DESSING

ISSUE FOCUS ///

INDUCTION HEATING / QUENCHING

THE SUBTLETIES OF INDUCTION PROCESSING

COMPANY PROFILE ///

Applied Test Systems











FROM BEAVERMATIC STANDARD DESIGNS TO CUSTOM SOLUTIONS

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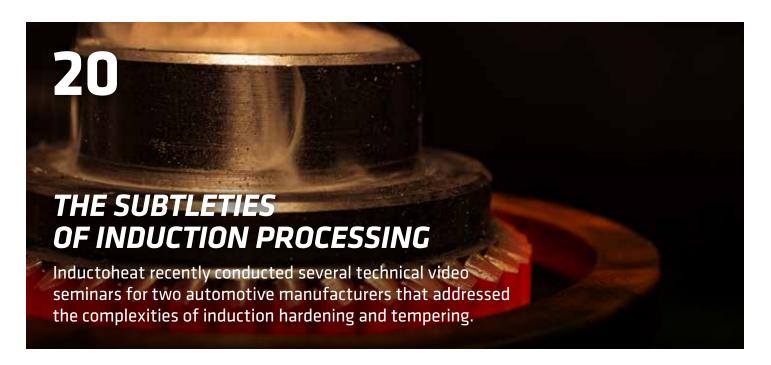






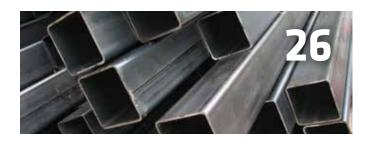


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IMPROVING THE MECHANICAL PROPERTIES OF MEDIUM CARBON STEEL

In a total of nine experiments, the optimization of heat-treatment parameters of medium carbon steel quenched in different media was conducted using the Taguchi method and Grey relational analysis.



CARBURIZING CLEAN WITH METHOD 4

Method 4 gives new meaning to a continuous furnace operation without expensive down time for soot removal and a clean furnace to produce more workloads in less time. **36**



COMPANY PROFILE ///

GIVING CUSTOMERS GOOD LONG-TERM VALUE FOR THEIR INVESTMENT

Applied Test Systems offers custom solutions by providing quality furnaces, ovens, and other products that are reliable, accurate, and user friendly, while offering outstanding field service and worldwide calibration on all manufacturers equipment.

2 | JULY 2021 COVER PHOTO: SHUTTERSTOCK



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DEPARTMENTS ///

JULY 2021

VOLUME 10 / NUMBER 7

UPDATE ///

New Products, Trends, Services & Developments



- >> Ceramics Expo returns for 2021, readies for Cleveland.
- >> XLE series box furnace shipped to aerospace leader.
- >> MIM manufacturer chooses Ipsen for vacuum furnaces.

Q&A ///

TOM SCHULZ SALES MANAGER /// L&L SPECIAL FURNACE CO., INC.

RESOURCES ///

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International Federation for **Heat Treatment (IFHTSE)**



The international association whose primary interest is heat treatment and surface engineering shares news of its activities IFHTSE to promote collaboration

on issues affecting the industry.

Industrial Heating Equipment Association (IHEA)



The national trade association representing the major segments of the industrial heat processing equipment industry shares

news of it's activities, training, and key developments in the industry.



HOT SEAT ///

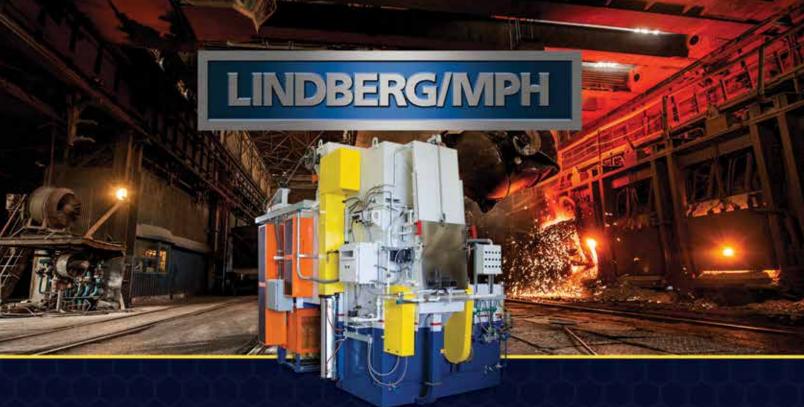
Heating parts in a salt bath is a fast, inexpensive, and efficient process but there are hazards to consider as well. 16

OUALITY COUNTS ///

Finding the "flow" at work can mean hitting the balance of feeling challenged and invigorated. Work should be recognized as a chance for creation and a chance to feel individual success. 18

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FROM THE EDITOR ///



We take your message farther than anyone

f the global climate has taught us anything, it's shown us that the industry is made up of an amazing network of companies that are changing and adapting in order to keep those furnaces and ovens hot and running.

Was it easy? The answer to that would be an emphatic "no." But it's been a necessary task that has proven the industry's mettle — or should that be metal?

Thermal Processing wants you to know that we are here for you, and in ways that continue to make us your No. 1 source for heat-treating news and information on a variety of platforms.

What do I mean by that?

Thermal Processing is the only heat-treat magazine that presents this information in print as well as online.

What does that mean for you?

It means your information — whether it's an eye-catching advertisement or an intelligently written article presented by an industry expert — is not only visible and available on the internet through our website and social media, but it also enjoys a long shelf life as a physical printed vehicle in offices and homes around the country.

That's good news for your audience in search of the very services and products that you can provide every day. And with the world still recovering from economic and medical hardships, the deep reach *Thermal Processing* can provide is more important than ever.

With that in mind, I hope you find the articles in our July issue of interest as you work to get back to normal or are still busy navigating a new normal.

Our July issue takes a deep dive into induction hardening and quenching.

In our Focus section, experts from InductoHeat look at the subtleties of the induction process by reviewing several technical seminars conducted for two automotive manufacturers addressing the complexities of induction hardening and tempering.

On the subject of quenching, we share an article that looks at optimizing the heat-treatment parameters of medium carbon steel as it is quenched in different media using the Taguchi method and Grey relational analysis.

In addition to those main articles, this issue also offers up a look at a method for continuous furnace operation without expensive down time for soot removal, as well as ensuring a clean furnace that can produce more workloads in less time.

That's just a taste of what July's issue has in store for you.

Thermal Processing is here to serve you. With that in mind, if you have any suggestions or would like to contribute, please contact me. I'm always looking for exciting articles to share

Stay safe and healthy out there, and, as always, thanks for reading!

KENNETH CARTER, EDITOR

editor@thermalprocessing.com (800) 366-2185 x204



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UPDATE /// HEAT TREATING INDUSTRY NEWS



The Ceramics Expo conference program, which will include floor-plan changes to accommodate social distancing between its more than 250 exhibitors, will present more than 30 speakers tackling the most pressing industry and supply chain challenges. (Courtesy: Ceramics Expo)

Ceramics Expo returns for 2021, readies for Cleveland

Ceramics Expo will return as planned on August 30-September 1, 2021, in Cleveland, Ohio, changing venues for the first time since its inception in 2014.

The event will be held at The Huntington Convention Center—in downtown Cleveland. This location allows delegates to combine their Expo trip with a visit to some of the leading restaurants, entertainment centers, hotels, and cultural attractions nearby.

The large venue will enable safety measures for Ceramics Expo visitors, including floor-plan changes to accommodate social distancing between its more than 250 exhibitors. The exhibition will take place with leaders in the ceramics and advanced materials space such as NASA, McDanel Advanced Ceramic Technologies, Fiven, Kyocera, and

Ferro signed on to attend.

The 2021 conference program theme 'Enabling a Clean, Efficient And Electrified Future' will present more than 30 speakers tackling the most pressing industry and supply chain challenges, with experts discussing sustainability, diversity and inclusion, industrial applications, and resilience post-COVID-19.

The conference stage will host panel discussions on areas such as additive manufacturing, the role of ceramics in 5G, and energy storage. Speakers include eminent voices from global companies and academia, including Northrop Grumman, Skyworks, GE Aviation, and Coorstek.

Raymond Pietersen, Ceramics Expo event director, said, "This is the largest in-person event for the global ceramics industry in 2021. We're very proud to have retained over 80 percent of our exhibitors — which is not only a testament to the resilience of the industry, but a hopeful sign that we're going to continue to grow post-COVID.

We're really looking forward to reuniting with our peers, colleagues, friends, and customers face-to-face in August."

Mark Mecklenborg, executive director at The American Ceramics Society, said, "With exceptional opportunities for collaboration, Ceramics Expo plays a pivotal role in gathering all the leading stakeholders in our industry. I'm thoroughly looking forward to meeting everyone in the new venue, with renewed energy and focus following the challenges of 2020."

The three-day event includes networking, lead generation, and knowledge-sharing.

MORE INFO wwww.ceramicsexpousa.com

XLE series box furnace shipped to aerospace leader

L&L Special Furnace Company has shipped a floor-standing box furnace used for ceramic coating applications in the aerospace industry to a leader in the coating industry located in eastern Canada.

The L&L Model XLE214 is used for curing and bonding ceramic coatings to various steel bodies primarily deployed in the aerospace industry. This process provides extra strength to aerospace parts that are subject to various heats and stresses under normal operating conditions.

The furnace has an effective work zone of 22" wide by 16" high by 20" deep. A horizontal door with ceramic hearth and support bricks is included to incorporate the customer's loading system. Nickel-chrome elements are used in the furnace that are resistant to any potential contamination the process may cause. Heat shields provide a safe-to-touch case temperature under operating conditions.

The model XLE214 is controlled by a Eurotherm program control with overtemperature protection, chart recorder with



SEND US YOUR NEWS Companies wishing to submit materials for inclusion in Thermal Processing's Update section should contact the editor, Kenneth Carter, at editor@thermalprocessing.com. Releases accompanied by color images will be given first consideration.



L&L Special Furnace Co., Inc., XLE series box furnace. (Courtesy: L&L Special Furnace Co.)

jack panel, solid-state relays, and zone controls for balance of temperature gradients. Thermocouples, fusing and electrical interconnections are included. The furnace control circuit is completely tested to ensure proper operation prior to shipping.

The furnace case is sealed for use with inert atmosphere to help reduce oxygen impregnation with the parts. The furnace has a manual inert flow panel to control the inert gas flow into the oven.

The model XLE214 also includes a high-convection fan for uniformity of ±10°F/5.5°C above 500°F/260°C to 1,875°F/1,023°C. There is a 4-inch diameter venturi with a variable frequency drive to evacuate outgassing that occurs during the curing of the ceramics to the steel part. The system is completely auto-

mated through the program control logic.

All L&L furnaces can be configured with various options and be specifically tailored to meet customers' thermal needs. The company also offers furnaces equipped with pyrometry packages to meet ASM2750F and soon-to-be-certified MedaCred guidelines.

Options include a variety of control and recorder configurations. A three-day, comprehensive startup service is included with each system within the continental United States and Canada. International startup and training service is available by factory quote.

MORE INFO www.llfurnace.com

MIM manufacturer chooses Ipsen again for vacuum furnaces

An international leader in metal injection molding chose Ipsen to supply furnaces capable of both debinding and sintering for their growing fleet, ordering their 17th and 18th Titan furnaces.

The partnership with Ipsen, an ongoing iterative process, has resulted in a total purchase of 18 Titan® DS6 2 bar vacuum







Ipsen's Titan furnace is rugged and features a large work zone volume. (Courtesy: Ipsen)

furnaces. Year after year, engineers on both teams have had open conversations regarding process and furnace design, working to perfect product functionality.

"When this relationship started a decade ago, I did not anticipate how much we would learn from each other," said Ipsen Group CEO Geoffrey Somary. "After all these years we still enjoy a collaborative exchange of ideas, which supports this customer's drive to deliver excellence across hundreds of part variations."

While most MIM parts producers rely on costly lab-size furnaces for post-processing, this manufacturer requires a "work horse" that can handle large volume, demanding applications. Ipsen's rugged furnaces are distinguished by a work zone volume of 36 x 36 x 48 in (915 x 915 x 1,220 mm), a load capacity of 3,000 lbs (1,360 kg) and a right-sized filtration system — equipment made for full-scale continuous production. Even at such a large size, Ipsen's Titan furnace fits into a single shipping container, enticing buyers from around the globe with low transport costs.

Ipsen has a long history working with customers in additive manufacturing. As AM and the related MIM segment become more common and diverse, industries realize the potential cost savings, resulting in more and more AM and MIM parts being designed into their products from the start.

With numerous worldwide locations, Ipsen also offers local support for the life of the furnace in more than 40 countries.

MORE INFO www.ipsenusa.com/am

Advanced Heat Treat has new premium black oxide service

Advanced Heat Treat Corp., a recognized leader in heat treatment and metallurgical solutions, has a new black oxide option. The oxidation is a darker black color than the original offering. The additional option will be available as a stand-alone black oxide treatment and as part of the UltraOx® heat treatment (referred to as UltraOx Hyper).

AHT President Mike Woods said, "Now our customers have a choice when it comes to the appearance and metallurgical results of their carbon steel and alloy parts. They can opt for our standard offering or choose an even darker oxide finish."

UltraOx and black oxide are often used by manufacturers serving industries such as firearms, agriculture, automotive, and more. The treatments provide an aesthetic black color and protection against wear and corrosion. UltraOx has been proven to last more than 300 salt spray hours before developing signs of rust.

AHT's new black oxide and UltraOx Hyper are available at its Monroe, Michigan location. The facility also offers ion nitriding, gas nitriding, ferritic nitrocarburizing, stress relieving, and more.

MORE INFO www.ahtcorp.com

Lucifer Furnaces delivers small custom box furnace

Lucifer Furnaces designed a small box furnace reaching 2,300°F for a U.S. manufacturer of RF/microwave components who needed precision heating to anneal its parts before milling.

Model HL7-A12 has a 6"x 6" x12" chamber, which is well insulated with a combined five-inch hot face insulating firebrick and cold face mineral wool backup. Built with the same quality as larger models, this box furnace is complete with a cast hearth plate to protect the floor insulation, and heats with easy-to-replace coiled heating elements in cast assemblies for easy replacement.

