"W 48"D 2"H Lindberg (Inert Gas) Elec. 1022ºF. **REF #103**
12"W 15'D 4"H Sargent&Wilbur'94(Mufflel) Gas 2100ºF. **REF #103**
16"W 24'D 4"H Abbott-Retort (1996) Elec 2400ºF. **REF #103**
24"W 12'D 6"H Heat Industries Elec. 750ºF. **REF #103**
24"W 40'D 18"H Despatch Elec. 500ºF. **REF #103**
24"W 40'D 18"H Despatch Gas 650ºF **REF #103**
60"W 45'D 12"H Roller Hearth Annealer (Atmos) Gas 1700ºF **REF #103**
72"W 30'D 15"H Unitherm Gas 500ºF **REF #103**

ALD-Holcroft Expands Sales Representative Network

ALD-Holcroft has signed Telesis HV, LLC as exclusive sales representatives in Kansas, Louisiana, Oklahoma and Texas. Telesis HV, LLC is a manufacturer's representative firm that has been serving customers involved in vacuum-related processing for 30 years in the Southwest. They have a broad based knowledge of both vacuum and thermal processing. President Rob Armstrong said, "We are excited to be associated with ALD-Holcroft. We feel there is a synergy with our other products and are impressed with their technology and business plan."

"Telesis has a line-card that closely parallels the customer base we're focused on," says Bill Gornicki, vice president sales & marketing for ALD-Holcroft. "Their long and successful history will most certainly be a benefit to us as we continue our focus on increased market share."

ALD-Holcroft manufactures vacuum-based thermal processing systems for the United States, Canada, and Mexico. Products include ModulTherm®, SyncroTherm®, MonoTherm®, and DualTherm® vacuum furnace systems. For additional information on vacuum-based product offerings call ALD-Holcroft Vacuum Technologies Co., Inc. at (248) 668-4130, or visit at www.ald-holcroft.com.

Solar Atmospheres of California Approved By General Electric Aviation, UTC Aerospace Systems, and Moog

Solar Atmospheres of California (SCA) is now an approved supplier of General Electric Aviation (GEA), UTC Aerospace Systems (UTAS) and Moog Corporation. These well-known companies were recently added to a rapidly growing list of prime contractors on the West Coast who have audited and approved Solar to meet their stringent quality specifications for vacuum heat treating.

Derek Dennis, president of Solar Atmospheres of California explains, "These significant achievements mark another step forward in our ongoing commitment to exceeding our customers' quality and operational expectations. We will continue to expand our list of approvals and cultivate strong relationships with customers for which vacuum heat treating is a critical part of the supply chain. We are also rising to meet our customer's growing requirements by adding capacity with new, state-of-the-art equipment and increasing our workforce. Throughout this evolution, our Quality Management System and its constant review facilitates our superior operations and leads us to new opportunities to better serve our customers."

Solar Atmospheres of California specializes in vacuum heat treating, vacuum brazing and vacuum carburizing services. Using state-of-the-art furnace technology, Solar serves over 18 metal working industries including Aerospace, Medical, and Power Gen. With processing expertise and responsive service, Solar processes small or large parts efficiently with a wide range of vacuum furnaces. Sizes range from lab furnaces to 24 feet long. Solar's unique capabilities, consistent quality and responsive service produce bright scale-free parts with minimal distortion that are delivered on time. With an in-house R&D team of metallurgists, Solar works with customers to develop innovative, custom solutions. For more information or to request a quote, please contact Mike Drakeley to discuss Solar Atmospheres of California's capabilities at 866-559-5994 ext. 1303 or visit www.solaratm.com.

Aerospace Testing & Pyrometry Announces the Hiring of Colin Thomas

Aerospace Testing & Pyrometry would like to announce the hiring of Colin Thomas as the newest addition to the ATP team. With over 30 years of professional experience, Colin has in-depth knowledge of all major aerospace heat treating systems and processes. He has extensive experience with research, development, and introduction of high temperature materials for gas turbine airfoil manufacture. He successfully led process ownership teams involved with establishing best practices for vacuum heat treatment processes across multiple domestic and international manufacturing sites. Colin holds a B.S. degree in Metallurgical Engineering from the University of Manchester, England. Upon completion of his studies, he joined Howmet Corporation, a world leader in superalloy and titanium alloy investment casting production, working in the areas of advanced material development and manufacturing processes. From 1982 through 2002 he held various engineering leadership, technology management and process ownership positions within Howmet Corporation. Colin has been a special process heat treat auditor for Performance Review Institute from 2002 to 2013 with over 250 successful Nadcap audits. During that time, he encountered many diverse heat treatment practices and used his knowledge to identify critical non-compliance issues relative to heat treatment, materials testing, and quality systems. He has cultivated strong interpersonal skills and fostered positive working relationships with many aerospace heat treatment suppliers. Colin will be assisting clients with Heat Treat consulting, Nadcap/Aerospace consulting, as well as Pyrometry Training. For more information, log on to www.atp-cal.com.

