

Technologies and Processes for the Advancement of Materials

# Thermal processing

ISSUE FOCUS ///

THERMOCOUPLES / MEDICAL APPLICATIONS

## ***EXECUTION STANDARDS FOR ON-SITE DIRECT GAS FIRE PWHT ON LARGE PRESSURE VESSELS***

COMPANY PROFILE ///

The Cluster for Industrial  
Decarbonization (CDI)

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## **EXECUTION STANDARDS FOR ON-SITE DIRECT GAS FIRE PWHT ON LARGE PRESSURE VESSELS**

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## Thermocouples and medical applications

**F**or the past few years, *Thermal Processing* has added a medical-applications Focus topic because, like aerospace, heat-treating is also a big part of products that not only keep us alive, but also help make living more comfortable.

In addition to medical applications in heat treat, this issue will also look at applications that need thermocouples.

Thermocouples may seem like a routine piece of equipment for a heat-treating operation, and it might be easy to dismiss them, but not using the proper thermocouple could mean a huge dent in your company's bottom line.

But just because something isn't flashy, doesn't mean you should take it for granted.

In our cover article, James Benefield shares his insights on the execution standards for on-site direct fire post weld heat treatment on large pressure vessels. These standards involve the proper placement of thermocouples, where accuracy is non-negotiable.

In this month's second Focus article, Zhipo Zhao, Yidi Wang, Jiqiang Wang, Tianying Xiong, and Xinyu Cui take a deep dive in the heat-treatment effects on the properties of cold spraying additive manufacturing titanium. Titanium (Ti) and its alloys possess unique mechanical and chemical properties, including high specific strength, excellent corrosion resistance and biocompatibility, rendering them promising materials in various fields such as the medical and chemical industries.

In addition to those two articles, be sure and check out our Q&A spotlighting Tenova R&D Director Enrico Malfa. In the Q&A, Malfa discusses how Tenova technologies have been featured in the INCITE platform, a public digital initiative by the European Commission.

But the May issue's thermal-processing coverage is just getting started. Don't forget to read what subjects our monthly columnists are tackling that are vital to heat treating.

I hope you enjoy this month's content, and if you'd like to contribute to a future issue, please don't hesitate to contact me. I'm always on the lookout for expert advice that furthers the advancement of the heat-treat industry.

Yes, May is finally here with — hopefully — a relaxing summer close on its heels.

So, grab our latest issue and take it to the deck. It may not keep you cool, but the information inside certainly is.

As always, thanks for reading!

**KENNETH CARTER, EDITOR**

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processing



Bodycote's installation of Hgen equipment at the Rancho Dominguez plant in the U.S. supports commercial and environmental objectives. (Courtesy: Bodycote)

### Bodycote deploys on-site hydrogen generation system

Bodycote has deployed an on-site hydrogen generation system from Hgen at its Rancho Dominguez facility in California, United States. The new system will deliver a cleaner, more resilient, and lower-cost hydrogen supply while contributing to sustainability and decarbonization objectives.

Bodycote is a world-leading provider of advanced heat treatment and specialist thermal-processing services.

Hydrogen is an essential industrial gas used in Bodycote's precision heat treatment and surface coating technologies, treating metal and metal-alloy components for the aerospace, defense, automotive, and energy sectors. This installation provides a lower-cost, lower-emissions solution.

The new system at Rancho Dominguez generates hydrogen at the point of use from electricity and water, eliminating impacts associated with bulk hydrogen transportation, distribution, and vendor handling and reducing associated emissions by more than 90%. It will also help drive down the cost of hydrogen.

Bodycote partnered with industrial gas innovator Hgen to deploy the hydrogen generation system at the plant. The Hgen module footprint is 20 times smaller than alternatives that produce the same gas volume, reducing system cost and space requirements. Its modular, expandable design allows production capacity to scale with process demand, supporting efficient resource use at Bodycote's California site while strengthening long-term supply security.

The containerized module was supplied pre-assembled, minimizing custom integration, and installation took less than two weeks.

"On-site gas generation avoids the need for expensive gas compression, transport, and storage," said Molly Yang, chief executive officer at Hgen. "The high efficiency of Hgen's technology allows Bodycote to reduce gas costs while advancing its sustainability goals." Success at Rancho Dominguez is expected to pave the way for broader deployment of distributed hydrogen generation across additional sites, reinforcing Bodycote's long-term energy transition strategy and sustainability commitments.

The Rancho Dominguez facility offers a complete range of heat-treatment and joining technologies, including annealing, vacuum heat treatment, diffusion bonding, and multiple brazing methods such as vacuum, hydrogen, inert atmosphere and induction brazing.

**MORE INFO** [www.bodycote.com](http://www.bodycote.com) or [www.hgen.com](http://www.hgen.com)

### Advanced Heat Treat Corp. announces building expansion

Advanced Heat Treat Corp.<sup>®</sup> (AHT), a recognized leader in heat-treat services, announced an 18,000-square-foot building expansion at its facility located at 2839 Burton Avenue, Waterloo, Iowa. Groundbreaking for the project took place April 6, with construction anticipated to be complete by fall 2026.

The expansion will house a new custom-built furnace. The equipment will increase AHT's size capabilities in length, height, and weight for heat treatments such as carburizing, through hardening, normalizing, and more.

"This expansion is about giving our customers more — more capacity, more capability, and more confidence in turnaround," said Adam Kane, plant manager at AHT's Burton Avenue facility. "With added production space and additional equipment, we'll



**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](mailto:editor@thermalprocessing.com). Releases accompanied by color images will be given first consideration.

be able to process larger and heavier components, and we'll have room to add even more equipment and services in the future."

The facility is one of two locations in Waterloo, Iowa. The Burton Avenue location has been in operation since 1981 and currently provides heat-treat services such as induction hardening, annealing, cryogenic treatment, carbonitriding, stress relieving, and other furnace-related heat-treat services. The other location in Waterloo on MidPort Boulevard – the corporate office – offers nitriding and nitrocarburizing services.

"Between the two Iowa locations, customers have access to multiple heat treatments within a short drive, allowing them to consolidate their vendors and potentially reduce freight costs," said Mike Woods, AHT president.

Aside from its two locations in Waterloo, Iowa, AHT is also located in Monroe, Michigan, and Cullman, Alabama.

**MORE INFO** [www.ahtcorp.com](http://www.ahtcorp.com)

## Turkish steel producer contracts with Pomini Tenova

Pomini Tenova, a Tenova brand and a global leader in roll shop equipment and services, announced a new contract with Gazi Metal, Türkiye's historic steel producer and the country's fifth-largest cold rolling manufacturer. The agreement covers the supply of a foundation-free work roll grinding machine which will expand the roll shop capacity at Gazi Metal's Karasu Sakarya facility.

The newly ordered Pomini Tenova work roll grinder is a technologically advanced machine designed for maximum precision. Its foundation-free design offers Gazi Metal significant advantages, including:

» Installation flexibility: simplified integration into existing facility layouts.

» Reduced civil work: lower costs and shorter timelines for site preparation.

» Enhanced throughput: specifically configured to increase the overall production capacity of the roll shop.

The delivery of the new machine is scheduled for early 2027, with commissioning to follow shortly thereafter.

"This project further strengthens a long-standing and successful partnership," said Mustafa Gazioglu, CEO Gazi Metal, who visited the Pomini workshop in December 2025 for the contract signing. "When Gazi Metal first established its cold rolling facilities, Pomini Tenova was selected as the roll shop

partner of choice. Our consistent satisfaction over the years with the performance of the Pomini combi grinder and the integrated mill communication system, ensuring seamless data exchange between the roll shop and the mill, has been a key factor behind our decision to expand our collaboration."

"The introduction of PDSA (Pomini Digital Surface Analysis) is particularly impressive," Gazioglu said. "This solution leverages artificial intelligence to detect surface imperfections that were previously identifiable only by the most experienced operators. We are seriously evaluating its implementation to

ensure that Gazi Metal remains at the forefront of quality control."

"Our continued collaboration with Gazi Metal is a testament to both the reliability of our technology and the strength of our relationship with the Turkish steel industry," said Petar Rokić, sales area manager at Pomini Tenova. "When a long-standing partner chooses to further expand its capacity with us, it represents the highest form of validation for our engineering and innovation." 🔥

**MORE INFO** [www.tenova.com](http://www.tenova.com)



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# INTERNATIONAL FEDERATION OF HEAT TREATMENT AND SURFACE ENGINEERING

## Mark your calendars for these important conferences scheduled for 2026



The 7th Asian Conference on Heat Treatment and Surface Engineering of Materials (7AHTSE2026) will be in Chengdu. (Courtesy: Shutterstock)

### *7th Asian Conference on Heat Treatment and Surface Engineering September 10-12, 2026 Chengdu, China*

The 7th Asian Conference on Heat Treatment and Surface Engineering of Materials (7AHTSE2026) will be in Chengdu, Sichuan Province, China, September 10-12, 2026. The conference will focus on the latest research progress, technological frontiers, and future trends in the field of material heat treatment and surface engineering and is committed to promoting deep integration and collaborative innovation in this field in the Asian region.