Controls include a Honeywell digital time proportioning temperature controller and a TP1 Soak Timer which starts when the furnace reaches setpoint temperature and shuts off the elements at the end of the heating cycle. A door safety switch automatically disengages power to the elements when the door is opened.

This furnace is part of Lucifer's standard, general purpose, Series 7000 box furnace line ideal for bringing a customer's heat treating in-house to gain control over work flow and product quality.

MORE INFO www.luciferfurnaces.com

Powder metallurgy self-study course now available

APMI is offering a self-study course on powder metallurgy and particulate materials processing provides a broad introduction to the fundamental principles of powder metallurgy. The user will gain an understanding of basic science and engineering as it relates to the technology. Practical applications of metal and alloy behavior, various manufacturing processes, and management objectives will be explored. This technically in-depth course provides valuable knowledge for career development.

The course will be presented by global expert Dr. Randall M. German, FAPMI, research professor at San Diego State University, previously serving as dean of engineering research.

This course contains 30 pre-recorded videos that average 60 minutes each and will be open to the student for six months from the date of purchase.

APMI International is a non-profit professional society which promotes the advancement of powder metallurgy and particulate materials as a science. Its purpose is to disseminate and exchange information about PM and particulate materials through publications, conferences, and other activities of the society.

MORE INFO www.apmiinternational.org

Dante Solutions releases VCarb and GCarb updates

Dante Solutions, Inc. updated the VCarb and GCarb utilities, which can be used for recipe design and predicting given carburization recipes for vacuum carburization (VCarb) and gas carburization (GCarb) processes.

The most notable update includes the ability to use the Dante material database for design and analysis. This change allows the user to use one of the many materials already defined in the Dante database, or any user-defined materials that have been developed, further expanding the capabilities of Dante analysis.

Using the Dante material database opens the ability to use the carbide formation and dissolution models present in the full Dante package, which are paramount in high-carbon gradient processes such as vacuum carburization.

Another important inclusion is the addition of the geometry tab, which allows the user to better define an inside (concave) or

outside (convex) curvature to the point being analyzed, which will alter the profile and concentrations of carbon in the case.

Lastly, in VCarb, a load surface area input was added to help predict the amount of carburization gasses consumed by the parts in the furnace. Coupled with gas and furnace efficiencies in the controls tab, the user can estimate the amount of gas used by the process and apply that to costs for accounting purposes.

MORE INFO www.dante-solutions.com

New handbook on tungsten-heavy alloys available

Tungsten Heavy Alloy Handbook — Applications, Compositions, Fabrication, Properties, Microstructures, and Modeling of Sintered Tungsten Heavy Alloys by Dr. Randall M. German, FAPMI, is available for purchase through the MPIF website.

Tungsten Heavy Alloy Handbook Randall M. German

The handbook contains 27 sections, each composed of small segments that can be consulted without reading the entire book. The handbook organizes the facts on the process options, applications, compositions,

shaping, measurement tools, sintering, heat treatment, embrittlement, microstructures, and more

The handbook is designed to provide solutions to typical challenges. Both the table of contents and index help find specific data, relations, models, and correlations. It's in a searchable, full color PDF format, 458 pages, MPIF © 2021—ISBN No. 978-1-943694-26-6 List: \$185 MPIF/APMI: \$148.

Metal Powder Industries Federation is the North American trade association formed by the powder metallurgy industry to advance the interests of the metal powder producing and consuming industries and provides a single point of reference for all MPIF member companies.

MORE INFO www.mpif.org

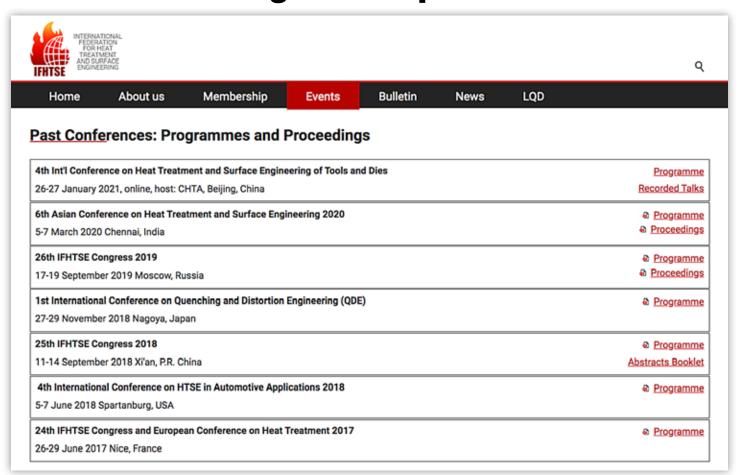




INTERNATIONAL FEDERATION OF HEAT TREATMENT AND SURFACE ENGINEERING



IFHTSE website gets an update



he website of IFHTSE (www.ifhtse.org) recently has been upgraded to include the program and proceedings of many of the member conferences and IFHTSE congresses. IFHTSE is working to include many of the early conference proceedings. As you can imagine, this is a long and tedious process, as it entails finding the conference proceedings (some from 50 years ago), carefully removing the binding, and scanning each of the proceedings.

SPOTLIGHT ON MEMBER ORGANIZATIONS

IFHTSE is a federation of organizations not individuals. There are three groups of members: scientific or technical societies and associations, universities and registered research institutes, and companies.

In this segment, we will highlight our members. This month we highlight AAGES SA.

AAGES designs and manufactures induction heating machines

for a large range of applications. AAGES, a joint stock company in Romania, has been designing and manufacturing induction heating machines for a large range of applications for more than 31 years.

AAGES was founded in 1990 by a group of engineers from the Research and Design Institute for Electrical Engineering (ICPE) Bucharest, branch Targu Mures.

The first products of the company were the static converters for induction heating applications. Partnering with a German company in the late '90s, AAGES developed in less than one year the new family of converters with IGBT transistors, and they delivered more than 1,200 units over the years all across the globe.

The number of employees has increased steadily since 1990, reaching today more than 110 employees, many of them having an advanced professional degree and long-term experience in the field of induction heating.

MEMBERS IN THE NEWS

Dr. U. Kamachi Mudali



Dr. U. Kamachi Mudali, FASM, vice chancellor, VIT Bhopal University, Madhya Pradesh, India, has been nominated as Trustee-Elect of ASM International. In accordance with the ASM Constitution, these nominees will be elected at the ASM Annual Business Meeting on September 13, 2021.

Dr. Mudali is a distinguished scientist and chairman and chief executive of the Heavy Water Board (HWB). He is responsible for the smooth and efficient operation of Heavy Water Plants and other diversification activities at Kota, Manuguru, Thal, Hazira, Baroda, Tuticorin, and Talcher. These facilities produce heavy water, organic solvents, sodium, potassium, oxygen-18, enriched boron and B4C, and deuterated solvents and compounds.

Dr. Mudali was at IGCAR, Kalpakkam, for 33 years since 1984, and was director of Materials Chemistry and Metal Fuel Cycle Group before joining HWB. Dr. Mudali is an internationally-known professional in advanced materials, coating technology, corrosion engineering, and R&D projects of reactor and reprocessing materials, processes, and equipment relevant to fast breeder reactors. He has, to his credit, 441 papers in various national and international journals, four patents, and has co-edited 17 books/proceedings. He has guided/coordinated 162 students for their UG, PG, and PhD degrees.

Massimo Pellizzari



Massimo Pellizzari, PhD, Associate Professor, Department of Industrial Engineering, Università degli Studi di Trento, Italy, was elected to serve as vice president for 2022-2023 of IFHTSE. He will serve as president of IFHTSE in 2024-2026.

His primary research activity is focused on heat treatment and surface engineering of steels, deep cryogenic treatment,

properties of tool steels, special cast irons, development of powder metallurgical tool steel by ball milling, spark plasma sintering, and additive manufacturing. He speaks Italian, English, and German, and he is a member of Associazione Italiana di Metallurgia.

IFHTSE 2021 EVENTS

Due to the pandemic, many conferences planned for 2021 have either been delayed or canceled. Please watch this space for updates on current conference planning.

SEPTEMBER 5-9

6th International Conference on Steels in Cars and Trucks Milan, Italy 1 www.sct2020.com

SEPTEMBER 8-10

4th Mediterranean Conference on HTSE Istanbul, Turkey | mchtse2020.com

SEPTEMBER 13-16

ASM International Materials Applications & Technologies St. Louis, MO, USA | www.asminternational.org/web/imat

SEPTEMBER 29-OCTOBER 1

14th HTS International Exhibition and Conference

Mumbai, India I www.htsindiaexpo.com

OCTOBER 26-28

HK 2021

HK is the largest materials technology industry meeting in Europe Cologne, Germany | www.hk-awt.de

APRIL 2022

12th Tooling Conference & Exhibition (Tooling 2022)

Örebro, Sweden

SEPTEMBER 2022

27th IFHTSE Congress / European Conference on Heat Treatment Salzburg, Austria

APRIL 2023

5th International Conference on Heat Treatment and Surface Engineering of Tools and Dies

Liangzhu Dream Town, Hangzhou, China

NOVEMBER 13-16, 2023

28th IFHTSE Congress

Yokohama, Japan

For details on IFHTSE events, go to www.ifhtse.org/events



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ONLINE www.ifhtse.org | EMAIL info@ifhtse.org



INDUSTRIAL HEATING EQUIPMENT ASSOCIATION

The value of in-person industry events



Getting back to business is what every company wants to do, and the IHEA Annual Meeting is one of the ways our members can resume business relationships.

or most of us, it's been a very long time since we've attended an in-person meeting. But the time has come where IHEA can safely hold its 2021 Annual Meeting, and we want you to be there.

The historic Don CeSar Hotel situated on America's No. 1 beach will play host to the Industrial Heating Equipment Association (IHEA) 92nd Anniversary and Meeting. Scheduled for July 26–28 on beautiful St. Pete Beach, Florida, this will be the first time our membership will have the opportunity to be together in person in almost two years.

Face-to-face meetings are critical for our industry to thrive, and this event is the perfect way to reconnect with industry peers and make new contacts.

"It's been far too long since our membership has had the opportunity to see each other in person," said IHEA Executive Vice President Anne Goyer. "The connections people make during in-person events are so important, and, after more than a year, our members are looking forward to getting together at an IHEA meeting."

Getting back to business is what every company wants to do, and the IHEA Annual Meeting is one of the ways our members can resume business relationships. IHEA's Annual Meeting combines an outstanding program with ever-popular social events. The featured presentations cover thought-provoking topics and information designed



to strengthen members' organizations. The social gatherings and activities provide opportunities for members and guests to network with professional contacts and grow their business.

In-person events stimulate human connection. Personal connec-



The social gatherings and activities provide opportunities for members and guests to network with professional contacts and grow their business.



tions reach beyond sitting next to someone in a meeting. Now you have a face to put with the email, and communication becomes easier for you and your team. This has been a missing component for far too long, and IHEA is happy to offer the opportunity to connect again. No matter what valuable content you deliver through webinars and email campaigns, there is nothing that can replace human interaction at an in-person meeting.

In addition to all the benefits of being together with friends, The Don CeSar provides a beautiful backdrop to welcome IHEA members and guests. Situated on the Gulf Coast of Florida just west of Tampa, The Don is a historic hotel on a stretch of beach that, according to TripAdvisor, is second to none.

Register now for IHEA's 2021 Annual Meeting. For complete program information and to register, please visit www.ihea.org/event/21AM

IHEA members receive significant discounts on events. Consider joining IHEA and take advantage of these cost savings. IHEA membership includes vouchers that can be used toward event registration fees. Visit www.ihea.org for more information about membership and how to join.

IHEA 2021 CALENDAR OF EVENTS

JULY 26-28

IHEA 2021 Annual Meeting

Don CeSar Hotel | St. Pete Beach, Florida

AUGUST 10-11

Powder Coating & Curing Processes Seminar

Alabama Power Technology Applications Center | Calera, Alabama

This day and a half Introduction to Powder Coating & Curing
Processes Seminar will include classroom instruction and hands-on
lab demonstrations. Registration is \$325 for IHEA members, \$425
for non-members. Fee Includes: Seminar materials, Powder Coating
Manual, Infrared Manual, breakfast and breaks both days, lunch Day 1,
Networking Reception, Certificate of Completion.

For details on IHEA events, go to www.ihea.org/events

INDUSTRIAL HEATING EQUIPMENT ASSOCIATION

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/////////////////// D. SCOTT MACKENZIE, PH.D., FASM

SENIOR RESEARCH SCIENTIST-METALLURGY /// QUAKER HOUGHTON INC.

Heating parts in a salt bath is a fast, inexpensive, and efficient process, but there are hazards to consider as well.

Use of molten salt in heat treatment

t the turn of the 20th century, the use of molten salt as a heating and quenching medium for steels was developed in England. It rapidly came into use in Europe as a low-cost method of heat treating. Equipment was inexpensive, and molten salt provided a reproducible method of heat treatment.

In this short article I will review the types of salts used for heat treating and some hazards associated with molten salt heat treatment.

ADVANTAGES OF MOLTEN SALT HEAT TREATING

Parts that are heated in salt baths are heated by conduction. The thermal mass of the molten salt provides a large thermal source for heating of parts. Heating of parts in a salt bath is much more rapid than

in air or atmosphere furnace. The heat-up of the parts is only limited by the thermal conductivity of the part. Since metals have high thermal conductivity, the core of the part lags the surface by only a small amount. A 25 mm diameter of steel would require four minutes to reach the austenitizing temperature, while it would take 30 minutes or more in a standard radiation furnace [1].

Salt bath furnaces are efficient at heating parts, with more than 90 percent of the heat applied to the furnace going directly to the part. Atmosphere furnaces are approximately 60 percent efficient. Temperature uniformity is excellent, with uniformity less than ± 3°C throughout the bath.

When parts are heat treated in a molten salt, they are completely immersed. Surface protection from the salt can reduce decarburization and the formation of scale.

Quenching in a molten salt can reduce distortion. Since heat transfer is by conduction, a much more uniform heat transfer occurs across the surface of the part. Further,

due to buoyancy effects, sagging of parts during heat treating is minimized.