 Continued on pg. 70

Modultherm from ALD-Holcroft: Automated Vacuum Furnace Systems Centered on Process Flexibility

ModulTherm is a highly flexible, fully automated concept in vacuum thermal processing technology. It combines high productivity with virtually unlimited flexibility, while reducing thermal treatment costs and ensuring the high quality you expect from vacuum processing.

ModulTherm combines three basics into one linked multi-chamber vacuum furnace system: heat treatment, quenching, and material handling. The quenching and hot vacuum transfer chambers are integrated into a rail-mounted shuttle module that can service two to 12 or more independent treatment chambers. This modular design makes it easy to adapt the system to meet your particular production requirements with direct integration into your manufacturing cells.

ModulTherm benchmarks the competition with several innovative features and options:

- Highest equipment availability (flexible and modular designs)
- 25% larger volume treatment chambers 2,200 lb gross load capacity on original system, 7,000 lb capacity on the new large size.
- Convective heating to reduce cycle times Identical "time-to-quench" for every load
- Reversible quenching gas flow improves uniformity and reduces distortion
- Dynamic quenching (also know as interrupted quench)

ModulTherm delivers cutting-edge enabling technology to give you a competitive advantage across a broad range of process applications. To learn more, visit www.ald-holcroft.com, or call 248-668-4130.

MARKET PLACE

Manufacturing excellence through quality, integration, materials, maintenance, education, and speed.

 Continued from pg. 68

Wirco, Inc. Acquires Salloy, Inc.

Wirco, Incorporated is pleased to announce the recent acquisition of Salloy, Incorporated located in Simpsonville, South Carolinia. For over 30 years, Salloy has produced the highest quality alloy rod and wire fabrications for customers located throughout the east coast and midwestern states. Salloy was founded and managed by Sal Postich with the orginal fabrication shop located in commercial heat treater Carolina Commercial Fountain Inn, SC (now Bodycote). Current Salloy president Sam Postich has been appointed as Wirco's new direct sales representative for the southeastern commercial and captive thermal processing customers as well as certain select customers throughout the US. "We are very excited to welcome Sam Postich to the Wirco Team. His decades of experience and dedication to our industry will serve our customers well. Salloy and Wirco have similar histories as quality based manufactures. We will continue this tradition with Sam at the helm of our southeastern sales effort," said Chad Wright, president, Wirco Inc. Wirco Incorporated is a US based manufacturer of heat and corrosion resistant castings and fabrications with facilities located in Avilla, Indiana, and Champaign, Illinois. For more information, visit www.wirco.com or call 260-897-3768.

Advanced Heat Treat Corp. Completes Quality Systems Section of Nadcap

Advanced Heat Treat Corp. (AHT) completed the Quality Systems section of the Nadcap (National Aerospace Defense Contractors Accreditation Program) audit with zero findings. The audit took place February 25-March 1st at their Waterloo, Iowa facility, and although it doesn't officially grant the company final Nadcap accreditation, it is a major step in the process and final approval is expected within the next 30-60 days. Nadcap certification is something Advanced Heat Treat Corp. has been considering over the last two years. Advanced Heat Treat Corp. employees undergo intense training to ensure proper procedures are in place for ion and gas nitriding processes. AHT staff proficiency is tested every two years and AHT will be subjected to an annual audit with recertification every three years. According to PRI: "Nadcap is an industry-managed approach to conformity assessment that brings together technical experts from both industry and government to establish requirements for accreditation, accredit suppliers, and define operational program requirements. This results in a standardized approach to quality assurance and a reduction in redundant auditing throughout the aerospace industry because prime contractors, suppliers, and government representatives have joined forces to develop a program that:

- Establishes stringent industry consensus standards that satisfy the requirements of all participants
- Replaces routine auditing of suppliers with one approved through a consensus decision-making process of members from the user community
- Conducts more in-depth, technically superior special process audits
- Improves supplier quality throughout industry through stringent requirements
- Reduces costs through improved standardization
- Utilizes technically expert auditors to assure process familiarity
- Provides more frequent audits for Primes, fewer audits for suppliers

"Advanced Heat Treat Corp. takes pride in holding ourselves to the highest quality standards and looks forward to providing the Nadcap certification for our aerospace and defense customers," quality director Tom Hafele stated. "The certification is something we've been discussing for a couple of years and are very excited the audit went well" Advanced Heat Treat Corp. (AHT) is a recognized leader in providing heat treat services and superior metallurgical solutions to companies across the globe. In just over 30 years, AHT has developed into a multi-service heat treat company that takes pride in fitting the ideal solution to any application. AHT's UltraGlow® family of processes includes Pulse Plasma Ion Nitriding, Ferritic Nitrocarburizing (FNC), Gas Nitriding, UltraOx®, Through Hardening (i.e. Quench & Temper), Carburizing, Carbonitriding, Induction Hardening, and many more services. The company's unsurpassed customer service, high quality standards, prompt turnaround, commitment to research and development, and state-of-the-art equipment and technology have led AHT to where it is today. To learn more about AHT's capabilities, contact Mr. Mikel Woods (Sales / Marketing) at 319-232-5221 or woodsm@ion-nitriding.com, or visit AHT online at www.ahtweb.com. About Nadcap; Created in 1990 by SAE Inc., Nadcap is administered by the not-for-profit Performance Review Institute. PRI exists to advance the interests of the mobility and related industries through development of performance standards and administration of quality assurance, accreditation, and certification programs as well as related activities for the benefit of industry, government, and the general public. PRI works closely with industry to understand their emerging needs and offers customized solutions in response. Learn more at www.pri-network.org or contact PRI at PRINadcap@sae.org.