The Asian Conference on Heat Treatment and Surface Engineering of Materials (AHTSE) is an important series of international conferences jointly initiated by China, Japan, South Korea, and other countries. It focuses on the latest research and developments in surface engineering and heat treatment.

#### **DEADLINES**

- » **Extended abstracts/full papers submission:** July 31, 2026.
- » **Notification of acceptance:** August 5, 2026.
- » **Early bird registration:** August 31, 2026.

### *31st IFHTSE World Congress October 13-15, 2026 Cologne, Germany*

The 31st IFHTSE World Congress is organized by AWT – Arbeitsgemeinschaft Wärmebehandlung + Werkstofftechnik e. V. and will be in Cologne, Germany, October 13-15, 2026, at the International Conference and Trade Fair.

In addition to the World Congress, the event will also feature HK 2026 and the European Conference on Heat Treatment 2026.

This will truly be a huge event. If you have never attended the AWT HK (Härtereikongress) event, this is one of the largest (if not the largest) heat-treating trade show in the world. This, combined with ECHT 2026 and the 31st World Congress, will be the one event to attend.

The largest European congress on topics of heat treatment and materials technology, manufacturing and process engineering in 2026 is organized in cooperation with the International Federation for Heat Treatment and Surface Engineering (IFHTSE) as well as the European heat treatment associations from France, Austria, Switzerland, the Czech Republic, Slovakia, and the Benelux countries. Due to the expected number of lecture registrations, the congress event is planned as a three-day event. The language of the conference will be English.



The 31st IFHTSE World Congress will be in Cologne, Germany. (Courtesy: Shutterstock)

## TOPICS

### *HeatTreatmentCongress, IFHTSE World Congress, ECHT 2026*

- » Heat treatment – processes, systems, media, safety.
- » Sustainability concepts for heat treatment plants and process chains.
- » Artificial intelligence, simulation and digitalization.
- » Production and processing of components in the process chain.
- » Properties of components in processing.
- » New material developments.
- » Material analysis and quality control.

### *Steel Innovation*

- » Materials Engineering steel.
- » Digital steel technology.
- » High strength and wear-resistant steels.
- » Sustainable steel – recycling, re-use and re-manufacturing.
- » Corrosion-resistant steels.
- » Hydrogen embrittlement / steel development for the hydrogen economy.

- » Materials testing for steel.
- » Increasing the damage tolerance of steels.
- » New steel concepts for additive manufacturing.

## CROSS GLOBAL INDUSTRY HIGHLIGHT

In addition to the extensive scientific and technical program, attendees will have the unique opportunity to experience a major international exhibition and trade fair with approximately 150 exhibitors. Leading companies from around the world will present their latest developments in equipment, services, operating materials, and other relevant technologies essential for the heat treatment and surface engineering industries. The exhibition will provide invaluable networking opportunities and foster collaborations between academia and industry.

## DEADLINES

- » **Notification of abstract acceptance:** May 15, 2026.
- » **Deadline for proceedings manuscript (extended abstract 2-4 pages):** July 15, 2026.

**MORE INFO** [www.hk-awt.de](http://www.hk-awt.de)



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Learn more and explore membership benefits at [www.ihea.org](http://www.ihea.org).

### MASTER THE ESSENTIALS: FUNDAMENTALS OF INDUSTRIAL PROCESS HEATING

IHEA's comprehensive online learning program is designed to support professionals at every stage, starting with a strong foundation. The Fundamentals of Industrial Process Heating course provides essential knowledge and practical skills needed to understand core principles and real-world applications. Whether you're new to the industry or looking to strengthen your expertise, this course offers a valuable starting point to build confidence and capability in industrial process heating. The Fundamentals of Industrial Process Heating Online Learning Course has been a successful source of high-level learning for those in the industrial heat-processing industry for more than 10 years. The flexible online format and interactive forums are just some of the benefits of this class.

This affordable course is ideal for students to learn through a virtual format while at home or in the office, allowing them to go at their own pace. It offers indispensable tools to industrial process heating operators and users of all types of industrial heating equipment. Throughout the in-depth online course, students learn safe, efficient operation of industrial heating equipment, how to reduce energy consumption, and ways to improve the bottom line. The content provides an excellent overview of the essential information used throughout the industry.



IHEA is pleased to have retired industry expert Dan Curry on board as the instructor for the course. Curry has experience in product development and management in industrial burners, burner control systems, temperature controls, and combustion systems. Throughout his working career he served on various technical committees for ISO TC244, NFPA 86, NFPA 87, CSA B149.3, and IHEA's Safety Standards & Codes Committee. He started in 1976 as a repair and service technician and expanded his experience and responsibilities through hands-on continuous learning over various industries, business roles, buy-outs, acquisitions, re-assignments, and global travels.

The curriculum for the Fundamentals course includes the basics of heat transfer, fuels and combustion, energy use, furnace design, refractories, automatic control, and atmospheres as applied to industrial process heating. Weekly course work, quizzes, and a final exam project are administered to guide students on their progress and evaluate their knowledge of the material.

Cost for IHEA members is \$775, and cost for non-members is \$950. Registration fee includes an electronic course handbook, course instruction, quizzes, projects, and class forums. Students who successfully complete the course will receive 18 PDHs. Printed materials are available for an additional fee. There is also a group discount available when two or more people from the same company register at the same time. The first person will receive the regular rate, and each additional attendee will receive a \$125 discount.

Dates for the fall course will be announced soon. For additional information, go to [www.ihea.org/page/OnlineCourse](http://www.ihea.org/page/OnlineCourse).

### IHEA WEBINARS: ENERGY MANAGEMENT DISCUSSION THAT FITS YOUR SCHEDULE

With the popularity and success of IHEA's Sustainability and Energy Management Initiative, IHEA has built a library of recorded webinars on various subjects related to this critical topic.

"The IHEA Board of Directors feels there is a strong need to continue providing valuable information that will assist our industry in

navigating sustainability issues," said IHEA Executive Vice President Anne Goyer.

All webinars are free.

IHEA's Sustainability & Energy Management Webinar Series focuses on carbon producing heating processes and provides methods to optimize their efficiency and thereby reduce their carbon emission intensity. The webinars cover the various scopes of carbon emissions and the methods to determine your site, or specific equipment, carbon footprint.

Be sure to check out the complete collection of free webinars at [www.ihea.org/page/Webinars](http://www.ihea.org/page/Webinars) and view them on your own time.



### IHEA'S ANNUAL SUMMIT IS GOING VIRTUAL IN 2026

Mark your calendars for December 2 and 3 when IHEA's popular annual SUMMIT takes a deep dive into energy management & sustainability. Scheduled for the afternoon of December 2 and the morning of December 3, this format will allow you to participate

without the cost of travel.

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*Quantifying the fin effect during thermal processing, during which the presence of a thermocouple wire can significantly alter the measured response of a component.*

## Wired for cooling

**T**hermocouples are one of the most practical and widely used tools for gathering time/temperature data in thermal processing environments. Ranging from laboratory-scale experiments to full industrial heat-treatment operations, these sensors provide direct insight into how materials respond to heating and cooling cycles. By embedding or attaching thermocouples to components, engineers can capture transient thermal histories that reflect the furnace conditions and the complex system of conduction, convection, and the thermal effects from phase transformations within the material.

One important application of this data is for calibration of boundary conditions such as convective heat transfer coefficients (HTCs) used in computational models to simulate the heat transfer in the process that are otherwise difficult to measure directly.

Despite their utility, thermocouples are not passive measurement tools. Their physical presence, particularly the geometry and placement of the thermocouple wire, can influence the temperatures they record. One notable phenomenon is the “fin heating/cooling” effect, in which the thermocouple wire acts as an extended surface that enhances the local heat transfer. This can distort recorded temperatures and introduce systematic error into both experimental interpretation and subsequent modeling efforts. The present work examines this effect in detail through a combination of finite element modeling and fitting to ultimately quantifying the fin effect and to propose practical mitigation techniques.

### MODEL SETUP

To investigate the fin effect, a simplified finite element model was developed. The geometry consists of a cylindrical specimen with a diameter of 25.4mm (1 inch) and a length of 101mm (4 inches). A thermocouple is attached at the mid-height of the cylinder along its axis, with the thermocouple wire modeled as a 2mm diameter (12 AWG) extension normal to the cylinder surface, as shown in Figure 1. This configuration reflects a common industrial setup in which thermocouples are tack-welded or otherwise affixed to part surfaces during process characterization.