TYPES OF SALTS - SALT COMPOSITION

There are several different types of heat-treating operations that can be performed in molten salts. The first is to solution heat treat the part (austenitize in steel) to bring it to the desired temperature. The second operation is to quench the part in the molten salt as part of martempering operation or austempering. Lastly, there is the tempering or aging operation (non-ferrous alloys). All these unit operations can be performed in a molten salt.

There are also specialized salts used for carburizing or nitriding operations. These usually contain a form of sodium cyanide or cyanate. These salts will be mentioned briefly, as their use has significantly declined due to environmental and safety considerations.

Molten salts can be used at a temperature range of 150° C to $1,287^{\circ}$ C (300° F to $2,350^{\circ}$ F). Molten salts are divided into three temperature ranges, with characteristic chemistry. The ranges are low temperature (150° - 620° C); medium temperature (650° - 982° C); and high temperature (982° C - $1,287^{\circ}$ C) molten salts.

LOW TEMPERATURE (150°-620°C)

Low temperature salts are used for a wide variety of unit operations, such as solution heat treating of aluminum, or martempering and



Parts that are heated in salt baths are heated by conduction. The thermal mass of the molten salt provides a large thermal source for heating of parts.

austempering of steels. They are usually mixtures of various nitrates and nitrates of sodium and potassium. These salts are completely molten at 150° C. Some salts, used for energy storage in solar applications, are molten at 121° C (250° F. These salts contain up to 25 percent lithium nitrate. There are no known heat-treating applications using lithium nitrate as a component of the low temperature salt due to the high cost of lithium salts.

Use of these mixtures of nitrate/nitrite baths at temperatures above 620°C is not recommended. These baths are unstable above 620°C, and a strong exothermic reaction can result. This is particularly true when in contact with aluminum.

	Working Range (°F) Working Range () Composition (%)							
Class	Min	Max	Min	Max	NaNO ₂	NaNO ₃	KNO ₃	Na ₂ CO ₃	NaCl	KCI	BaCl ₂	BaCl ₂ plus SiO ₂	CaCl ₂
1	325	1099	163	593	37-50	0-10	50-60	-	-	-	-	-	-
2	550	1099	288	593		45-57	45-57	-	-	-	-	-	-
3	1150	1701	621	927	-	-	-	45-55	-	45-55	-	-	-
4	1099	1650	593	899	-	-	-	-	15-25	20-32	50-60	-	-
4A	1026	1400	552	760	-	-	-	-	10-15	25-30	40-45	-	15-20
5	1299	1650	704	899	-	-	-	-	40-60	40-60	-	-	-
6	1650	1999	899	1093	-	-	-	-	-	5-15	85-95	-	-
7	1900	2401	1038	1316	-	-	-	-	-	-	-	98 (1)	-
8	1650	2350	899	1288	-	-	-	-	3-7	-	93-97	-	-

Note: (1) Class 7 salt is further classified into four subclasses, depending on the amount of silica present as a rectifier: 7A No silica; 7B 0.25-1.25% Silica; 7C 1.5 – 2.5% Silica; and 7D 4.0 – 5.0% Silica.

Table 1: Molten salt classifications per MIL-S-10699B [6].

MEDIUM TEMPERATURE (650°-982°C)

Since nitrates and nitrites are unstable at temperatures above 620°C, another type of molten salt chemistry is required. Molten salts in this class of salts are mixtures of sodium chloride (NaCl), potassium chloride (KCl), calcium chloride (CaCl $_2$), sodium carbonate (Na $_2$ CO $_3$), and barium chloride (BaCl $_2$). At lower temperatures within the operating range, the composition would be primarily potassium chloride and sodium carbonate. At the top end of the range, barium chloride would be the primary constituent. For most general-purpose heat treating to 900°C, a 50/50 mix of sodium chloride and potassium chloride is the most common. This avoids any environmental or disposal issues with barium salts.

While these salts are neutral to steel, they will decarburize steels as the salts oxidize. As temperature is increased, the salts will tend to oxidize more rapidly. Initially, the chlorides form oxides in the form of $\mathrm{Na_2O}$ or $\mathrm{K_2O}$. This occurs due to the presence of air at the liquid interface. Formation of sodium carbonate eventually occurs, with further increases in decarburization. The use of a rectifier, such as borax, boric acid, silicon carbide, or ammonium chloride [2], added to the bath can restore the neutral character of the bath. Previously, methyl chloride was used as a rectifier, by bubbling the methyl chloride through the bath [3]. However, due to health and safety concerns, the use of methyl chloride has largely been discouraged.

HIGH TEMPERATURE (982°C-1287°C)

The high temperature molten salt baths are predominately barium chloride, with either potassium chloride or sodium chloride added to the composition. However, the most common bath is barium chloride with a small amount (up to 5 percent) of silica added as a bath rectifier.

SPECIALIZED SALTS - NITRIDING AND CARBURIZING

There are also specialized salts for molten salt carburizing and nitriding, as well as salts for blackening or bluing steels.

In carburizing molten salts, the salts consist of a mixture of barium chloride and sodium cyanide. Concentration of sodium cyanide is on the order of 30-35 percent [4]. Temperatures used are like those used in atmosphere carburizing (850° to 950°C). The depth of carburizing is generally low at 0.5 mm. Because of the relatively shallow carburizing depths, the corresponding time at temperature is short. The concentration of the sodium cyanide can be increased if the depth of carburized case is deeper. Since the cyanide is the source of carburizing, it will deplete over time. To prevent depletion, a cover of carbon is usually added. This prevents oxidation of the cyanide and prevents radiation heat losses. Typical drag-out of about

6 percent means that fresh salt must be added daily.

Obviously, the presence of sodium cyanide can be a serious health and environmental problem if the necessary steps are not taken to mitigate possible release of hydrogen cyanide. Cyanides will decompose in a bath to carbonates [5]. Some hydrogen cyanide may be produced during this decomposition. Therefore, it is necessary that strong mechanical exhaust be used [5]. The storage of any sort of acids should be prohibited from areas where the carburizing salt is stored. If there are acids used in the production process, such as pickling, it is critical that the parts are thoroughly washed and rinsed prior to the acid-containing process. Mechanical ventilation is strongly recommended.

The cyanide wastes (used salt or contaminated rinse water) must be chemically decomposed before they are disposed. Decomposition is usually done by treating the salt in aqueous solution with an oxidizing agent such as sodium hypochlorite [5]. Strong ventilation is required.

CONCLUSIONS

In this column, the advantages of the use of molten salt were illustrated. The salt composition of the various temperature ranges of salt were explained. In later columns, the application of molten salt quenching (martempering and austempering) will be discussed.

As always, should you have any comments or questions regarding this column, please contact the editor or myself. &

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QUALITY COUNTS ///

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Finding the "flow" at work can mean hitting the balance of feeling challenged and invigorated. Work should be recognized as a chance for creation and a chance to feel individual success.

The paradox of work and happiness

here are obviously a lot of factors that go into making a company successful. Probably the biggest factor is the people who work there. There are employees who love their jobs, employees who don't love their jobs, and employees somewhere in between. Finding a company culture that encourages all employees to feel invested, valued, and productive is a tricky prospect.

There is a known paradox in the psychology world based on psychologist Mihaly Csikszentmihalyi's famous studies on the concept of "flow" — a state of total being consisting of joy, creativity, and total

involvement in life. He found a contradiction of the opportunities of this concept of flow at work, with the perception of what work actually was to the participants. What most of American culture generally considers "work" — a 9 a.m. to 5 p.m., Monday through Friday, retire in 40 years model — provides ideal characteristics that can bring about this state of flow. It provides structure, rules, objectives, development of skills/talents, and competition — a game, in a sense.

However, when interviewing the participants about the study after statistically showing more states of flow at work than at leisure, participants contradicted their own results indicating they would rather be on vacation than at work as they had convinced themselves there was more joy, creativity, and total involvement on the beach. They were supposedly happier.

DEFINING FLOW

Flow is the state in which runners reach what is called a runner's high after long miles and miles. Or, it is described by the superstar athlete from the championship game in an interview stating he or she "was in the zone" after a record-breaking game.

Flow could arguably be described as partying on the beach.

What is interesting is people find this zone and flow state more times at work than they do while performing leisure activities. But when asked where they would rather be, the answer wasn't "at work." It was wanting to be doing more leisure activities. Work provides structure with meetings and expectations; sitting at the beach does not (aside from the cooler needed for partying). Work provides a test of skills; sitting at the beach does not (aside from the occasional jump in the water to cool off). Work provides challenges, a chance to make something (aside from the sand castle with a water moat).

So, why the misperception?

DEFINING WORK

"Work" is a noun when used in the context of "the place you work." Work is a verb when used as, "I would rather work on my truck." Our bodies work every day to move us around from the bed, to the car, to the office, back to the car, and back to the bed. Our lives every day consist of getting up, playing out the meetings, activities, and events of the day, and going back to bed. This describes most American lives in its most bleak description. Work is seemingly boring; certainly it's often perceived as boring. Work is painted as something to dread



Work must be recognized as a chance for creation, a chance for individuals to feel success (and not just the paycheck being cashed in every pay period).

due to the misalignment of the company goals and one's own life goals. The idea that an employee at a company is "making money for someone else's dream" can cripple an employee's psyche if the workplace culture isn't properly set up to prevent that.

DEFINING PLAY

"Play" is a noun when used in the context of "we saw the play." Play is a verb when used as, "I like to play golf, but don't like playing those political games at work."

After failing to make the college golf team my freshman year in college, I was very humbled and convinced that I would never be a professional golfer. Knowing I had to "go pro" in something other than sports, I couldn't get away from the idea of me being the lucky one on TV playing a game of golf for money and the other idea of facing this supposed game of life called "going to work." At first, it was crippling to know I had to shuffle in and find my cubicle where my employee number potentially identified me if I somehow drowned in the sea of work and papers on my desk.

TOWARD A NEW TYPE OF WORK

Let's face it. No athlete who becomes a superstar in the sport they play does it without putting in a great deal of hard work. In the same vein, no company employee becomes a great worker without bringing a sense of play to the challenges and skills required at the company. The language of a company is insight as to the values it imposes through the culture it hopes to create. There isn't one task or event that automatically makes a company be seen as a great company to work for, where people want to work on the actual business.

And if the company culture could design the meetings, the dialogues, the activities both in the office and out of the office to make work also seem like play for every team member involved, the company can begin to really grow. Employees would be engaged, excited to show up. Who would have thought of that? The sense of a chal-

lenge — the thrill of the game — can be energizing.

Work must be recognized as a chance for creation, a chance for individuals to feel success (and not just the paycheck being cashed in every pay period). Csikszentmihalyi convinced me that if I could recognize challenges and anticipate success, make games to excel, I would get more out of life and out of the work that I do. That work would feel more like play and — as the cliché goes — "love what you do, and you never work another day." I could find the zone with whatever I was doing, be it hitting a golf ball or sending out a report.

That is the work and play we need to develop as a workplace culture. That vacation can still be taken and enjoyed (and, yes, drinking beers and building the epic sand castle still counts), but viewed as halftime shows after which employees are excited to get back into the game. This type of game isn't finite, though. It is an infinite game, as Simon Sinek suggests in his book *The Infinite Game*. Employees don't win at business. People don't win at life. We win (and the company wins) when we think of it as developing a mindset of work and play for each and every individual at the company.

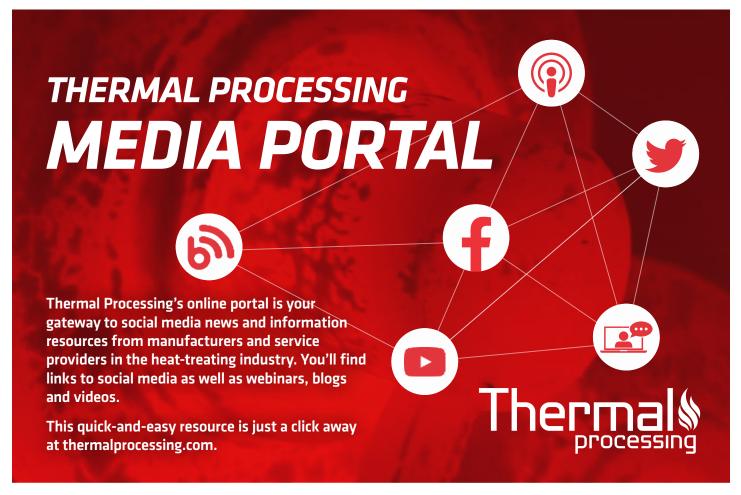
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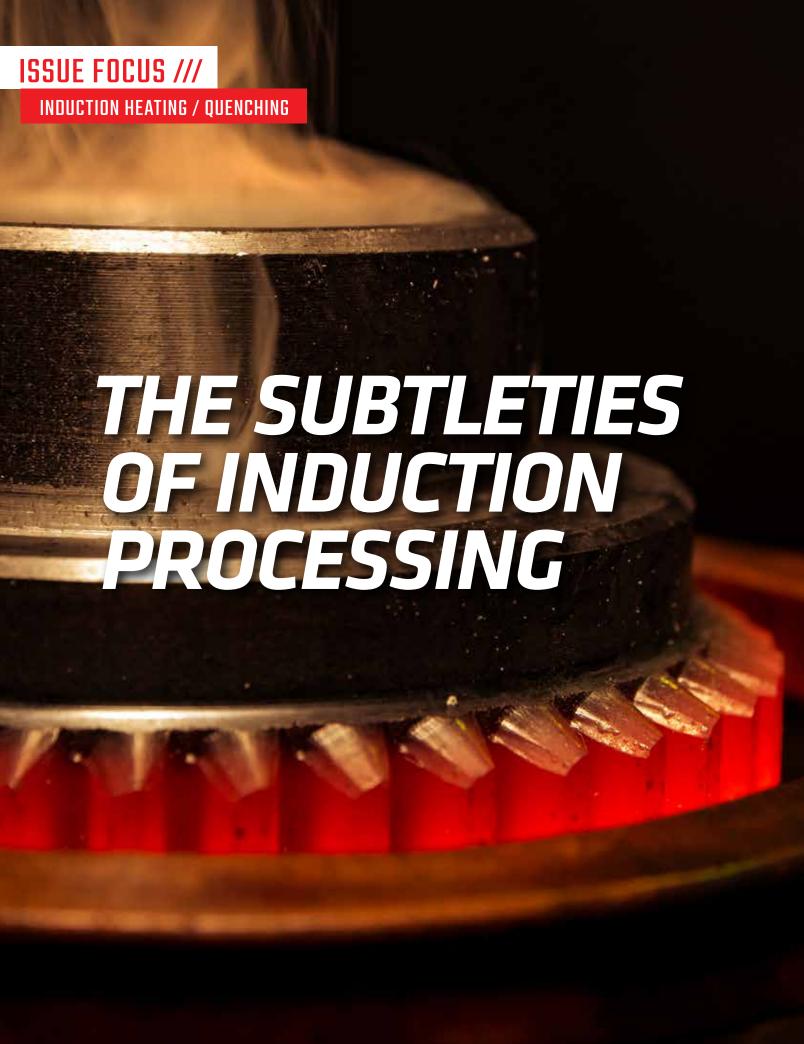
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Inductoheat recently conducted several technical video seminars for two automotive manufacturers that addressed the complexities of induction hardening and tempering.