AD INDEX

TOM OTT
SALES MANAGER – PROCEQ

Q: Most people don't associate hardness testing with heat treatment, but it's very relevant. You say there are a number of products that are really appropriate for use in hardness testing of heat-treated gears. What kinds of products does Proceq offer in that regard?

TO: With any instrument, you have to have access, of course, to the area you want to test for hardness. The space has to be large enough to accommodate the largeness of the instrument's probe. This can be a problem when you talk about measuring down inside the roots of gear teeth—you don't have a large space to work with.

To solve this problem, Proceq created a probe called the DL, which has a thin 1.5-inch long nose on it. This allows you to get down into the roots of gear teeth to test the hardness. It began as a separate probe that you hooked up to the Proceq instrument, which could prove fairly costly, and a little bit cumbersome. So a couple of years ago, Proceq took that probe tip and made it into our integrated tester, the Piccolo 2 and Bambino 2. Now, it's all one small handy contained unit that you can slip into your shirt pocket and carry around with you while you're walking the floor if you need to do some testing with it. The portability and ease-of-use has really proven itself. It's become very popular for us.

Q: Is there a specific testing method used with these kinds of probes?

TO: These instruments measure hardness using the rebound method. Inside the probe, there's a little metal body with a tungsten carbide tip; this body is loaded up against a spring. When you press a button, it releases the body, which gets propelled against the surface and bounces back. The rebound technique measures the ratio of rebound speed to impact speed (just before and just after impact).

The only limitation is this: A lot of gears are case-hardened, and the gear manufacturers need to get an accurate reading of that case hardening. The limit on the rebound-method to read is about 0.030 inches with the DL device. The case hardened layer has to be thicker than this. On some of the new, more modern heat treated gears, this could be a problem, because they're getting thinner and thinner.

This is where another product, the Equostat 3, can really come in handy. It's been around for a couple of years now, but it's still new enough that we're trying to get the word out. It uses a different test technique than the rebound testers. Instead of measuring the ratio of the rebound speed, you're measuring a depth of indentation. The probe applies force to a conical diamond, pushing that diamond into the surface, and measuring how deep it goes. This type of test is not restricted to heavy mass, like the rebound testing technique. It's also a light-load tester, so it can measure effective cases down to 0.002 inch or 0.003 inch thickness, depending on the hardness. Usually, since it's a case hardening, it's very hard.

Q: What's the difference between the Piccolo 2 and the Bambino 2?

TO: The portable metal hardness test of the Equotip Piccolo 2 features the same advances as the Equotip Bambino 2, but also allows user-defined hardness conversions, free Piccolink software for download and export of stored readings, and full remote control of the Equotip Piccolo 2 settings. With this instrument for the portable metal hardness test, customers can enjoy full bi-directional communication via USB interface and free online firmware updates.

With any instrument, you have to have access to the area you want to test for hardness. The space has to be large enough to accommodate the largeness of the instrument's probe. This can be a problem when measuring down inside the roots of gear teeth—you don't have a large space to work with.

FOR MORE INFORMATION: Proceq SA of Switzerland, founded in 1954, is a leading manufacturer of high quality portable instruments for non-destructive testing of materials such as concrete, metal, or paper. Visit www.proceq.com or call 1-724-512-0330

SECO/WARWICK GROUP

ATM

CAB

VAC

AP

VME

Spare Parts & Service

SECO/WARWICK is a global supplier of industrial equipment and modern technologies for metal heat processing. Owing to their innovativeness and adaptation to new (lean) industrial process philosophy, our products provide our customers with competitive edge in production processes.

SECO/WARWICK pursues its mission through:

- Long-term presence on the most important global metallurgy markets
- Long-term cooperation with global leaders of modern industries
- Well-developed in-house R&D activities, combined with long-term cooperation with the leading R&D and academic centers in Poland, the US, China and Denmark
- High competences and continuing professional development of our employees
- Flexible approach to cooperation with customers – custom-made solutions proposed by experienced and efficient product

Your Local Partner

USA

SECO/WARWICK Corp.Mercer Street 180
16335-6908 Meadville
T: +1 814 332-8400
F: +1 814 724-1407
E: info@secowarwick.com

SECO/WARWICK S.A.
ul. Sobieskiego 8, 66-200 Świebodzin, POLAND
Tel. +48 68 38 20 500, Fax +48 68 38 20 555
e-mail: info@secowarwick.com.pl

www.secowarwick.com

SECO/WARWICK