The thermal process applied to this model includes a simple heating and quenching process. The specimen is first heated to 900°C under a convective boundary condition corresponding to an HTC of 75 W/m<sup>2</sup>-K over a period of 1.5 hours. Following this, the part is quenched in a 20°C ambient environment with an HTC of 5,000 W/m<sup>2</sup>-K for one hour. These conditions are representative of a general heat-treatment operation where large thermal gradients and rapid cooling rates are present.

A transient-thermal finite element simulation is used to track temperature evolution throughout the part, with particular attention paid to two locations: the “far surface” (a point on the cylinder unaffected by the thermocouple wire) and the thermocouple attachment

point. By comparing these locations, the influence of the thermocouple geometry on measured temperature can be directly assessed. Figure 2 shows an overview of the thermal process and cross-sectional contour of the geometry at about two seconds into the quenching process, with the two nodes highlighted where the time/temperature data was collected.

Note the latent heat of phase transformation captured when the part begins to transform to the austenite phase.

### RESULTS

The simulation results show the presence and significance of the fin heating/cooling effect. There exists a difference in recorded temperature during the modeled furnace heating process step, but the heat transfer from the part to the environment is slow enough to reduce the fin heating effect to about 20°C difference between the thermocouple measurement and the far surface. However, during the initial stages of the quench, the thermocouple location experiences accelerated cooling relative to the surrounding material, due to the increased surface area provided by the thermocouple wire, shown in Figure 3.

At approximately 1.9 seconds into the quench, the maximum temperature difference between the thermocouple location and the far surface reaches nearly 75°C, at a time when the average part temperature is around 400°C, right around the martensite start temperature for the AISI 4120 steel modeled in this work.

At 20 seconds into the quench, when the part temperature has dropped to approximately 85°C, a temperature difference of about 14°C is still observed. By 30 seconds, this difference falls below 5°C, suggesting that the fin effect becomes less significant as the overall temperature gradient is reduced. While the fin cooling effect is most pronounced during the early stages of rapid cooling, its influence can extend into later stages and should not be neglected, particularly when high accuracy is required.

### HEAT TRANSFER COEFFICIENT FITTING

Thermocouple data are often used to back-calculate heat transfer coefficients, which serve as critical boundary conditions in heat-treatment simulations. One common approach is to use inverse or forward finite element methods to fit an HTC value that reproduces the observed time/temperature response.

For this example, the commercial tool DANTE HTC Fit is used to perform the analysis. HTC Fit uses a forward finite element method, iteratively running simulations with varying HTC values to minimize the difference between predicted and measured temperature histories.

The inputs for the fitting process include the time/temperature data (in this case, derived from the simulation with a known constant HTC), the ambient temperature (20°C), and a range of HTC values

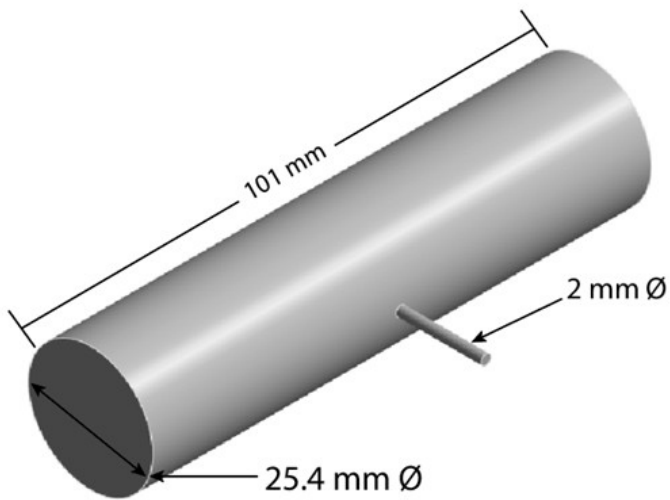


Figure 1: Schematic of the cylinder and fin geometry used in the study described in the article.

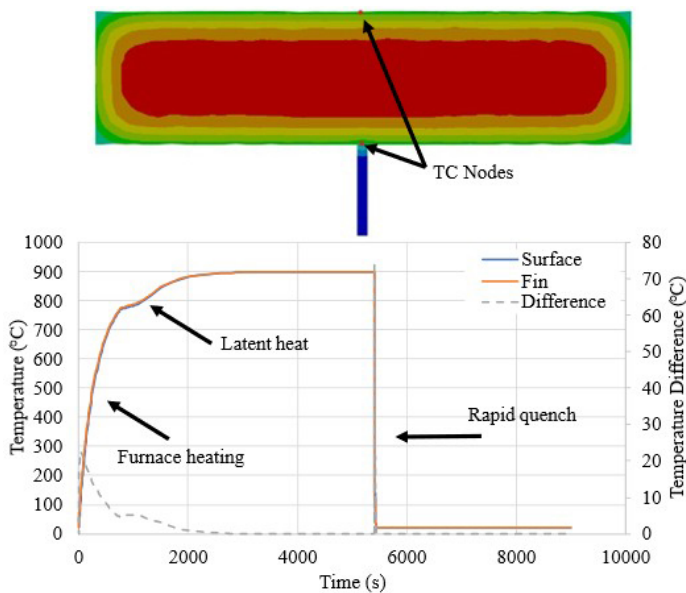


Figure 2: Time/temperature history and part geometry used in the model described in the article.

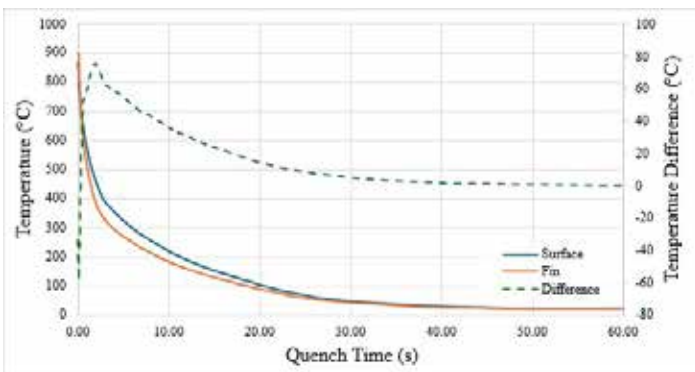


Figure 3: Time/temperature and temperature difference during the quenching process.

bounded between 1,000 and 9,000 W/m<sup>2</sup>·K, an initial guess of 4,000 W/m<sup>2</sup>·K was used, and multiple random iterations (20 loops) were performed to improve the fit. Fitting was conducted at several key time points during the quench, specifically at two, 10, and 20 seconds,

	HTC at 2s	HTC at 10s	HTC at 20s	Fitting error %
Surface	5154	5438	4950	0.817
Fin	6903	6117	4960	1.806
Percent difference	29.01	11.74	0.20	

Table 1: Results of fitting the time/temperature data for the surface and fin thermal histories.

to evaluate how the HTC difference varies depending on the portion of the data used. The results reveal a clear and consistent trend that when the thermocouple data influenced by fin cooling are used, the fit HTC values are significantly higher than the true value used in the simulation as shown in Table 1.

The fitting results show the presence of the thermocouple wire can increase the HTC fit by nearly 30 percent. This overestimation is because the increased local cooling caused by the wire is interpreted by the fitting algorithm as evidence of a higher convective heat-transfer rate at the surface. In reality, the bulk surface of the part does not experience this elevated HTC and is an artifact of the measurement method.

Such inflated HTC values can lead to inaccurate predictions of temperature evolution, phase transformations, distortion, and residual stress in process models. The error introduced at the measurement stage propagates through the entire modeling workflow.

## DISCUSSION AND CONCLUSIONS

This work demonstrates that the presence of a thermocouple wire can significantly alter the measured response of a component during heat treatment, leading to errors in recorded temperature data. Through finite element modeling of a cylindrical specimen with an attached thermocouple, the fin cooling effect was quantified, revealing peak temperature differences of nearly 75°C early in the quench step.

When these data are used to determine heat transfer coefficients, the resulting values can be overestimated by as much as 30 percent, which has direct consequences for the accuracy of heat-treatment simulations, potentially leading to incorrect predictions.

To mitigate the fin cooling effect and improve measurement accuracy, engineers and technicians can position the thermocouple wire along the surface of the part rather than perpendicular to it, where it would not interfere with the flow of the quenchant or bubbles, reducing its effectiveness as a cooling fin. A small hole can be drilled from the opposite side of the part, and the thermocouple can be inserted to be near the surface without exposing the wire directly to the quenching medium.