By INDUCTOHEAT INC

nductoheat was recently asked to conduct three technical video seminars on modern induction thermal technologies for automotive industry:

"The first seminar was April 28, 2021 Title:

"Troubleshooting Failures and Prevention in Induction Hardening: General Useful Remedies, Impact of Geometrical Irregularities and Improper Designs." Format: 90 minutes of oral presentation followed by 15-20 minutes of Q&A session.

>> The second seminar was May 11, 2021. Title: "Induction Thermal Technologies: Basics and Beyond." Format: 70 minutes of oral presentation followed by 30 minutes of Q&A session.

>> The third seminar was May 20, 2021. Title: "Novel Developments and Prospects of Using Induction Heat Treating for Electrical Vehicles (EV)." Format: 90 minutes of oral presentation followed by 15-20 minutes of Q&A session.

Attendees of those seminars included heat-treat practitioners, engineers, metallurgists, managers, failure analysts, and scientists within the induction-heating and heat-treating technologies in application to automotive industry.

INTRODUCTION

The technology of heat treating by means of electromagnetic induction is advancing at an accelerated rate, addressing new challenges associated with rapidly changing business environment (Figure 1). Factors traditionally used by heat treaters to evaluate induction equipment include technical capability, performance consistency, delivery time, machine longevity, and price. With recent industrial trends, the decision to purchase heat-treat equipment also requires consideration of additional factors, including superior equipment flexibility, traceability

of components, sustainability, and digital connectivity, while still satisfying continuously increasing demands for higher-quality products, energy efficiency, and environmental friendliness. Several newly developed innovative induction-heat-treat processes and systems, as well as novel theoretical discoveries, have been unveiled in these educational seminars with practical implementations. Subjects related to quality assurance, process monitoring, and system robustness, as well as overall cost reduction and aspects of realizing Industry 4.0 operating strategy, also have been addressed.

Hardening of steels, cast irons, and PM materials represents one of the most popular applications of induction heat treatment. One of the main goals of surface hardening is to form a martensitic layer on specific areas of the workpiece to increase the hardness, strength and wear resistance while allowing the remainder of the part to

be unaffected by the process. Formation of desirable compressive residual stresses is another important aspect of surface hardening.

COMMON MISPOSTULATION

Recognizing the importance of all electromagnetic phenomena, the skin effect represents a fundamental property of induction heating (IH). Unfortunately, in many publications devoted to IH, distributions of electrical current and power density (heat source) along the work-piece thickness/radius are simplified and introduced as being exponentially decreasing from the surface into the workpiece. However, this common postulation is correct only for a homogeneous non-magnetic solid body with constant electrical resistivity. Therefore, realistically speaking, this assumption can be made for only some unique cases because, for the great majority of IH applications includ-





Figure 1

ing surface hardening, there are always appreciable thermal gradients within the heated workpiece. These thermal gradients result in non-constant distribution of both electrical resistivity and relative magnetic permeability. Therefore, the main postulation of exponential heat-source distribution does not "fit" its principle assumption due to the presence of the non-linearities of physical properties of the heated workpiece.

In reality, at different stages of IH, the heat source distribution along the radius/thickness of the workpiece may have a unique wave shape, which differs significantly from the commonly assumed exponential distribution. As an illustration, Figure 2 shows a radial distribution of power density while surface hardening 24-mm diameter carbon steel shaft at different stages during surface austenitization.

A nonexponential (wave-shape) heatsource distribution has a noticeable impact on the selection of process parameters, heating protocol, final temperature distribution, and hardness pattern. This happens because, if the frequency has been chosen correctly for surface hardening, the thickness of the austenitized layer (the nonmagnetic layer) is less than current penetration depth in austenitized steel, and the wave-shape heat source distribution takes place during the majority of the heating cycle for induction surface hardening.

METALLURGICAL SPECIFICS OF INDUCTION HARDENING

It should be recognized that, metallurgically speaking, there are a number of factors differentiating induction hardening from alternative heat-treatment processes. Two of the most obvious factors are:

>> Since induction hardening does not change the chemical composition of steel, the steel grade must have sufficient carbon and alloy content in order to be capable to achieve a certain surface hardness, case depth, and core hardness.

>> Rapid heating exhibits certain metallurgical implications compared to alterna-

tive thermo-chemical heat-treat processes, drastically affecting the kinetics of austenite formation.

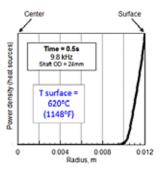
One of the most attractive features of induction heating is its high production rate and an ability to provide a rapid heat generation in required regions of the workpiece. The intensity of heating in induction hardening applications frequently exceeds 200°C/s (Table 1) and, in some cases, reaches 1,800°C/s and even higher (e.g., dual-frequency gear hardening).

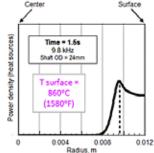
Rapid heating considerably affects the kinetics of austenite formation, shifting it toward higher temperatures according to the continuous heating transformation (CHT) diagrams. Unfortunately, some heat-treat practitioners are unaware of those important diagrams. The seminars unveiled an importance of considering heat intensity and specifics of prior microstructures of steels (e.g., annealed vs. normalized vs. quench and tempered) while choosing appropriate temperatures for induction-hardening applications.

SUPER HARDENING PHENOMENON

When surface-hardening steels, a combination of using "friendly" prior microstructures, rapid heating rates, and intense quenching could result in the so-called super-hardening phenomenon. This phenomenon refers to obtaining greater hardness levels in the case of surface hardening compared to through hardening or hardness levels that would normally be expected. Because of this phenomenon, for identical steel composition, the surface hardness of an induction surface hardened part could be 2 to 4 HRC (1 to 3 HRC being more typical) higher than normally expected for a given carbon content for through-hardened steel.

The super-hardness phenomenon is not clearly understood, and its origin has not been established or widely accepted worldwide by metallurgists. However, it has been obtained experimentally on numerous occasions, and several interpretations have been offered. Conditions imperative for exhibiting the super-hardness phenom-





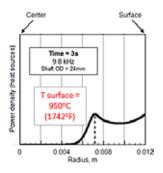


Figure 2

Application	Heat Intensities (°C)
From room temperature to Ac3 temperature range	
Contour hardening of small and medium-size gears	300 - 1800
Surface hardening of shaft-like components	150 - 900
Through hardening or deep case surface hardening	50 - 400
Normalizing of thin wires, ropes, rods, strips, etc.	150 - 400
Through heating prior to warm and hot working	2.0 - 60
From room temperature to temperatures below Ac1 critical temperature	
Subcritical annealing of "thin" workpieces	50 - 350
Stress-relieving and high temperature (650oC) tempering	20 - 60
Low-temperature tempering (300oC) of medium size components	5.0 - 40

Table 1: Typical Heat Intensities in Selected Induction Heating Applications.

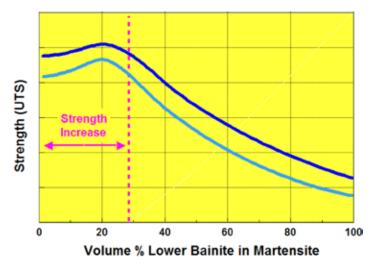


Figure 3

enon and explanation of its causes and benefits have been reviewed during these video seminars.

SUBTLETIES OF MIXED AS-HARDENED STRUCTURES

It is widely accepted that the hardness level of as-quenched steel increases as quenching severity rises. As the intensity of the cooling rate increases from air cooling through oil quenching to water quenching, it is expected that hardness will follow the cooling severity. Therefore, a fully martensitic structure exhibits the higher hardness and strength than alternative phases, but lower toughness and ductility. Though it is generally a correct assumption, the works of several researchers have indicated that, under certain conditions, the strength (UTS) of the tempered mixture of martensite and lower bainite can exceed the strength of the martensite alone (Figure 3) and yet, can be tougher than the cor-

Current Penetration Depth	n (mm)				
			Frequency		
Temperature (°C)	60 Hz	500 Hz	3 kHz	10 kHz	30 kHz
20	4.7	1.6	0.7	0.4	0.2
620	15.5	5.4	2.2	1.2	0.7
900	70	24.3	9.7	5.5	3.2

Table 2



One hurdle to the wide acceptance of induction tempering is that some metallurgists are not comfortable with shorter-time/higher-temperature rapid tempering. They feel an oven that heats the entire part and holds it at a temperature for hours is more suitable. Recent studies might change this opinion.

responding homogeneous phases [3]. Studies have also revealed that the mixed microstructures of lower bainite and martensite also may exhibit greater wear resistance than martensite.

The rule of mixtures, where the strength is expressed as a weighted average of component phases, does not explain this phenomenon. Several scientists (including Edwards, Mutiu, Zhou, Bhadeshia, and others) offered explanations of the causes of this phenomenon. Those explanations have been reviewed in presented materials.

INDUCTION TEMPERING VS. OVEN TEMPERING

Special attention has been paid to a comparison of rapid tempering vs. oven tempering applying following criteria:

- >> Time-temperature correlations.
- >> Required shop floor space.
- >> Heating uniformity.
- >> Metallurgical and performance characteristics.
 - >>> Energy efficiency and controllability.
- >>> Ergonomics and environmental friendiness.
- » In-line and single-piece processing capability, quality assurance, and monitoring.
- >> Cost factor, maintenance, and labor savings, etc.

Frequently, customers ask equipment manufacturers to quote the same system to induction harden and temper parts. It is possible to harden and temper parts using the same coil and the same power supply. In some cases, it is the best concept and has an obviously low capital cost advantage and less tooling to store; however, in other cases, it might not best suit the customer's requirements. Due to several reasons, in the great majority of applications, the inductor designed for hardening is not used for tempering. Some of those reasons include:

» In induction hardening, to obtain the required hardness pattern for a workpiece of complex shape, it is necessary to redistribute the electromagnetic field so as to introduce more energy in specific areas. However, an optimal field distribution for hardening might not be desirable for tempering. It is frequently recommended that the temper inductor should not heat only the selected hardened area but a much larger region or, in some cases, even the entire workpiece. Thus, substantially different coil design and frequencies might be required for tempering compared to hardening.

>> Depending on the type of power supply, load-matching restrictions might occur when trying to run an inverter at low power levels (e.g., 2 to 5 percent) suitable for tempering using an inverter designed for a hardening application.

>> In order to optimize a metallurgical quality of heat-treated products, it is advantageous to apply substantially lower frequencies for induction tempering compared to hardening because the tempering tempera-

tures are always below the Curie point. Since the workpiece retains its magnetic properties, the skin effect is pronounced. Table 2 illustrates typical current penetration depths (depth where the greatest majority of heat sources will be generated during induction heating) in medium carbon steel vs. frequency for different temperatures: room temperature (20°C), high tempering temperature (620°C) and for temperature exceeding Ac3 point (900°C). Analysis of Table 2 reveals that it is advantageous to use significantly lower frequencies for induction tempering. Besides that, the typical inductor designed for hardening at a high frequency might perform poorly in low-frequency tempering and vice versa. An exception is the application of IFP™ technology where an inverter can change frequency instantly more than 10 fold.



EV powertrain components must be strengthened to withstand the additional loads and stresses, enhancing metallurgical properties, yet minimizing distortion and noise characteristics.

>> Tempering is a diffusion-driven process; therefore, the time needed to complete it might be noticeably longer than for hardening. It may take seconds to induction harden but tens of seconds or even minutes to induction temper. Therefore, the production and power supply utilization might suffer if the same system is used for hardening and tempering.

Rapid heating deviates tempering kinetics and may even produce a nonsequential order of tempering stages [1], and this might be beneficial for heat treaters.

One hurdle to the wide acceptance of induction tempering is that some metallurgists are not comfortable with shorter-time/higher-temperature rapid tempering. They feel an oven that heats the entire part and holds it at a temperature for hours is more suitable. Recent studies may change this opinion.

However, relatively recently studies conducted by various researchers worldwide have suggested that rapid tempering at high temperatures (500 to 700°C range) can noticeably improve the impact toughness thanks to retardation of both: a dislocation recovery and cementite coarsening. This allows a noticeable increase in the number of nucleation sites and promotes a formation of fine dispersed cementite particles, reducing the amount of grain boundary carbides and enhancing the "toughness-to-hardness" ratio. Rapid tempering also may help to noticeably minimize or even eliminate temperembrittlement (TE) phenomenon.

Besides that, recent studies conducted by scientists from the Colorado School of Mines suggest that undesirable phenomenon such as tempered martensite embrittlement (TME) that could appear within the 200 to 400°C range can be minimized or, in some cases, even eliminated by applying rapid tempering. It has been reported

that SAE 4340 steel rapid tempering can improve fracture behavior and enhance impact toughness by an impressive margin exceeding 43 percent at a strength level of 1.7 GPa. Strength (UTS) is also noticeably improved over 0.5 GPa at an impact toughness of 30 J compared to conventional slow-tempered steel [2].

ICE VEHICLES VS. ELECTRIC VEHICLES

While it is expected that internal-combustion-powered vehicles will be part of the automotive landscape for decades to come, Inductoheat is adapting induction-thermal technologies for the electric-vehicle market [4]. Electric vehicles produce instant and noticeably higher torque over ICE vehicles when accelerating or changing speed. In addition, EV drivers can truly enjoy a smooth and quiet performance. Because of these factors, powertrain components must be strengthened to withstand the additional loads and stresses, enhancing metallurgical properties, yet minimizing distortion and noise characteristics.

Different aspects of applying modern induction thermal processing for both traditional ICE-vehicle and electric-vehicle markets have been discussed during the earlier-mentioned video seminars, which have been specifically created by Inductoheat Inc. for the needs of the modern automotive industry, unveiling recent theoretical discoveries and practical breakthroughs.

CONCLUSION

There are thousands of highly successful induction heat treating machines that produce millions of parts supplied to various industry segments. However, newly employed heat-treat practitioners, designers, failure analysts, and engineers may need an appreciable amount of time to gain the required knowledge and experience in understanding the subtleties of induction processing. Underestimating specific geometrical features of parts and hardness patterns by novices, as well as negligence in understanding an impact of different process factors on the outcome of heat treatment, may produce faulty results. Finding that your completed parts have cracked after heat treating is frustrating, wasteful, and expensive. The goal of these training video seminars is to minimize the impact of a workplace generation gap by helping professionals involved in induction hardening and tempering better understand critical factors and be aware of novel developments in induction-thermal processing.

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ABOUT THE COMPANY

Inductoheat is a global leader in induction thermal technology. It designs, builds, and repairs high-quality general purpose, turn-key, and fully automated induction heating and heat-treating equipment providing flexible long-life solutions used in high-, medium-, and low-frequency thermal applications. Inductoheat's experienced team of scientists, metallurgists, engineers, application experts, and aftermarket representatives stand ready to work with you. Inductoheat Inc. is part of 40 companies that make up the Inductotherm Group. For more information, go to www.inductoheat.com.





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In a total of nine experiments, the optimization of heat-treatment parameters of medium carbon steel quenched in different media was conducted using the Taguchi method and Grey relational analysis.

By O.O. AGBOOLA, P.P. IKUBANNI, A.A. ADELEKE, A.A. ADEDIRAN O.S. ADESINA, S.J. ALIYU, and T.S. OLABAMIJI

uenching is one of the major processes of heat treatment of medium carbon steel that aims at improving its mechanical properties. However, the effectiveness of this process is dependent on several control factors that must be maximized to obtain optimum results in terms of hardness, yield strength, and ultimate tensile strength, among others. This study aims at optimizing the process of improving the mechanical properties of medium carbon steel by varying some key factors such as the quenchant used (A), heat-treatment temperature (B), and soaking time (C). The measured responses in this study were the hardness, yield strength (YS), and ultimate tensile strength (UTS).

Optimization was conducted in two stages: The first stage dealt with the mono-optimization of process parameters using Taguchi's Signal-to-Noise (S/N) ratio. A total of nine experiments were performed based on standard L9 orthogonal array because each of the three control factors has three levels. The second stage was a multi-objective optimization using Taguchi-based grey relational analysis (GRA). The optimal conditions for hardness, YS, and UTS were obtained at $A_2B_3C_3$, $A_3B_2C_3$, and $A_3B_3C_3$, respectively. Using ANOVA as statistical analysis, it was observed that the soaking time was the main control factor for all three measured responses (31.95% contribution ratio for hardness, 62.46%, and 66.76% for YS and UTS, respectively), while the quenchant had the least contribution. Analysis of the Taguchi-based GRA revealed that the results obtained are in total conformance to that of the Taguchi method, with soaking time having the highest contribution ratio of 69.41%.

1 INTRODUCTION

Heat treatment is a property enhancement process that deals with the heating and cooling of metal in a solid-state. The objective of heat treatment is to impart certain desirable properties on metals (Ahaneku et al., 2012). Heat treatment can be performed on metals, ceramics, and composite material. Heat-treated materials undergo phase, microstructural, crystallographic, and phase transformation (Sreeja et al., 2016). The major aim of heat treatment is to enhance the mechanical properties of steel such as hardness, yield strength, tensile strength, ductility, and impact resistance. Heat treatment of steel involves the combination of controlled heating and cooling operations (Adeleke et al., 2019). The cooling process could be achieved by allowing the heated material to cool slowly under natural air or by dipping it in a quenchant. As reported by Ikubanni et al. (2017), quenching is a major process of heat treatment in enhancing the properties of carbon steel. Quenching is carried out to disallow the formation of ferrite or pearlite but to support the formation of bainite or martensite. Oil is a major quenchant (quenching medium), which consists of water, aqueous polymer solution, and various additives. Owing to the importance of quenching in the heat treatment

process, several researchers had previously used different kinds of quenching media to improve the properties of steels (Adeleke et al., 2018; Ikubanni et al. 2017, 2018; Adekunle et al., 2013; Odusote et al., 2012; Ndaliman, 2006).

The Taguchi method was first used in 1987 by Genichi Taguchi. It is one of the prominent optimization and statistical tools used in ranking the importance of different factors for a target function (Taguchi, 1987). Though the method was majorly applicable in experimental analysis, it could also be used in theoretical and numerical analysis (Hu et al., 2018; Naqiuddin et al., 2018; Arslanoglu and Yigit, 2017; Bao et al., 2013). In the study of Ikubanni et al. (2017), quenching media, heating temperature, and soaking time were identified as the major process parameters in the heat treatment of medium carbon steel (MCS). The mechanical properties evaluated were hardness, yield strength, and ultimate tensile strength. However, to optimize these process parameters, a further study involving the use of Taguchi analysis as well as Grey Relational Analysis (GRA) is required to be carried out. The Taguchi method allows a fewer number of experimental tests because it uses orthogonal arrays to minimize the effects of noise factors (Palanikumar, 2011; Taguchi and Konishi, 1987). The Taguchi method uses a loss function to determine the deviation between the experimental results and the desired values. This loss function is further converted into Signal-Noise (S/N) ratio (Asilturk and Akkus, 2011). There are three types of quality characteristics in the analysis of S/N ratio: the lower-thebetter, the nominal-the-best, and the higher-the-better (Gupta et al., 2011; Gunes et al., 2011; Liu et al., 2009; Jun et al., 2005).

Though Taguchi is a powerful optimization tool, it is not a suitable method for the simultaneous optimization of multi-objective functions (Canbolat et al., 2019). Therefore, GRA was applied to the mechanical properties of MCS to obtain the order (rank) of the importance of each process factor by maximizing the hardness, YS, and UTS of MCS. The concept of the Taguchi design of experiment, which is now applicable in all fields of research was first introduced in agriculture. According to Turgay (2014), the Taguchi method has been widely used in engineering applications such as design, analysis, engineering management, and so on. Hussein et al. (2018) optimized the heat-treatment parameters for the tensile properties of medium carbon steel. The optimal factors of heat treatment such as tempering temperature, nanoparticles percentage, base media type, nanoparticles type, and tempering time that would increase the yield strength, ultimate tensile strength, and ductility of the MCS were determined using the Taguchi technique. In manufacturing processes, Kumar and Singh (2019) optimized the rotary ultrasonic drilling of BK-17 optical glass using the Taguchi method and utility approach. The study focused on enhancing the machining efficacy by simultaneous optimization of conflicting target functions

using utility approach. The L9 orthogonal array was adopted for the experimental work. Feed rate, rotational speed of the tool, and ultrasonic power were selected as process parameters to evaluate their effects on the material removal rate and surface roughness.

Several studies have been done in the utilization of combined Taguchi-based and GRA methods in optimizing different processes. For instance, the milling characteristic was optimized using Taguchibased GRA by Sarikaya et al. (2016). The effects of the process parameters such as depth of cut, feed rate, cutting speed, and the number of inserts on the cutting force, vibration, and surface roughness were investigated. The findings revealed the optimum conditions were achieved at the depth of cut of 1 mm, feed rate of 0.05 mm/ rev, cutting speed of 308 m/min, and the number of insert of 1. A similar study was conducted by Meral et al. (2019) to optimize the characteristic of the hole drilled by novel drill geometries. In this study, the selected input parameters were drill geometries, cutting speed, and feed rate; while the measured responses were drilling torque, thrust force, and surface roughness. It was concluded that the desired surface roughness and thrust force were obtained with the geometry 4.

Nguyen et al. (2020) and Muthuramalingam et al. (2020) also adopted Tagugi-based GRA in the electrical discharge machining (EDM) process. In their study, Nguyen et al. (2020) chose peak current, pulse off time, pulse on time, and gap voltage as controllable factors. Responses such as average surface roughness, material removal rates, average layer thickness, and microhardness were obtained based on the selected controllable factors. Also, in the wire EDM process, Muthuramalingam et al. (2020) affirmed the selection of the wire electrode was the main factor that affects the quality measures in the wire EDM process, owing to its ability to create the energy required for a spark. In energy studies, the Taguchi method together with the GRA was used in a sizeable number of researches such as the use of the Taguchi method and GRA on a tubulated heat exchanger (Celik et al., 2018); multi-response optimization of geometric and flow parameters in a heat exchanger tube with perforated disk inserts by Taguchi grey relational analysis (Chamoli et al., 2016); and flat-plate collector process optimization with multiple quality characteristics in solar energy collector manufacturing (Kuo et al., 2011).

From the available literature, little or no study has been conducted on the application of the Taguchi-based method with GRA technique on the optimization of heat-treatment parameters of MCS. Therefore, this study aims at optimizing process parameters for the enhancement of the mechanical properties of MCS by using liquids that could have been termed as wastes such as engine oil (spent), coconut, and pap water as quenchants. The study optimized the responses such as hardness, yield strength, and ultimate tensile strength of heat-treated MCS by adopting the higher-the-better characteristics. The mono-objective optimization was done via Taguchi's S/N analysis while Taguchi-based gray relational analysis was used for the multi-objective optimization of the responses.

2 MATERIALS AND EXPERIMENTAL METHOD

2.1 Specimen preparation, heat treatment, and quenching The sample used in this study is a medium carbon steel (MCS) obtained from Omu-Aran metropolis market, Nigeria. The chemical composition of the MCS is as shown in Table 1.

Quenchants used were coconut water (CW), pap water (PW), and spent engine oil (SPE). With the aid of a medium-size lathe machine, specimens for hardness testing and tensile testing were prepared from MCS following ASTM standards. For induced stress reduction during machining, metallurgical re-conditioning, phase re-adjust-

С	Si	Mn	S	Cr	Ni	Cu	Fe
0.39	0.18	0.98	0.03	0.11	0.14	0.37	97.81

Table 1: Chemical composition of the medium carbon steel.

Parameters	Symbols			
		1	2	3
Quenchant	Α	CW	PW	SPE
Temperature	В	730	760	790
Soaking time	С	30	45	60

Table 2: The three process parameters and their levels.

ment, and homogenous structure, the specimens prepared were initially heat-treated to a temperature of 840°C using a muffle furnace and normalized. The prepared specimens were later heated in a muffle furnace to 730, 760, and 790°C, and soaked for 30, 45, and 60 minutes, respectively. After, the samples were quenched in the different quenchants (CW, PW, and SPE). Mechanical tests such as hardness and tensile tests were later conducted on the quenched samples.

2.1.1 Hardness test

Brinell hardness tester (EEDB 0006/43, Edibon) was used in determining the hardness values of the samples base on the ASTM E10-18 standard. A load of 500 N was used to cause an indent on the samples using a ball indenter. The dwelling time of 15 seconds was used. The indented diameter value was obtained. Equation 1 was employed to evaluate the Brinell's hardness number (BHN) for each sample. The average value of the BHN was recorded after triplicates hardness tests were done on each sample.

$$BHN = \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})}$$
 Equation 1

where:

F is the Force (N).

D is the indenter's diameter (mm).

d is the average indentation's diameters (mm).

2.1.2 Tensile test

Tensile testing was done on a Testometric machine (M500-50AT model) based on the ASTME8 standard. The tensile test specimen was loaded until it fractured. Recording of the gauge lengths of the samples was done before applying load. The yield and tensile strengths of each sample were also estimated from the generated data.

2.2 Experimental design and optimization

2.2.1 Taguchi method and design of experiment

The experimental design followed the Taguchi method to obtain the ranking of importance of different process parameters for the target functions (responses). In this study, the three process parameters considered are quenchant, heating temperature, and soaking time. The three levels for each factor chosen are shown in Table 2.

The Taguchi method was applied to the heat-treatment process in this study to maximize the hardness, YS, and UTS of MCS. The L9 orthogonal array was chosen to allow the three process parameters at the three different levels considered (Table 2). In the Taguchi analysis, the values of the responses were transformed into signal-to-noise (S/N) ratios. Since all three responses (hardness, YS, and UTS) were desired to be maximum, the higher-the-better performance characteristics for calculating the S/N ratio was chosen in this study by using Equation 2.

Exp No.	Process parameters			Respon	ses (Target fi	ınctions)	S/N ratio	S/N ratio for various Responses		
	Α	B(°C)	C (mins)	Hd (BHN)	YS (MPa)	UTS (MPa)	Hd	YS	UTS	
1	CW	730	30	166.40	162.90	171.10	44.423	44.238	44.665	
2	CW	760	45	609.97	264.80	268.80	55.706	48.458	48.589	
3	CW	790	60	573.35	358.50	399.20	55.168	51.090	52.024	
4	PW	730	45	349.19	116.10	138.50	50.861	41.297	42.829	
5	PW	760	60	532.37	407.40	427.80	54.524	52.200	52.625	
6	PW	790	30	471.59	224.10	252.60	53.471	47.009	48.049	
7	SPE	730	60	332.27	342.20	399.20	50.430	50.686	52.024	
8	SPE	760	30	243.48	236.30	277.00	47.729	47.469	48.850	
9	SPE	790	45	311.41	317.80	342.20	49.867	50.043	50.686	

Equation 2

Table 3: Experimental results and their S/N ratios.

$$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right)$$

where:

n is the number of replication for each experiment.

 y_i described the result value for the i_{th} performance characteristics.