Another approach is to use thinner thermocouple wires to reduce heat transfer along the wire. Simulations can also be performed to explicitly account for the thermocouple geometry. Ultimately, accurate thermal characterization requires high-quality data, and a clear understanding of how that data is obtained.

By recognizing and addressing the fin cooling effect, engineers can improve both experimental practices and simulation reliability, leading to better-informed decisions in heat-treatment process design and optimization. ☞

## ABOUT THE AUTHOR

Jason Meyer joined DANTE Solutions full time in May 2021 after receiving his Master's degree in mechanical engineering from Cleveland State University. His main responsibilities include marketing efforts, project work, and support and training services for the DANTE software package and the DANTE utility tools. Contact him at [jason.meyer@dante-solutions.com](mailto:jason.meyer@dante-solutions.com).



*Alpha and near alpha, alpha-beta, and beta and metastable-beta titanium alloys are processed to optimize strength and fatigue resistance using one of four basic methods.*

## Heat treatment of titanium alloys

Last month, I discussed the different types of titanium alloys. In this column, I will discuss the heat treatment of alpha and near alpha, alpha-beta, and beta and metastable-beta titanium alloys.

### INTRODUCTION

With all the titanium alloys, there are four basic heat treatments used [1] [2] [3]:

» Stress relief is used to reduce residual stress from welding, machining, and forming to improve dimensional stability and fatigue life without altering microstructure.

» Annealing improves ductility, fracture toughness, and thermal stability by recovery and recrystallization and, for  $\alpha$ - $\beta$  alloys, by refining the  $\alpha/\beta$  distribution.

» Strengthening by solution heat treatment and aging, in  $\alpha$ - $\beta$  and  $\beta$  alloys, achieves high strength by creating supersaturated solid solutions that decompose into fine  $\alpha$  precipitates during aging.

» Beta annealing or duplex annealing is used to create lamellar microstructures that improve crack-growth resistance and high-temperature performance.

### HEAT TREATMENT OF ALPHA, NEAR-ALPHA ALLOYS

Heat treatment is, for the most part, used for stress relief, annealing, and for optimizing creep resistance rather than increasing strength. Common practices include [1] [4] [5] [5]:

» Stress-relieving: Typically, 595–705 °C for  $\alpha/\alpha$ - $\beta$  alloys for 1–2 h followed by air cooling, used to remove fabrication-induced residual stresses without significant phase redistribution. [2] [5]

» Mill or sub-beta transus annealing: Annealing below the  $\beta$  transus (in the  $\alpha+\beta$  or single- $\alpha$  range) increases fracture toughness, ductility, and dimensional stability by promoting recovery and limited recrystallization of  $\alpha$  [6] [7].

» Duplex and recrystallization annealing uses higher-temperatures than sub-beta annealing by annealing in the upper  $\alpha+\beta$  range. This is followed by controlled cooling to produce a duplex microstructure of primary equiaxed  $\alpha$  in a transformed matrix, which is beneficial for creep and fatigue resistance [6] [7].

» Solution treatment and aging is applicable to some near- $\alpha$  alloys containing Cu or moderate  $\beta$  stabilizers. In one example, Ti-2.5Cu can be solution treated at about 795–815°C, followed by water or air quenching. It is then aged in one or two steps to produce fine Ti<sub>2</sub>Cu precipitates that increase strength. More heavily alloyed near- $\alpha$  materials (e.g., IMI-834) are solution treated just below the  $\beta$  transus and aged to approximately 600–625°C to optimize the balance of creep strength and toughness via controlled secondary  $\alpha$  precipitation [3].

### HEAT TREATMENT OF ALPHA-BETA ALLOYS

Titanium alloys of the  $\alpha$ - $\beta$  class are the most heat treatable of titanium alloys [1] [4].

» Stress-relief is like  $\alpha$  alloys, with temperatures in the range of 595–705°C for about 1–2 hours to reduce machining and forming stresses without major microstructural changes. For  $\beta$ -rich alloys, slightly higher stress-relief temperatures (700–800°C) with shorter times are common.

» Sub-transus annealing is done by heating within the  $\alpha+\beta$  range followed by air cooling to refine the balance between primary  $\alpha_p$  and transformed lamellar  $\alpha$ , improving toughness and fatigue resistance. Mill anneal temperatures for Ti-6Al-4V are typically just below the  $\beta$  transus to preserve a desired  $\alpha_p$  fraction.

» Duplex and recrystallization annealing is accomplished by heating to the upper  $\alpha+\beta$  field to partially dissolve  $\alpha_p$  and refine prior  $\beta$



grains. It is then cooled in a controlled manner to produce a duplex structure. Recrystallization anneals use higher temperatures and hold times to promote new grain formation where hot working has generated heavily deformed microstructures.

» Beta annealing is performed by heating above the  $\beta$  transus to obtain a fully  $\beta$  microstructure. This is followed by relatively slow cooling (e.g., furnace or air) to room temperature. This yields coarse lamellar colonies and is often used to enhance fracture toughness and crack-growth resistance in thick sections, at the expense of yield strength and low-cycle fatigue performance.

» Solution heat treatment and aging is accomplished by heating in the  $\alpha+\beta$  field (or just above the transus in some cases). For example, Ti-6Al-4V is heated to 955–970°C to adjust the amount and composition of  $\beta$ . The part is then rapidly cooled by water or polymer quenching to retain a supersaturated mixture of  $\beta$  and possibly martensitic  $\alpha'$  or  $\alpha''$  [2] [6]. The alloy is then aged for several hours at 480–595°C to precipitate fine secondary  $\alpha$  within  $\beta$  and refines the martensitic decomposition. This raises the strength significantly while maintaining fracture toughness [8].

### HEAT TREATMENT OF BETA ALLOYS

Heat treatments for beta alloys are designed to use solution heat

treatment and aging to produce fine precipitates of alpha or other precipitates.

Typical solution temperatures range from about 690–925°C, depending on composition. The times and temperatures are selected to ensure a fully  $\beta$  microstructure while avoiding excessive grain growth. For example, Ti–13V–11Cr–3Al is solution treated around 775–800°C, Ti–10V–2Fe–3Al around 760–780°C, and Ti–15V–3Cr–3Al–3Sn around 790–815°C [2] [6] [4] [3]. Quenching is usually by water quenching or polymer quenching, depending on section size or distortion constraints. However, if the alloy is very strongly  $\beta$  stabilized air cooling may be appropriate. The aim is to retain a supersaturated  $\beta$  phase with minimal continuous grain boundary  $\alpha$  [5] [2].

Aging temperatures for  $\beta$  alloys are often between 425 and 595 °C for times from a few hours up to ~100 hours, producing controlled precipitation and growth of  $\alpha$ . Lower temperatures and longer times favor very fine dispersions and peak strength, while higher temperatures promote coarser precipitates and better ductility [4] [3] [5] [7] [9].

## CONCLUSION

In this article, the heat treatment of different titanium alloys was discussed.

For further details regarding the heat treatment of titanium alloys, and the commonly used processing times and temperatures for specific alloys, it is recommended that readers review AMS 2801D – Heat Treatment of Titanium Alloy Parts [10].

Should there be any comments or questions about this article, or suggestions for further articles, please contact the writer or editor. ✉

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**EXECUTION STANDARDS  
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DIRECT GAS  
FIRE PWHT  
ON LARGE  
PRESSURE  
VESSELS**

A GCC technician works the thermocouple grid on a large pressure vessel prior to the heat cycle. Thermocouples are attached directly to the vessel surface to ensure accurate surface temperature measurement throughout the PWHT cycle. (Courtesy: GCC)

# Wind, ambient temperature, vessel orientation, burner placement can affect the heat cycle in ways that a furnace environment does not.

By JAMES BENEFIELD

**P**ost weld heat treatment on large pressure vessels is not a simple operation. When a vessel weighs hundreds of thousands of pounds, spans 70 to 100 feet in length, and carries a wall thickness measured in inches rather than fractions, every decision made during setup and execution has consequences. Do it right and you relieve residual weld stresses, improve toughness, and send a code-compliant vessel into service. Get it wrong and you may not know until something fails in the field.

Gulf Coast Combustion has specialized in on-site high-velocity direct gas fire PWHT since 2014. Over that time, it has heat treated vessels across a wide range of sizes and configurations. Most jobs involve vessels under 200,000 pounds. Some are considerably larger. Every one of them has followed the same structured execution standard, because consistency is what produces repeatable, code-compliant results.