2.2.2 Analysis of variance (ANOVA)

ANOVA is a statistical tool used in determining the individual interactions and the contribution ratio of all the parameters in the experimental design. ANOVA was used to analyze the effects of quenchant, heating temperature, and soaking time on the hardness, YS, and UTS of the MCS. Since ANOVA highlights the importance order of influencing parameters on the response, it helps in validating the results obtained through the Taguchi method. In this study, Minitab 19 (Statistical software) was used for both ANOVA and Taguchi analysis.

2.2.3 Confirmation test

After establishing the optimum values of hardness (Hd_{opt}), yield strength (YS_{opt}), and ultimate tensile strength (UTS_{opt}) using the Taguchi method, a confirmation test was conducted to validate the optimum conditions (Mandal et al., 2011). Optimum values of the responses were estimated using Equations 3, 4, and 5:

$$Hd_{opt} = m_h + (A_2 - m_h) + (B_3 - m_h) + (C_3 - m_h)$$
 Equation 3

$$YS_{opt} = m_y + (A_3 - m_y) + (B_2 - m_y) + (C_3 - m_y)$$
 Equation 4

$$UTS_{opt} = m_u + (A_3 - m_u) + (B_3 - m_u) + (C_3 - m_u)$$
 Equation 5

where $(A_2B_3C_3)$, $(A_3B_3C_2)$, $(A_3B_3C_3)$ represent the values of the optimum level of hardness, yield strength, and ultimate tensile strength respectively. m_h , m_y , and m_u are the average of all the Hd_{opt} , YS_{opt} , and UTS_{opt} , respectively, obtained from the experimental study.

To determine if the optimum values of the responses agree with the experimental values, confidence intervals (CI) were calculated for each response (Dvivedi and Kumar, 2007) using Equations 6 and 7.

$$CI = \sqrt{F_{a, 1, fe} \ V_e \left[\frac{1}{n_{eff}} + \frac{1}{R} \right]}$$
 Equation 6

$$n_{\text{eff}} = \frac{N}{1 + T}$$
 Equation 7

where

 $F_{\alpha_{1}f_{e}}$ = F ratio at a 95% confidence.

 α = significance level.

 f_e is the degrees-of-freedom of error.

 V_e = variance's error.

 $n_{\rm eff}$ = effective number of replications.

R = number of confirmation experiments' replication.

N =total number of experiments.

 T_{dof} is the total main parameters degrees of freedom.

2.2.4 Grey relational analysis (GRA)

Taguchi is an unsuitable method for the simultaneous optimization of multiple-objective functions. Hence, the GRA method was applied to achieve the ranking of importance of each process parameter on multiple performance characteristics by maximizing all the responses (hardness, yield strength, and ultimate tensile strength) simultaneously.

First, the experimental results were normalized (usually in the range of 0-1). The higher-the-better performance characteristic in Equation 8 was used for all the target functions because the maximum values of all the three responses are desired.

The higher – the – better,
$$yi(s) = \frac{x_i(s) - minx_i(s)}{maxx_i(s) - minx_i(s)}$$
 Equation 8

After normalization, the grey relational coefficient is calculated using Equations 9 and 10 $\,$

$$arepsilon_i(s) = rac{\Delta_{min} + arphi \Delta_{max}}{\Delta_{oi}(s) + arphi \Delta_{max}}$$
 Equation 9

$$\Delta_{oi}(s) = |x_o(s) - x_i(s)|$$
 Equation 10

where $\Delta_{oi}(s)$ is the deviation sequence calculated from Equation 10 $x_i(s)$ is the comparability sequence, $\max x_i(s)$ and $\min x_i(s)$ are maximum and minimum comparability sequence respectively, $x_o(s)$ is the referential sequence, ϕ is the identification coefficient, which ranges from 0 to 1. In GRA, using any value between 0 and 1 for ϕ would not change the order of importance of the parameters but 0.5 is normally chosen (Naqiuddin et al., 2018; Acir et al., 2017; Chamoli et al., 2016; Turgut et al., 2012; Kuo et al., 2011; Tosun, 2006).

The grey relational grade (GRG) was then estimated by using Equation 11 before the final ranking was done.

GRG = 0.3547 Hardness + 0.3246 YS + 0.3207 UTS Equation 11

3 RESULTS AND DISCUSSION

3.1 Analysis of the signal-to-noise ratio (S/N)

The hardness (Hd), yield strength (YS), and ultimate tensile strength (UTS), which are the responses (target functions) of the MCS, are displayed in Table 3. Table 3 also presents the S/N ratios for the various responses.

3.1.1 Analysis of a response (Hardness)

The average S/N ratios and the ranking of the importance of process parameters on the hardness value (Table 4). Figure 1 represents the main effect of each parameter on the hardness of the MCS.

According to Canbolat et al. (2019), when the highest and lowest S/N ratios variation is small, it implies there is a relatively low effect of the parameter on the response. More so, the design parameters level with maximum S/N indicates the optimum conditions of the system. Hence, the process parameters to obtain the optimum values for maximum hardness are determined as Quenchant = PW, Temperature 790°C, and Soaking time = 60 minutes (Figure 1). This implies that when the heat treatment is done in PW at a heating temperature of 790°C with a soaking time of 60 minutes, i.e. $A_2B_3C_3$, the highest hardness can be obtained. Therefore, the optimum hardness from the operating condition range of this study is found when the heat-treatment process was done under the optimum working condition ($A_2B_3C_3$). This agrees with the study of Ikubanni et al. (2017), which opined that CW and PW could be used as quenchants when improving the hardness of MCS.

For the results to be statistically reliable, the ANOVA method was used to validate the Taguchi analysis results (Sarikaya and Güllü, 2014). This is done to estimate the percentage contribution of each parameter of the heat-treated samples in the different media on the hardness property of the MCS. The usage of the ANOVA shows the impacts of process parameters on the hardness, as shown in Table 5 and Figure 2.

Soaking time was observed to be the major process parameter on the hardness of the heat-treated MCS with an impact ratio of 31.95% based on the ANOVA results. Contribution ratios, shown in Table 4, also indicates that the ranking of the importance of the process parameters on the hardness of the MCS was Soaking time > Temperature > Quenchant. The main effect plots of the Taguchi method and the ANOVA results gave a similar ranking of the effect of the process parameters on the hardness of MCS. The results in the present study affirm the report of Singh et al. (2013) on the effect of soaking time on the behavior of carburized mild steel, where it was stated that the soaking time increment has a direct influence on the hardness value increment of the mild steel used. It was similarly reported by Valdes-Tabernero et al. (2019) that fraction of the recrystallization ferritic matrix with embedded martensitic and retained austenite grains generally tends to increase with increasing soaking time, thus, the tendency of an increased hardness in mild carbon steel. Therefore, an increase in soaking time above all other process parameters during the heat treatment of MCS has the largest impact on its hardness.

3.1.2 Analysis of target functions (Yield strength and ultimate tensile strength)

Table 6 shows the average S/N ratios and the rank of the importance of the process parameters on the values of YS and UTS. Figures 3 and 4 represent the effect of each parameter on the YS and UTS, respectively. It can be observed from Table 6 that soaking time was ranked first with a higher influence on the yield strength of the heat-treated MCS among the three process parameters that were considered. Similarly, Table 6 shows that soaking time, which was constantly ahead of temperature, had the highest influence on the ultimate tensile strength of the heat-treated MCS. The use of SPE as quenchant while operating at 760°C and soaking for 60 minutes was the optimum values of the process parameters for which the maximum YS, as shown in Figure 3 (A₃B₂C₃). While the soaking (60 minutes) and the quenchant (SPE) were unchanged as the optimum values as process parameters to obtain optimum ultimate tensile strength for the treated MCS, the temperature changed from 760 to 790°C, as shown in Figure 4. The

Level	Quenchant	Temperature	Soaking time
1	51.77	48.57	48.54
2	52.95	52.65	52.14
3	49.34	52.84	53.37
Delta	3.61	4.26	4.83
Rank	3	2	1
Σ Delta	12.7		
Weight	35.4749%		

Bold value signifies to show the level at which the optimum condition is achieved for each process parameter.

Table 4: Response for S/N ratios (hardness vs. quenchant, temperature, and soaking time).

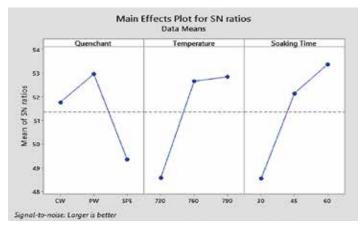


Figure 1: The main effect plots for S/N ratios on hardness (Taguchi).



Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	R-sq
Quenchant	2	47902	47902	23951	1.73	0.366	0.86
Temperature	2	54349	54349	27175	1.97	0.337	
Soaking Time	2	60981	60981	30491	2.21	0.312	
Error	2	27625	27625	13813			
Total	8	190858					

Table 5: ANOVA results on the hardness of MCS.

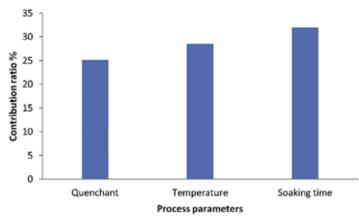


Figure 2: Contribution ratio of each process parameter on the hardness of MCS (ANOVA).

Level Yield strength	Quenchant	Temperature	Soaking time
1	47.93	45.41	46.24
2	46.84	49.38	46.6
3	49.4	49.38	51.33
Delta	2.56	3.97	5.09
Rank	3	2	1
Σ Delta	11.62	•••••	•••••
Weight	32.46%		••••••
Ultimate tensile st	trength		
1	48.43	46.51	47.19
2	47.83	50.02	47.37
3	50.52	50.25	52.22
Delta	2.69	3.75	5.04
Rank	3	2	1
Σ Delta	11.48		••••••
Weight	32.07%	•••••	•••••

Table 6: Response for S/N ratios (YS and UTS vs quenchant, temperature, and soaking time).

maximum UTS was obtained when the heat treatment was done under the optimum working condition ($A_3B_3C_3$). The ANOVA results of the effects of various process parameters on the YS and UTS are presented in Table 7, while the contribution ratios are presented in Figure 5. This corroborates the study of Ikubanni et al. (2017).

It was stated that the usage of SPE would assist in improving the strength of the MCS. Oil gives better strength compared to water-based quenchants (Adeleke et al., 2018; Vivek et al., 2014; Odusote et al., 2012); hence, for utilization in areas where strength and ductility are important, SPE should be used. The ANOVA results in Table 7 show that soaking time has the largest influence on the YS and UTS of the heat-treated MCS. A similar trend was observed with the contribution

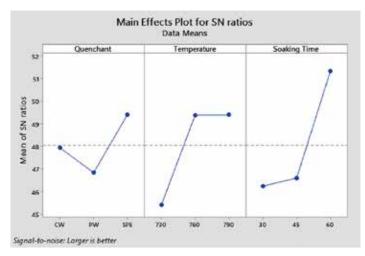


Figure 3: Main effect for S/N ratio of each parameter on yield strength (Taguchi).

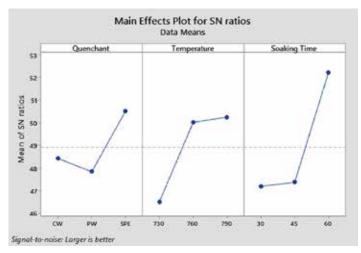


Figure 4: Main effect for S/N ratio of each parameter on ultimate tensile strength (Taguchi).

ratios in Figure 5, where soaking time has the highest values of 62.46 and 66.76% for the YS and UTS, respectively. Therefore, based on the contribution ratio, the important order of the process parameters on the YS of the heat-treated MCS was Soaking time > Temperature > Quenchant. For all the three target functions (hardness, YS, and UTS), the quenchant was less influential in determining the manner of behavior of the heat-treated medium carbon steel when compared with other parameters such as temperature and soaking time. An increase in soaking time yielded an increase in tensile strength. This agrees with the study of Valdes-Tabernero et al. (2019). The study reported the influence of soaking time on the heat-treatment process of MCS. The Taguchi analysis and ANOVA method used in this study also ranked the soaking time as the most influential factor, followed by the temperature, while the quenchant was ranked least. The ranking order of both methods was the same, which is a means of confirming the reliability of their use as optimization tool (Canbolat et al., 2019; Celik et al., 2018; Chamoli et al., 2016).

3.1.3 Confirmation test

This study conducts a confirmatory check to accurately determine the correct optimization of the process. The obtained result was conducted to check if the values are within the confidence interval (CI). CI was estimated using Equation 6. F_{0.05,1,2} = 18.51 (F-table), $V_{\rm eH}$ = 13,813 (Table 4), $V_{\rm eYS}$ = 2,728 (Table 8), and $V_{\rm eUTS}$ = 1,534 (Table 8), R=3, N=9, $T_{\rm dof}$ =6 and $t_{\rm eff}$ 1.2857 (Equation 7). Confirmation

experiments were conducted based on the established optimum conditions for each target function and the result is presented in Table 8. The computed values of CI in Table 8 show that experimental optimum values for each process parameter are within an acceptable limit.

3.1.4 Grey relational analysis (GRA)

The optimum working conditions obtained from Table 8 are not the same for hardness, YS, and UTS.

Hence, the multi-objective technique is required to complement the Taguchi method used. GRA method was adopted to reduce the three target functions (maximization of the hardness, YS, and UTS) of MCS into a single objective function (known as multiple performance characteristics, MPC). Using Equations 8, 9, 10, and 11, the result of the normalized response, grey relational coefficients (GRC), grey relational grade (GRG), and ranks were determined and presented in Table 9. The variation of the GRG is shown in Figure 6. According to Kuo et al. (2011), an experiment that has the highest GRG among all the experiments gives the maximum MPC. In this study, experiment 5 gave the maximum MPC. The response was generated, as shown in Table 10, for the GRG to estimate the ranking of the importance of each parameter. Accordingly, the importance orders were ranked as Soaking time > Temperature > Quenchant (Table 10). Figure 7 shows the main effect of each parameter on the MPC of the heat-treated MCS. The level three of each of the process parameters $(A_3B_3C_3)$ gave the optimum condition for multiple characteristics of MCS. ANOVA method was used to evaluate the results of GRG and the % contribution of each parameter, as displayed in Table 11. ANOVA method indicates the soaking time and temperature were the two parameters with the highest effect on MPC with a % contribution of 69.41% and 25.42%, respectively (Table 11). The ranking order is Soaking time > Temperature > Quenchant. These results are consistent with the responses in Table 10 for the grey relational grade.