## WHY DIRECT GAS FIRE FOR LARGE VESSELS

Large pressure vessels built to ASME Section VIII for oil and gas, chemical processing, and petrochemical service present a fundamental logistical problem for conventional furnace heat treating. A vessel that is 70 feet long and 16 feet in diameter cannot be moved to an outside furnace without significant cost, risk, and schedule impact. Oversized load permitting, specialized transport, rigging at both ends, and transit risk all compound the challenge. For many large vessels, transportation is not a practical option at all.

On-site heat treating solves this by bringing the equipment to the vessel. High-velocity direct gas fire combustion is particularly well-suited to large vessels because of its heating capacity and uniformity. Gas trains used operate at up to 10 million BTU, running on natural gas or liquid propane depending on site availability. High-velocity blowers circulate hot combustion gases inside the vessel, producing a convective heating environment that promotes temperature uniformity across the full shell length.

Electrical resistance heating is well established for smaller components and localized applications — pipe spools, flange faces, nozzle repairs. For large pressure vessels where the entire shell must reach uniform soak temperature, high-velocity gas fire provides the BTU capacity and internal circulation that resistance methods cannot match at scale.

## PRE-JOB PLANNING: THE EXECUTION PLAN

Every job begins with a written execution plan developed before mobilization. The plan is specific to the vessel, not a generic template. It defines the governing code, wall thickness, material specification, soak temperature and tolerance, minimum soak time, heat-up and cool-down rate limits, thermocouple count and placement, burner assignment, insulation specification, and vessel support requirements. GCC execution plans are written to the specific requirements of each vessel and governing code, with management and QC sign-off required before any job starts.

The execution plan becomes the controlling document for the heat cycle. Any major deviation during execution requires client and management approval before work continues.

## THERMOCOUPLE PLACEMENT: ACCURACY IS NON-NEGOTIABLE

The entire compliance case for a heat-treatment cycle rests on demonstrating that the vessel reached the required soak temperature and held it for the required time. Inaccurate temperature measurement means inaccurate documentation, regardless of what actually happened to the steel.

GCC uses Type K thermocouples attached directly to the vessel surface using a capacitor discharge spot welder. This creates a true surface junction: The thermocouple wire is welded directly to the steel, making the vessel surface itself the measurement point. Methods that hold the thermocouple junction away from the surface through clips, banding wire, or welded nuts introduce measurement errors that can be significant under PWHT conditions.

Thermocouple placement follows a grid pattern across the vessel shell, with spacing not to exceed 15-foot intervals. Placement accounts for vessel geometry, nozzle locations, and any features — heavy forged nozzles, lifting lugs — that may behave differently from the main shell during heating. On complex jobs, those high-mass features get their own thermocouples and, where needed, supplemental electric resistance consoles to bring them to temperature in step with the rest of the vessel.

Thermocouple count scales with vessel size and complexity. A straightforward job might run 10 to 12 thermocouples. A vessel with heavy forged nozzles and multiple lifting lugs can require 24 or more.

## INSULATION: CONTROLLING THE THERMAL ENVELOPE

Insulation serves two functions in on-site PWHT: It reduces the BTU input required to reach and hold soak temperature, and it limits the temperature differential across the vessel surface during heating and cooling. Both matter for code compliance and metallurgical outcome.

GCC standard insulation is 1-inch, 8 lb/ft<sup>3</sup> Kaowool ceramic fiber blanket applied in a single layer around the entire vessel surface with a minimum 3-inch overlap at all seams. The overlap accounts for thermal expansion of the vessel during the heat cycle and prevents gaps from opening as the steel grows. Insulation is secured using carbon steel banding straps and stud pins. All nozzles, attachments, and penetrations are individually insulated to prevent localized cold spots from pulling heat away from adjacent shell sections during soak.

Vessel supports require specific attention. Stationary structural supports cannot remain in contact with the vessel during PWHT. They create cold spots and restrict thermal growth. GCC uses temporary saddles on flat, smooth surfaces with high-temperature lithium grease between the saddle and the surface. The grease allows the vessel to grow and move freely as it expands during the heat cycle.



Figure 1: A large pressure vessel glows through the insulation wrap during an overnight PWHT cycle in the Permian Basin. GCC runs continuous temperature monitoring throughout the heat cycle. (Courtesy: GCC)



Figure 2: Seven high-velocity gas burners line the base of a 621,000-pound pressure vessel in Central Texas as insulation wrap nears completion. Gulf Coast Combustion documented the full PWHT cycle on this job via time lapse footage. (Courtesy: GCC)

## THE HEAT CYCLE: PARAMETERS AND DISCIPLINE

The heat cycle for carbon steel pressure vessels under ASME UCS-56 involves three controlled phases: heat-up, soak, and cool-down. Each phase has specific rate and temperature requirements. Monitoring begins at 300°F and continues through cool-down completion at 800°F.

### Heat-Up

The heat-up rate above 800°F is calculated as 400°F per hour divided by the governing wall thickness in inches, with an absolute maximum of 400°F per hour. A 2-inch wall allows 200°F per hour. A 3-inch wall allows approximately 130°F per hour. The calculation ties directly to wall thickness because thicker material requires more time for

heat to conduct through the cross-section. Pushing heat-up rates on thick material creates gradients through the wall that introduce the very stresses PWHT is designed to relieve.

### Soak

Soak temperature for most P-No. 1 carbon steels falls in the range of 1,100°F to 1,200°F. GCC standard is 1,150°F ±50°F. Soak begins when all thermocouples have reached the minimum soak temperature — not when the first one gets there. Every measurement point must be within the acceptable range before the hold clock starts.

Hold time is calculated from wall thickness: one hour per inch for the first two inches, then 15 minutes per additional inch beyond two inches. A 3-inch wall requires two hours and 30 minutes minimum.

During soak, the maximum allowable temperature differential between the highest and lowest reading thermocouple is 250°F per code. Client specifications sometimes require tighter tolerances than this, and GCC executes to whatever the job demands. Temperature differential control is a function of insulation quality, burner placement, and active monitoring throughout the hold period. (See Figure 1)

### Cool-Down

Cool-down rate from soak temperature to 800°F is calculated as 500°F per hour divided by wall thickness, with an absolute maximum of 500°F per hour. Below 800°F, free-air cooling is permitted, but burners remain in position until the vessel is cool enough to safely strip

insulation. Pulling insulation early introduces rapid localized cooling that can re-introduce stress into the weld zone.

## CASE STUDY: A LARGE VESSEL JOB IN CENTRAL TEXAS

A long-standing GCC client in Central Texas required PWHT on a vessel measuring 69 feet shell-to-shell, 16.5 feet inside diameter, with a 3-inch governing wall thickness, constructed from SA-516-70N carbon steel and governed by ASME Section VIII. Empty weight: 621,000 pounds. (See Figure 2)

A vessel of this size could go to a furnace, but the logistics are significant. Moving 621,000 pounds requires a specialized heavy-haul operation, oversized load permits across multiple jurisdictions, and rigging at both ends. The cost and schedule impact would be substantial, and transit risk to a finished vessel is real. On-site heat treating was the right call.

GCC mobilized with seven high-velocity gas burners running on liquid propane — six at 6 million BTU each and one at 3 million BTU. With a 3-inch governing thickness, heat-up rate above 800°F was held to 130°F per hour. Eighteen thermocouples were attached directly to the vessel surface in a grid pattern across four rows plus both heads, with spacing not exceeding 15-foot intervals. The client specification required a maximum 100°F temperature differential during soak — tighter than the code maximum — and GCC executed to that standard.

The full vessel surface was wrapped in insulation with 3-inch overlaps at all seams. Eight temporary saddle supports with high-temperature lithium grease allowed the vessel to grow freely during the heat cycle. Monitoring ran on NIST-calibrated Chino strip chart recorders from 300°F through cool-down completion.

GCC documented this job via time lapse footage, available at <https://youtu.be/UG9rjdfHpEE>, which illustrates the full sequence from insulation and setup through firing, soak, and strip. The scale of the operation is difficult to convey in text alone.

Most vessels GCC heat treats on-site are under 200,000 pounds. Vessel length is a different story — 70 to 80 feet is common, and GCC has heat treated vessels exceeding 100 feet. The execution standard does not change with vessel size: The equipment count scales up; the thermocouple grid expands, and the planning depth increases, but the underlying discipline of controlled ramp rates, verified soak, and complete documentation is constant.

## DOCUMENTATION: THE PERMANENT RECORD

Every GCC job produces a complete documentation package before the company leaves the site. Four components, every time: the heat treat record, the strip chart recorder trace, the recorder calibration certificate, and a job report log capturing any non-conformances during the process.

This documentation package is not a courtesy — it is the traceability record that quality systems, third-party inspectors, and ASME code compliance require. The paperwork is what proves the job was done correctly on a specific vessel on a specific date. If it is incomplete, illegible, or missing identification numbers, it fails — and failed paperwork is the same as no paperwork.

## TECHNICIAN QUALIFICATION

Equipment and procedures are only as reliable as the people running them. GCC maintains a four-level internal technician certification system. Level 1 is entry-level. Each subsequent level requires demonstrated field hours, written and practical examination, and expanding scope of independent authority. Level 4, the highest classification, requires a minimum of five consecutive years in the heat-treating



**Figure 3: Elevated view of a large pressure vessel fully insulated and ready for firing. Gas train consoles, burner hoses, and thermocouple lead runs are visible along the full vessel length. (Courtesy: GCC)**

industry. Level 4 technicians can make minor field adjustments to execution plans, manage multiple simultaneous jobs, and train lower-level technicians. Every job lead running a GCC heat treating job is level-certified.

The technician's judgment matters in the field. Job sites do not always match what was anticipated during planning. Experienced technicians recognize when something developing requires a pause, a call to management, or a documented deviation.

## CONSISTENCY AS THE STANDARD

On-site direct gas fire PWHT is harder than furnace heat treating. The temperature variables are real, the field conditions are unpredictable, and there is no controlled chamber to compensate for poor setup. Wind, ambient temperature, vessel orientation, burner placement — all of it affects the heat cycle in ways that a furnace environment simply does not present.

What makes the difference is not equipment alone. It is the consistency of the execution standard. A written plan specific to the vessel. Thermocouples attached to read true surface temperature. Insulation applied correctly to every nozzle and penetration. Heat-cycle parameters calculated from wall thickness and held within tolerance throughout. Documentation completed and signed before leaving the site.

Every vessel GCC heat treats gets that standard. The execution does not change based on vessel size, client relationship, or schedule pressure. That consistency is what fabricators, quality managers, and inspectors can rely on. (See Figure 3) 📌

## ABOUT THE AUTHOR

James Benefield is the founder and owner of Gulf Coast Combustion, based in Spring, Texas. He spent years inside the industry doing the work, saw how large vessel combustion jobs could be handled with more precision and consistency than what was commonly offered, and put everything on the line in 2014 to prove it. Gulf Coast Combustion is a family-owned operation that specializes exclusively in on-site direct gas fire PWHT for large pressure vessels, serving fabricators in oil and gas, chemical processing, and petrochemical industries across the Gulf Coast and nationally. Benefield can be reached at [james@gulfcoastcombustion.com](mailto:james@gulfcoastcombustion.com).



**HEAT-TREATMENT EFFECTS  
ON THE PROPERTIES OF  
TI MADE WITH  
COLD SPRAYING  
ADDITIVE  
MANUFACTURING**

# A pure Ti deposit with a porosity of merely 2.76% was fabricated via CSAM technology, and the effects of annealing treatment on the microstructure evolution, porosity reduction, and tensile properties of the CSAM Ti were systematically investigated.

By ZHIPO ZHAO, YIDI WANG, JIQIANG WANG, TIANYING XIONG, and XINYU CUI

**C**old spraying additive manufacturing (CSAM) Ti exhibits minimal plasticity, posing a significant challenge to its broader application. Heat treatment is recognized as a potent strategy to enhance the mechanical properties of additive manufacturing parts. However, prior investigations have struggled to discern the genuine impact of heat treatment on CSAM Ti due to the high porosity in initial deposits. This study addresses this gap by fabricating CSAM Ti deposits with a low porosity of 2.76%. The effects of annealing at various temperatures on the microstructure, porosity, and mechanical properties of the deposits were studied. The results show that annealing can promote recrystallization of CSAM Ti and reduce the porosity of CSAM Ti to 0.77%. This increases the strength of CSAM Ti to 780 MPa, which even exceeds that of wrought pure Ti. Despite the low elongation of 4.67%, the CSAM Ti after suitable heat treatment can be used in fields that don't require high plasticity.

## 1 INTRODUCTION

Titanium (Ti) and its alloys possess unique mechanical and chemical properties, including high specific strength, excellent corrosion resistance and biocompatibility, rendering them promising materials in various fields such as medicine, chemical industry and so on [1, 2, 3]. However, the relatively high cost has been a primary obstacle to broader adoption [4, 5]. Conventional manufacturing techniques, such as casting [6], powder metallurgy [7], and mechanical processing [8], entail substantial material and energy losses while struggling to produce complex geometries, exemplified by orthopedic implants [9]. An effective method to overcome these challenges is fabricating Ti components from powder directly via additive manufacturing such as selective laser melting (SLM) [10], electron beam melting (EBM) [11], cold spraying additive manufacturing (CSAM) [12], among others.

Cold spraying, in contrast to conventional thermal spraying — such as arc spraying [13], flame spraying [14], plasma spraying [15], HVOF [16], and HVAF [17] — offers distinct advantages. Notably, its spraying temperature remains well below the melting point of the feedstock powder, ensuring a purely solid-state deposition process. This characteristic mitigates issues such as oxidation, phase transformation, and uncontrolled grain growth in metallic powders during spraying [18]. Additional benefits encompass: (i) high deposition efficiency with low porosity [19]; (ii) induction of compressive residual stress that inhibit coating fracture [20]; (iii) capability to readily produce substantial thicknesses, reaching up to 50 mm [21]. These advantages make CSAM a promising development direction, especially for reactive raw metals (such as Ti and its alloys). However, a primary limitation lies in the near absence of ductility in as-sprayed deposits [22]. Therefore, for the components and parts prepared by CSAM, post-treatment becomes imperative to enhance their plasticity [23].

Various post-treatments have been developed to repair the defects

and improve their mechanical properties of cold sprayed deposits. Notable approaches, validated for their efficacy, encompass heat treatment [24], rolling [25, 26, 27], laser processing [28], friction stir processing [23], hot isostatic pressing [29], and so on. Of these, heat treatment stands out as the most straightforward and convenient, with negligible impact on the deposit's geometry, rendering it highly compatible with the CSAM process. However, Huang et al. [30] reported heat treatment did not significantly improve the properties of CSAM Ti deposits, a finding seemingly contradictory to general heat-treatment experiences. This discrepancy may be attributed to the high porosity (14.20%) inherent in the Ti deposits examined. To clarify this issue, this study employed Ti deposits with a substantially reduced porosity of 2.76%, thereby minimizing the impact of porosity and aiming to illuminate the genuine effects of heat treatment on the microstructure and mechanical properties of CSAM Ti deposits.

## 2 MATERIALS AND METHODS

### 2.1 Raw materials

Commercial pure Ti powder, sieved through a 325-mesh sieve, served as the raw materials. Figure 1 shows morphology (a) and particle size distribution (b) of the used commercial Ti powder in this work. The Ti powder exhibits irregular morphology with a size ranging from 15 to 60  $\mu\text{m}$ . Notably, the absence of satellite powder and agglomerations contributes to enhanced deposition efficiency superior deposit quality.

### 2.2 Fabrication of Ti deposits and heat treatment

A cold spraying system was employed to deposit Ti powder on a steel substrate. The process parameters were as follows: Compressed nitrogen served as the acceleration gas with a pressure of 4.0 MPa and a heating temperature of 800°C. A circular de Laval type nozzle, measuring 130 mm in length, 2.0 mm in throat diameter, and 8.0 mm in outlet diameter was used for the spraying process. The resulting Ti deposit exhibited a thickness of 4.0 mm.

Following the cold spraying process, electrical discharge machining (EDM) was employed to cut metallographic samples (8.0 mm  $\times$  3.0 mm  $\times$  4.0 mm) and tensile test samples (12.5 mm  $\times$  4.5 mm  $\times$  2.0 mm, with a gauge length of 5.0 mm and a cross-sectional area of 1.4 mm  $\times$  2.0 mm). A vacuum tube furnace protected by argon gas was used to anneal the samples at different temperatures for 2 hours. The CSAM Ti deposits and samples annealed at different temperatures (600°C, 800°C, 1,000°C) were noted as CS-Ti, CS-Ti-600, CS-Ti-800, CS-Ti-1000.

### 2.3 Microstructural characterization

The samples were embedded in epoxy resin, ground with abrasive paper (from 150 grit to 3,000 grit), and polished by diamond slurries (2  $\mu\text{m}$  and 0.5  $\mu\text{m}$ ). A field emission scanning electron microscope

(SEM, ZEISS, ULTRA PLUS) equipped with an EBSD system was used to study the microstructure of the samples. An optical metallurgical microscope (OM, ZEISS, Axio Observer Z1) was used to analyze the microstructure of the Ti deposits. The porosity of the deposits was evaluated via image analysis.