4 CONCLUSION

In the present study, the combination of the Taguchi method and the Grey relational analysis has been used to determine the optimal heat-treatment process parameters required to improve the mechanical properties of medium carbon steel. The heat-treatment parameters such as temperature, soaking time, and quenchant used have been used to analyze the effects on the hardness, yield strength, and the ultimate tensile strength. The experimental results were evaluated and validated by the ANOVA method. It can be concluded that:

» The optimal conditions for maximizing hardness, yield strength, and ultimate tensile strength were obtained with the combination found to be $A_2B_3C_3$ [quenchant (PW), temperature (790°C), and soaking time (60 minutes)]; $A_3B_2C_3$ [quenchant (SPE), temperature (760°C), and soaking time (60 minutes)], and $A_3B_3C_3$ [quenchant (SPE), temperature (760°C), and soaking time (60 minutes)], respectively.

>> The soaking time is the most significant parameter for all three target functions with 31.95% contribution ratio for hardness, 62.46% for yield strength, and 66.76% for ultimate tensile strength.

>> The measured values of the responses (hardness, yield strength, and ultimate tensile strength) were within a 95% confidence interval based on the confirmatory test results.

"The Grey relational analysis and Taguchi method confirmed soaking time as the major process parameters having the highest contribution ratios that were above 60% in both cases.

Source Yield strength	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	R-sq
Quenchant	2	3969	3969	1985	0.73	0.579	0.92
Temperature	2	17840	17840	8920	3.27	0.234	•••••••••
Soaking Time	2	45369	45369	22685	8.32	0.107	••••••••••
Error	2	5455	5455	2728	•••••	••••••	••••••••••
Total	8	72634	•	***************************************	•••••	•	••••••••
Ultimate tens	ile s	trength					
Quenchant	2	8040	8040	4020	2.62	0.276	0.96
Temperature	2	16875	16875	8437	5.5	0.154	••••••••••
Soaking Time	2	56197	56197	28099	18.32	0.052	••••••••
Error	2	3068	3068	1534	•	•	••••••••••
Total	8	84180					

Table 7: ANOVA results of the effect of process parameters on the yield and ultimate tensile strengths of MCS.

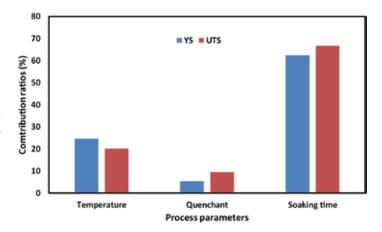


Figure 5: % contribution of each process parameter on the yield and ultimate tensile strengths of MCS (ANOVA).

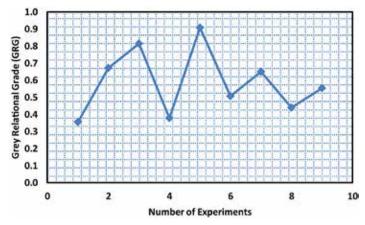


Figure 6: GRG for the maximum performance characteristic.

Target Function	Optimum condition	Optimum value by Experiment	CI
Hardness (BHN)	A2B3C3 (Q ¼ PW, Temp ¼ 790 C, St ¼ 60)	499.23	±533
Yield strength (Mpa)	A3B2C3 (Q ¼ PW, Temp ¼ 790 C, St ¼ 60)	382.90	±237
Ultimate tensile strength	A3B3C3 (Q ¼ PW, Temp ¼ 790 C, St ¼ 60)	325.90	±178

Table 8: Experimental values obtained for each target function based on optimum conditions.

Exp No.	o. Normalized Results			Grey Re	lational Coef	GRG	Rank	
	Hardness	YS	UTS	Hardness	YS	UTS		
1	0.0000	0.1607	0.1127	0.3333	0.3733	0.3604	0.3550	9
2	1.0000	0.5105	0.4504	1.0000	0.5053	0.4764	0.6715	3
3	0.9174	0.8321	0.9011	0.8583	0.7487	0.8349	0.8152	2
4	0.4121	0.0000	0.0000	0.4596	0.3333	0.3333	0.3781	8
5	0.8251	1.0000	1.0000	0.7408	1.0000	1.0000	0.9080	1
6	0.6880	0.3708	0.3944	0.6158	0.4428	0.4522	0.5072	6
7	0.3739	0.7762	0.9011	0.4440	0.6908	0.8349	0.6495	4
8	0.1738	0.4126	0.4787	0.3770	0.4598	0.4896	0.4400	7
9	0.3269	0.6924	0.7041	0.4262	0.6191	0.6282	0.5536	5

Table 9: Normalized results, grey relational coefficients, grey relational grade, and rank.

>> The results show that the Taguchi method as well as the Grey relational analysis is a reliable method for the maximization of mechanical properties (hardness, yield strength, and ultimate tensile strength) of medium carbon steel quenched in various media.

Future studies could be considered on the effect of the aforementioned process parameters on the properties and performance of MCS such as corrosion resistance, wear resistance, machinability, and so on.

Level	Quenchant	Temperature	-7.34 -5.68		
1	-5.34	-7.06			
2	-5.06	-4.27			
3	-4.74	-3.81	-2.12		
Delta	0.6	3.26	5.22		
Rank	3	2	1		

Table 10: Response for GRG.

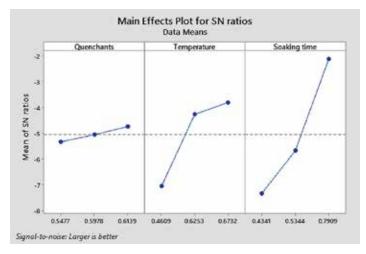


Figure 7: Main effect for S/N ratios of each parameter on the multiple performance characteristics.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	R-sq
Quenchants	2	0.00715	2.44%	0.00715	0.00358	0.9	0.527	0.97
Temperature	2	0.07442	25.42%	0.07442	0.0372	19.34	0.097	
Soaking time	2	0.2032	69.41%	0.2032	0.1016	25.5	0.038	
Error	2	0.00797	2.72%	0.00797	0.00398			
Total	8	0.29275	100.00%					

Table 11: ANOVA for Grey relational grade.

AUTHOR CONTRIBUTION STATEMENT

Agboola, O.O. and Ikubanni, P.P.: Conceived and designed the experiments, performed the experiments, analyzed and interpreted the data, wrote the paper. Adeleke, A.A.: Conceived and designed the experiments; performed the experiments, analyzed and interpreted the data. Adediran, A.A., Adesina, O.S., Aliyu, S. J., and Olabamiji, T.S: Conceived and designed the experiments; performed the experiments, contributed reagents, materials, analysis tools or data.

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COMPETING INTEREST STATEMENT

The authors declare no conflict of interest.

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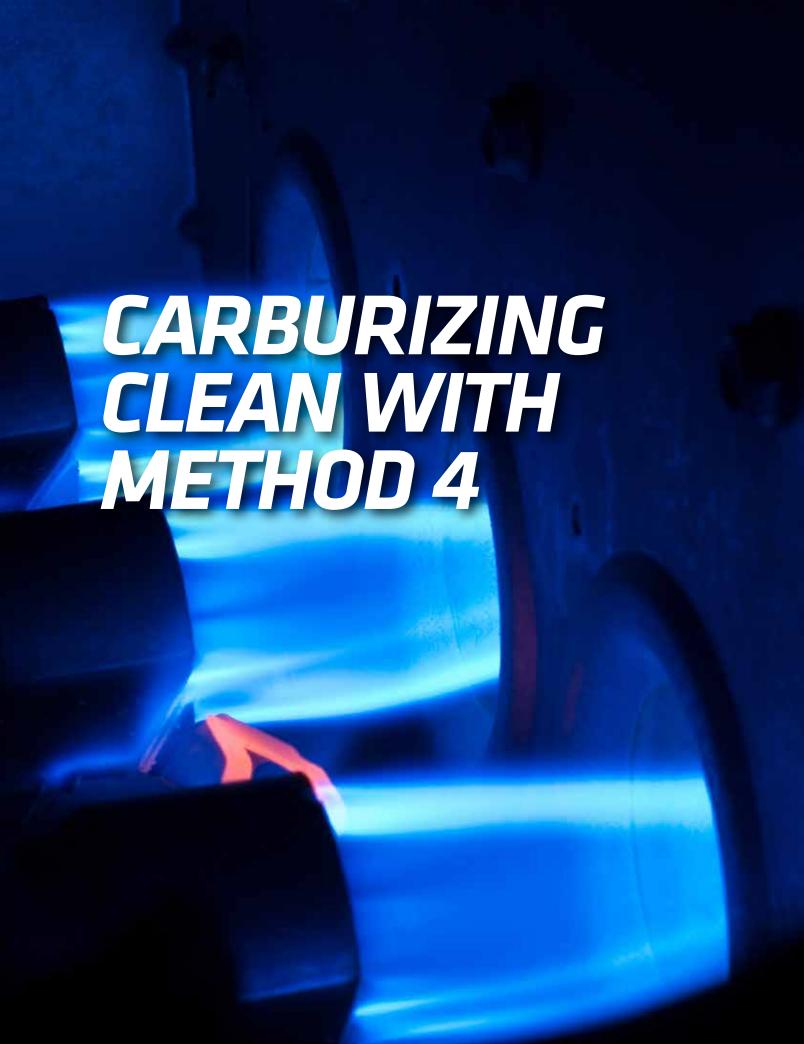
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Method 4 gives new meaning to a continuous furnace operation without expensive down time for soot removal and a clean furnace to produce more workloads in less time.

By GEORGE BARBOUR

he existing model for removing soot from a furnace is a burn-out consisting of three methods:

>> **Method 1:** Remove the load, lower the furnace temp, open the door, and let air burn out the soot.

>> **Method 2:** Remove the load and the atmosphere and add a small amount of air to the furnace for eight hours or more.

>> Method 3: Use a wand and direct a small amount of air to carbon spots.

These functions are difficult and need a trained operator to perform them. The furnace temperature is lowered to prevent

overheating the furnace when air is added to burn out the soot. This combustion could raise the furnace temperature beyond the set point and cause damage to the furnace.

There is a Method 4 (a product of the Heavy Carbon Co. endocarb system), which is very easy to use. Method 4 does not add air to the furnace for soot burn-out. Method 4 controls the soot level by controlling the CH4 in the atmosphere with changing of the air/gas ratio in the atmosphere for a rich or lean mix.

ELIMINATING SOOT BURN OUT

Method 4 eliminates the need for soot burn out. With this method, soot control is a matter of just setting the furnace control instrument set point to the desired carbon potential (CP) and let method 4 clean the furnace. This is possible even while carburizing a load of parts; method 4 is automatic as programmed. The endocarb atmosphere system is easy to program and use, but it is very precise (see Figure 1). Most any brand of control instrument will work with this system. The control instrument

is not the reason for this system to work. It only carries out the program in the menu.

This system will drive the CP through the steel surface at a higher rate than predicted by the Harris equation and will give a sharper RC dropoff at the effective case depth (ECD) for a more ductile core. Method 4 atmosphere will penetrate a very dense load such as bearing balls and rollers as well as gears. This will create gears and bearings with a high carbon content to the ECD and a high RC with a ductile core, as well as great gears and bearings for wind turbines.

Method 4 is used in a boost/diffuse cycle to drive a high CP through a steel surface while controlling the level of CH4 and maintaining the constant high CP in a clean furnace while producing an active reaction. The reaction does not perform well in a sooted furnace.

Method 4 operates in a 30-minute time frame in one or more cycles to complete a carburizing requirement time. A typical standard carburizing cycle operates with a CP set point of about 1.00%C or less. At a set point of 1.15%C, soot will start to form. A set point higher than 1.15%C will soot the furnace and hamper the reaction. Carburizing with method 4 starts a program much higher with a boost CP set point of about 1.70%C. The CP set point for the diffuse in each cycle is about 1.30%C.

In order to function at these high CP numbers, a few rules must be followed. It takes more than just programming a menu into an



Figure 1: Endocarb unit with burner, retort, and burner tube.

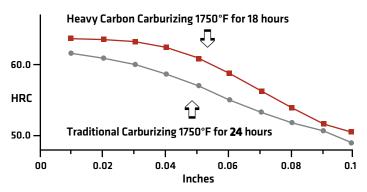
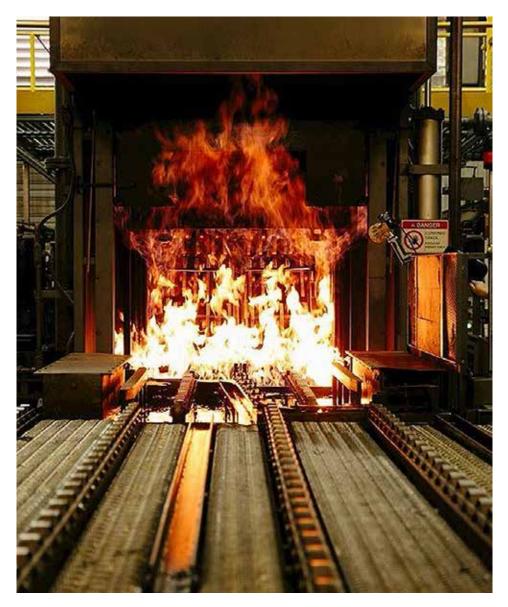


Figure 2: Endocarb results compared to standard carburizing.



Method 4 control will eliminate a very expensive soot burn-out time. This expense is from loss of furnace loads and also the expense of operating an empty furnace.

instrument to function at these extreme numbers. A few rules start with: catalytic action, air/gas ratios, time involvement, and rules pertaining to method 4. The lower CP in the diffuse will produce an atmosphere that is lean enough to bring down the CH4 level but not too lean to cause decarb in the load.