#### 2.4 Mechanical properties tests

A tensile test was carried out using an Instron MicroTester 5848 machine at a strain rate of  $10^{-3}$ /s. The dimensions of tensile test samples are schematically shown in Figure 7. SEM was used to analyze the fractures of CSAM Ti samples at different condition after tensile test.

### 3 RESULTS AND DISCUSSION

#### 3.1 Microstructure

Figure 2 shows the metallographic structure of CSAM Ti at various conditions. As it shown in Figure 2a, tightly bonded Ti particles with a wavy pattern are evident, a result of cumulative particle deformation during spraying. Numerous black pores at particle boundary sites originate from inadequate particle deformation. The porosity of CS-Ti is measured at 2.76% according to Figure 3. After the annealing treatment at 600°C, the metallograph of Figure 2a reveals cleaner and more distinct particle boundary outlines, accompanied by the disappearance of select micropores. Nonetheless, the deformed particle boundary features persist. Elevating the annealing temperature to 800°C leads to the vanishment of these boundary characteristics, as depicted in Figure 2c, where the emergence of equiaxed grains signifies recrystallization. Meanwhile, the porosity further reduces to 1.38%, leaving predominantly larger pores. Further increasing the annealing temperature to 1,000°C induces substantial grain growth and a porosity reduction to 0.77%. Notably, pores assume an elliptical morphology, indicative of extensive solid-state diffusion facilitating the healing of smaller pores and the transformation of larger ones into quasi-spherical shapes to minimize surface energy.

Figure 4 presents the band contrast (BC) maps, inverse pole figure (IPF) maps, and grain size distributions of cold sprayed Ti (CS-Ti) under different conditions. Severe plastic deformation during the cold spraying process induces significant residual stresses within the CS-Ti, particularly at particle boundaries, resulting in a low resolution in EBSD analysis. Despite this, the reconstructed BC map clearly shows deformed Ti particles (Figure 4a). The IPF map reveals fine grains around particle boundaries with a few larger grains corresponding to undeformed particle cores (Figure 4e). The grain size distribution indicates that approximately 90% of the grains are smaller than 7  $\mu\text{m}$  (Figure 4i). After annealed at 600°C, tiny grains form around the cores of prior Ti particles, creating a satellite ring around the large cores' grains (Figure 4b-f). Compared with CS-Ti, the average grain size increased slightly from 6.78  $\mu\text{m}$  to 7.55  $\mu\text{m}$  (Figure 4i-g). Annealing at 800°C results in complete recrystallization, with all particles growing uniformly (Figure 4c). The average grain size increased to 10.53  $\mu\text{m}$  (Figure 4k). However, core and boundary grains remain distinguishable. At 1,000°C, exceeding the  $\beta$ -Ti transformation temperature, the annealing process involves  $\alpha \rightarrow \beta$  and  $\beta \rightarrow \alpha$  phase transformations. The structure of CS-Ti-1000 is completely reconstructed, eliminating the cold spraying microstructure. The average grain size increased to 14.59  $\mu\text{m}$  (Figure 4l), indicating accelerated grain growth at 1,000°C,

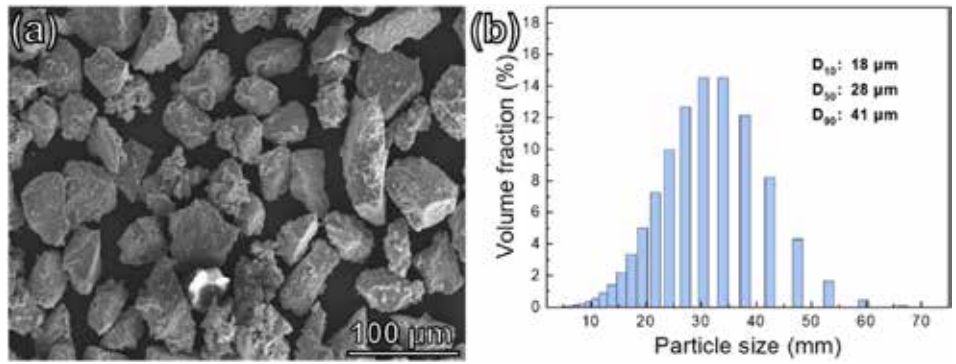


Figure 1: (a) SEM image and (b) size distribution of the commercial pure Ti powder.

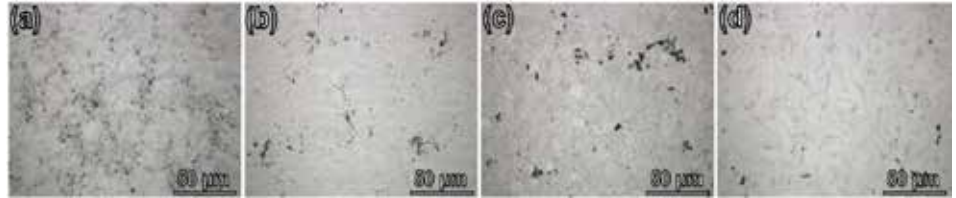


Figure 2: Metallograph of CSAM Ti at various conditions: (a) CS-Ti; (b) CS-Ti-600; (c) CS-Ti-800; (d) CS-Ti-1000.

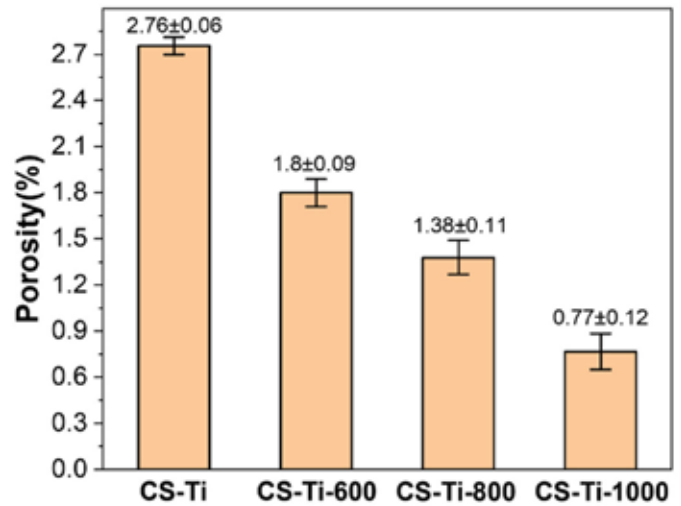


Figure 3: Porosity of CSAM Ti at different conditions.

suggesting that further increasing the annealing temperature is not advisable.

Figure 5a-d illustrate the phase maps of the samples at different conditions. The  $\beta$ -Ti contents for the four samples are 26.7%, 0.3%, 0, and 0.2% respectively. In CS-Ti, the  $\beta$ -Ti grains are small and arranged in a ring formation around the prior Ti particles. The  $\beta$ -Ti formation may be attributed to the severe deformation and localized temperature elevation during the impact moment. Consequently, during annealing at 600°C, most  $\beta$ -Ti transforms into stable  $\alpha$ -Ti. By the time the annealing temperature reaches 800°C,  $\beta$ -Ti has already disappeared. The reappearance of a minor amount of  $\beta$ -Ti in the CS-Ti-1000 sample could be due to insufficiently slow cooling rate during annealing. Figure 5e-h shows the (geometrically necessary dislocation) GND maps of the samples. It is evident that the substantial amount of GNDs introduced during spraying were largely eliminated by 800°C annealing. As for the CS-Ti-1000, high-density GNDs sporadically distributed between grains correlate significantly with pore defects and newly formed  $\beta$ -Ti grains. Figure 6 shows the GND curves of CSAM Ti, clearly indicating that, as the annealing temperature gradually increases, the GND curve shifts toward lower values. The

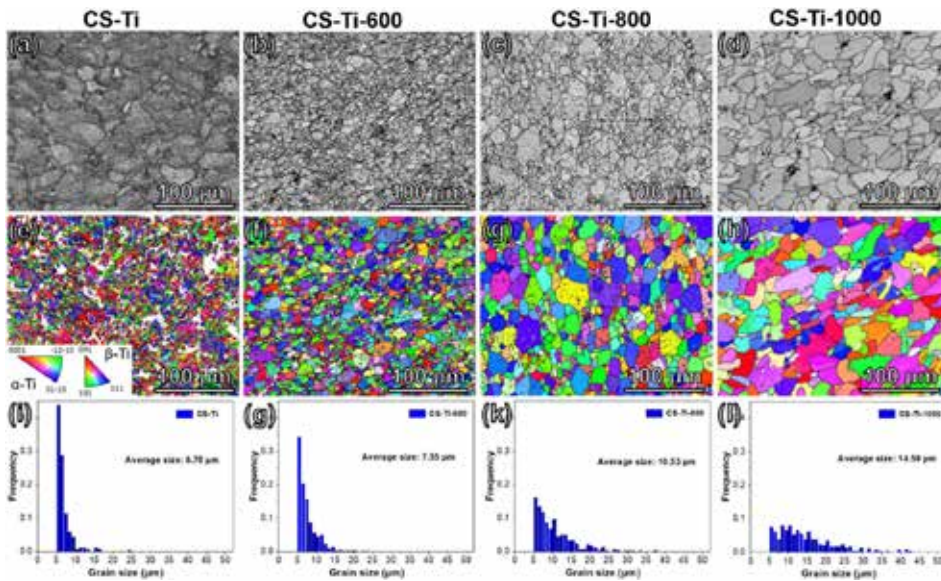


Figure 4: BC maps (band contrast), IPF (inverse pole figure) maps, and grain size distribution curves of CSAM Ti at different conditions.