SELF-ADJUSTING AIR/GAS RATIO MIX FLOW

This air/gas ratio mix flow into the endocarb is self-adjusting under the command of the furnace instrument. The command from the instrument is the CP setting. The ratio will change to meet that command. During the boost, the CH4 may reach a level as high as 5%CH4. This high level will be lowered to about 1%CH4 during the diffuse cycle. As the CH4 is lowered, the soot level is lowered, and the reaction is brought under control. This would not be possible without the endocarb atmosphere system. The operating temperature for the endocarb is about 1,825°F. An air/gas mix enters the endocarb where it is cracked into the proper atmosphere for the job required. Unlike standard carburizing, this atmosphere then enters the furnace at a temperature of 1,825°F.

With standard carburizing, an endogas atmosphere with enriching gas enters the furnace at a temperature that is less than 300°F and must react with a furnace temperature as low as 1,600°F. The endogas atmosphere will penetrate the load thoroughly and reach an effective case depth at a rate of up to 30 percent faster compared to the Harris equation. Results of a standard carburizing cycle compared to a carburizing cycle using the endocarb atmosphere system is displayed in Figure 2. This is a box chart to represent 0.100 ECD.

To cover this space, a standard carb cycle will require 24 hours. To cover the same space, the endocarb system with method 4 will require only 18 hours, resulting in a savings of six hours. At this rate, the endocarb savings using method 4 will pay for both the endocarb and the furnace quickly while using less energy.

ELIMINATING SOOT BURN-OUT TIME

Method 4 control will eliminate a very expensive soot burn-out time. This expense is from loss of furnace loads and also the expense of operating an empty furnace.

Once programmed into the system, method 4 will follow the command of the furnace-control instrument. Method 4 will control the ratio of the air/gas mix in the endocarb unit. It will add just enough air to the endocarb to eliminate the soot without damage to the furnace or the load.

With method 4, there is no need to lower the furnace temperature or to remove the load because the furnace will not overheat with this method. It is possible to use method 4 even while running a load of parts. Soot control is a matter of just setting the set point to the desired CP. Method 4 will operate safely even while carburizing a load of parts with no ill effects.

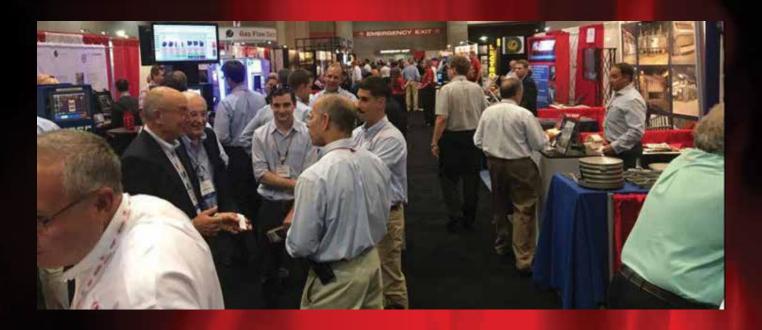
Ammonia may be added to the furnace at lower temperatures if desired, although, with method 4, that may not be necessary to produce a high RC.

For the method 4 operation, the endocarb is required.

ABOUT THE AUTHOR

George Barbour is retired, but for the last 20 years, he has worked with Euclid Heat Treating Co. in Cleveland, Ohio, on R&D and how to control the quality of atmosphere. While working on enhanced atmosphere control, Barbour discovered a way to drive a higher carbon content through a steel surface at a higher rate in less time.

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Applied Test Systems offers custom solutions by providing quality furnaces, ovens, and other products that are reliable, accurate, and user friendly, while offering outstanding field service and worldwide calibration on all manufacturers' equipment.

By KENNETH CARTER, Thermal Processing editor

he primary function of furnaces and ovens is to heat things up, but how efficiently that function is performed is the primary directive of Applied Test Systems.

ATS was founded by producing equipment for nondestructive testing for materials, mostly metals, according to COO Rob Carroll. But that task soon dovetailed into custom-designed furnaces and ovens for a wide range of industries, including heattreating.

"We just started adding product lines," he said. "A lot of it was driven by customers requesting something they couldn't find elsewhere in the market, who weren't satisfied with what they had and what was available at the time."

INITIAL OFFERINGS

Some of those products were used for creep testing and stress-rupture testing, used primarily for the metals, aerospace, and nuclear industries, according to Carroll. In order to use that equipment, the product has to be heated correctly for testing, which involves high-temperature characterization of metals, ceramics, and composites.

"Those required a furnace," he said. "And, at the time, we really couldn't find any on the market that would hold the uniformity—the tight temperature profile required. It's typically a three-zone application. We try to hold a very tight tolerance between those zones, so we developed our own line of furnaces specifically for that application."

More products sprung from that, including a line of universal testing machines for tension and compression of materials, according to Carroll.

"From that grew a lot of requests for furnaces and ovens that customers couldn't find in the market," he said. "They couldn't find the quality; they couldn't find the temperature uniformity or just the options for their applications."

CUSTOM SOLUTIONS

With increasing customer demand, ATS slowly added a full line of high-temperature furnaces and ovens, according to Carroll. More often than not, those customer needs resulted in custom-made solutions, mainly because no one else was capable of fulfilling them.

"We filled that role," he said. "And that line has continued to grow and evolve from that into different markets, different applications, and different customer bases where we now sell worldwide with a line of furnaces and ovens. We're really known throughout the world in a lot of industries for our quality and the unique features we can offer."

However, the results of those often-one-off custom solutions end up incorporated into ATS' everyday product line, according to Carroll.

"We do have standard product offerings for the furnaces and ovens, but I'd say 80 percent of what ships here is custom," he said.



A rotating furnace. (Courtesy: Applied Test Systems)

"It's a standard design, but it's tailored to that customer-specific application, be it temperature range, be it the zones, ports, you name it. There's pretty much nothing we can't tackle here, because we have the capability to add a lot of features to the product."

In that vein, ATS can boast of many certifications, including ISO 9001 and ISO 17025, used for calibrating laboratory equipment.

MULTIPLE HEAT-TREAT USES

And even though ATS doesn't specifically cater to the heat-treat industry, so many of its products are used for heat treating, according to Robert Antolik, vice president of sales.

"We might not be known in the heat-treat industry, because we're not heat-treat experts, but, yes, a lot of our furnaces are used in the heat-treat industry, but it's all different industries that they're used in," he said. "We have people shooting microwaves through them. We have people using them on testing machines. Some of our competitors that build machines buy our furnaces. We have companies heating things as large as 20 tons in some of our units, and then we make a small unit that might heat something that's a couple of ounces."

That flexibility is where ATS' custom-design engineering often comes into play, according to Antolik.

"The customer may want to heat up a pipe in a certain section, and it might go vertically 20 inches tall and then curve to the right," he said. "We can make all the custom designs to make that furnace adapt to those shapes. And then, being in the industry of testing machines, we can add a lot of PLC-controlled motions. In the heat-

"Like I always say about the heating industry, just about anywhere you go, there's somebody who has to heat something. That industry is going to continue to grow, and there's nothing out there that's going to replace it."



With increasing customer demand, ATS slowly added a full line of high-temperature furnaces and ovens. (Courtesy: Applied Test Systems)

treat industry, you have gas flows and things of that nature, and we can add all that to it."

Antolik added that ATS is one of the few companies that can offer that capability.

"I like to say that we're an engineering company first and want to design what you need and not sell you what we have," he said.

HIGH QUALITY

Because ATS offers custom applications for its customers' needs, the company considers itself on the high end of quality, according to Antolik.

"We build a product that's long lasting that can be rebuilt time and time again, giving the customer a good long-term value for their investment," he said.

Giving customers what they need begins with ATS' highly trained sales people, according to Antolik.

"Most of us actually were in engineering at first, and we're kind of oddballs that can speak, also," he said with a laugh. "We know what the customer wants, and we can design things in our heads, and, every time there's something different, it's a fun challenge. And if

it's very difficult, quite often we'll run that through our engineering department, and we'll have development meetings — we call them highly-engineered meetings — to see if we can come up with a solution for the customer."

OFFERING SOLUTIONS TO PROBLEMS

When a customer comes to ATS not knowing where to begin, Antolik said those types of customers are the ones ATS can serve extremely well

"That's probably the best kind of customer," he said. "Instead of them coming and telling you, 'This is what I want,' I prefer them to say, 'This is what I'm doing; tell me what I need. I'd like to heat something to this temperature, and it's this size,' instead of them telling me, 'I want this model.' We do this every day."

Carroll agreed.

"It's much better when they give us a problem, and we just give them a solution," he said.

That customer approach seems to be paying off as Carroll pointed out ATS' repeat customer base.

"We have extremely loyal customers, which I think is probably



ATS performs creep testing. (Courtesy: Applied Test Systems)



A car-bottom furnace. (Courtesy: Applied Test Systems)

the biggest achievement any company can obtain," he said. "Pretty much once we have a customer on board, it's not common we would lose that customer. That repeat customer who knows your product, buys it."

That customer base runs through many industries, as well as universities and government research facilities, according to Carroll.

"A lot of government testing facilities in the U.S. utilize our furnaces, ovens, and production facilities," he said. "We'll develop applications for production line use."

HEAT IS HEAT

ATS has certainly moved with the times since opening its doors in 1965, but as Carroll pointed out: As far as heating goes, heat is heat.

"That really will never change," he said. "Change has come mostly on the control side. Years ago, you had mercury contractors that operated furnaces. Now, you have smart SCRs that can tell you exactly what wattage and voltage and power consumption are being used."

With many large laboratories throughout the world using ATS' furnace and oven lines, the company is constantly developing quality products that often become new offerings, according to Carroll.

"There's always something new we have in the works," he said.

As ATS continues into the future, Carroll said the company will continue to develop niche applications where customers need excellent temperature uniformity.

"That's become a very important driver in the heat-treat market, and it fulfills those needs where customers want to see the value in a product that's going to be long lasting, not a throwaway product," he said.

The need for furnaces and ovens across a variety of industries and academic settings will only expand, and Antolik said ATS will be there to make sure its customers have the highest quality equipment available.

"Like I always say about the heating industry, just about anywhere you go, there's somebody who has to heat something," he said. "That industry is going to continue to grow, and there's nothing out there that's going to replace it. I just think it's a good market to be in."

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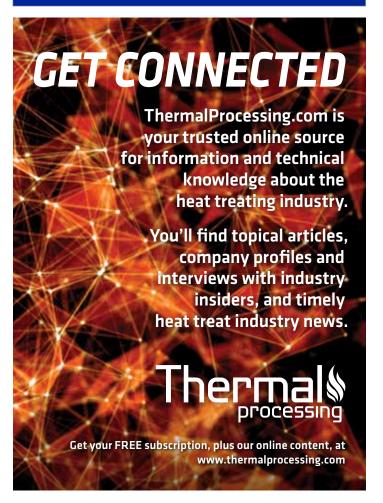
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Q&A /// INTERVIEW WITH AN INDUSTRY INSIDER



TOM SCHULZ /// SALES MANAGER /// L&L SPECIAL FURNACE CO., INC.

"All of our XLE furnaces come with many options so they can be used for multiple different applications."

What makes the L&L model XLE214 floor standing box furnace ideal for the aerospace industry?

L&L Special Furnace has grown to establish a major presence in the aerospace industry, and L&L has the ability to provide required uniformity for critical aerospace processes. Most aerospace specifications are written around a temperature uniformity specification along with strict thermal guidelines, and L&L prides itself in having high uniformity box furnaces. So, basically, what makes our furnaces ideal for the aerospace industry is temperature control and uniformity.

We used nickel chrome elements in this furnace just to help with the outgassing byproduct of this process. These elements are more resistive to many contaminants.

Then, we put heat shields on the case so the outside case temperature remains safe to touch. The furnace is sealed from inside out for use with inert atmospheres. What that does is displace all the oxygen that's within the furnace by using an inert gas, such as nitrogen. The nitrogen pushes all the oxygen out of the chamber. It gives us a better oxygen-free environment, thus giving better strength to the part and the coating, because there's less oxygen impregnation into the parts.

Oxygen basically equals weakness in that type of process. A manual inert flow panel controls the gas flow into the chamber.

How is the XLE214's curing and bonding process beneficial to aerospace parts?

It provides durability. It's more of a strengthening process for when there's friction between the parts. The bond goes on the metal to provide extra strength in parts that require it, and the advantage of putting a ceramic coating on a metal part is it provides abrasion resistance.

Basically, parts see fatigue over time, and this coating helps prolong the life of the part. So, they take an assembly, and coat it with proprietary ceramics. It provides overall strength to the whole assembly, especially where any wear or friction could be occurring.

Companies can use the furnace for curing and bonding a ceramic coating to steel bodies. The XLE214 furnace can provide extrastrength areas to parts that are subject to various heats and stresses under normal operating conditions.

Could you describe the XLE214's effective work zone?

The effective work zone is the area within the furnace where we will have the uniformity specified. In other words, we specify a work zone and then the required uniformity in the work zone. The XLE214's effective work zone is 22 inches wide by 16 inches high by 20 inches deep. These dimensions are slightly smaller than the actual inside of the chamber. What that allows us to do is to move the work zone

around a few inches if needed to get the ultimate effective work zone.

Is that something unique to this model furnace?

Each model furnace has a unique effective work zone. That's what makes the XLE series so versatile; L&L manufactures models from as small as 2 cubic feet up to 72 cubic feet.

How does the Eurotherm program control work with the furnace?

The program control contains 10 individual programs with 24 segments. There are also outputs from the program control that would turn the Venturi evacuation system on and off as needed through the cycle. The Venturi system basically removes any outgassing that's occurring from the parts and has a motor control to adjust the speed at which the effluents are removed.

Can the XLE214 be tailored to specific thermal needs?

Yes. All of our XLE furnaces come with many options so they can be used for multiple different applications. The XLE is L&L's most popular model series, and is the most versatile of all our furnaces, that's for sure, as far as options that can be incorporated and processes that can be used in conjunction with various options to meet specific process needs.

Does L&L offer other furnaces equipped with pyrometry packages?

Yes. In an effort to keep in line with ASM 2750F, all L&L furnaces can be equipped with pyrometry packages.

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