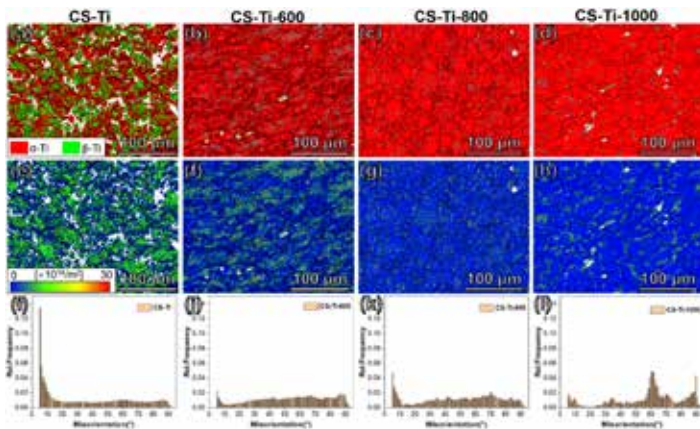


Figure 5: Phase maps, GND (geometrically necessary dislocation) maps and disorientation angle distribution of CSAM Ti at different conditions.

average GND value decreases from  $11.4 \times 10^{14} \text{m}^{-2}$  in CS-Ti to  $1.64 \times 10^{14} \text{m}^{-2}$  in CS-Ti-1000. The disorientation angle distribution in Figure 5i-l reveals some microstructure of the samples at different conditions. The high proportion of small angle disorientations in CS-Ti indicates its internal structure predominantly consists of deformed grains. As the annealing temperature rises, the proportion of low angle disorientation significantly decreases. There are three peaks in the misorientation angles ( $9.48^\circ$ ,  $60^\circ$ , and  $90^\circ$ ) of  $\alpha$ -Ti-1000, which result from the Burgers Orientation [31].

### 3.2 Mechanical properties

The engineering stress-strain curves of CSAM Ti at different condition is shown in Figure 7. Initially, the CS-Ti has a tensile strength of only 346 MPa and a minimal elongation of only 0.25%. Annealing at  $600^\circ\text{C}$  enhances the tensile strength to 512 MPa and the elongation to 0.92%. Further annealing at  $800^\circ\text{C}$  raises the tensile strength to 661 MPa and elongation to 2.53%, while annealing at  $1,000^\circ\text{C}$  results in a tensile strength of 780 MPa and a significant elongation of 4.67%. These results indicate annealing substantially improves both the strength and ductility of CSAM-Ti, with tensile strength increasing by 125% and elongation by a factor of 17.68 post-annealing. Comparatively, commercial pure Ti plate prepared by traditional rolling possess a tensile strength of 420 MPa and an elongation of 42% [30]. Although

CS-Ti annealed at  $1,000^\circ\text{C}$  surpasses pure Ti in tensile strength, its elongation remains considerably lower, primarily due to intrinsic porosity within CSAM Ti. Despite the porosity being reduced to less than 1% in CS-Ti-1000, the presence of pores can still lead to premature failure during deformation. As depicted in Figure 8, there exists an inverse correlation between porosity and both tensile strength and elongation for CSAM Ti. The elimination of porosity through methods such as hot isostatic pressing or additional rolling could potentially augment its mechanical properties. Nonetheless, considering the economic viability and simplicity of a single heat treatment, with its elevated post-treatment strength, can feasibly substitute for wrought Ti in applications where extreme toughness is not a primary concern.

### 3.3 Fracture morphology

Figure 9 illustrates the fracture morphologies of CSAM Ti at different conditions after tensile test. A notable presence of pores is evident on the fracture surface of CS-Ti, as highlighted by the white arrow in Figure 9a. In the higher magnification fracture image, these pores can be seen more clearly as unbonded areas during cold spraying process (Figure 9e). Since the bonding mechanism of powder particles in cold spraying are primarily reliant on cold deformation and mechanical interlocking, it allows for the distinction of original titanium particle boundaries, outlined in yellow dotted lines in Figure 9e. Persistent porosity is observed across the entire fracture surface of the CS-Ti-600 specimen. Nevertheless, an increase in surface roughness compared to CS-Ti signifies enhanced particle cohesion. While particle outlines remain discernible at sites indicated by yellow dotted lines in Figure 9f, evidence of intergranular cleavage fracture emerges, contributing to the improved tensile strength of this sample. In the overall fracture images of CS-Ti-800 and CS-Ti-1000 samples, some wavy tear marks are found, proving the improvement of toughness of the samples. Specifically, CS-Ti-800 displays a mixed fracture mode characterized by shallow dimples (yellow arrows) alongside brittle fracture features like tear ridges (red ovals), suggesting a combination of ductile and brittle mechanisms. Conversely, CS-Ti-1000 showcases a dense array of uniform dimples, signifying superior plasticity among the tested samples. However, compared with the fine and dense deep dimples in the forged pure Ti, the dimples in CS-Ti-1000 are larger in size and shallower in depth, indicating its toughness is far from reaching the level of wrought pure Ti [32]. This is still a difficult problem that needs to be overcome in CSAM Ti.

### 3.4 Discussion

Based on the earlier results, it can be inferred that the effects of heat treatment on the microstructure of the CSAM Ti deposits can be divided into three ranges: (i) low-temperature zone, which is below the recrystallization temperature, primarily involves dislocation recovery; (ii) medium-temperature zone, where recrystallization of  $\alpha$ -Ti occurs; and (iii) high-temperature zone, in which  $\alpha$ -Ti  $\rightarrow$   $\beta$ -Ti  $\rightarrow$   $\alpha$ -Ti transformation takes place during heating, holding, and cooling processes, completely reconstructing the microstructure of CSAM Ti. It can be seen that high-temperature treatment is beneficial for reducing porosity and increasing plasticity. However, the rapid grain growth at high temperatures will reduce the strength, which is unde-

sirable. In other words, sample heat treatment is difficult to obtain CSAM Ti with both good strength and ductility. If the cost allows, hot isostatic pressing (HIP) is undoubtedly the most effective way to improve the performance of CSAM Ti. However, it's unacceptable for most industrial products. To overcome this contradiction, follow-up studies will explore complex heat-treatment processes: first using high-temperature treatment to minimize porosity as much as possible, followed by cyclic annealing in the two-phase region to refine the grains, aiming to achieve a balance between strength, plasticity, and cost.

#### 4 CONCLUSIONS

In this study, a pure Ti deposit with a porosity of merely 2.76% was fabricated via CSAM technology, and the effects of annealing treatment on the microstructure evolution, porosity reduction, and tensile properties of the CSAM Ti were systematically investigated.

The key findings include:

**(1) Porosity reduction:** The primary source of porosity in CSAM Ti stems from inadequately deformed particles during the spraying process. Annealing facilitates atomic diffusion and recrystallization, leading to the disappearance of smaller pores and the elliptical transformation of larger ones. Notably, annealing at 1,000°C for 2 hours reduced the porosity to 0.77%.

**(2) Microstructural evolution:** Annealing at 600°C initiates recrystallization at the peripheries of original Ti particles. As the temperature rises to 800°C, full recrystallization is observed, subsequently giving way to grain growth. Following annealing at 1,000°C, the average grain size attains 14.59  $\mu\text{m}$ .

**(3) Mechanical properties enhancement:** Annealing concurrently enhances the tensile strength and ductility of CSAM Ti. Specifically, post-annealing at 1,000°C yields a tensile strength of 780 MPa, surpassing that of wrought pure Ti, albeit with an elongation of merely 4.67%, significantly trailing that of its wrought counterpart.

**(4) Future directions:** To reconcile the trade-off between porosity elimination and unchecked grain growth, future research will explore complex heat-treatment processes. These involve high-temperature exposures for porosity mitigation, succeeded by cyclic annealing within the two-phase domain to achieve grain refinement.

#### DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

#### ACKNOWLEDGEMENTS

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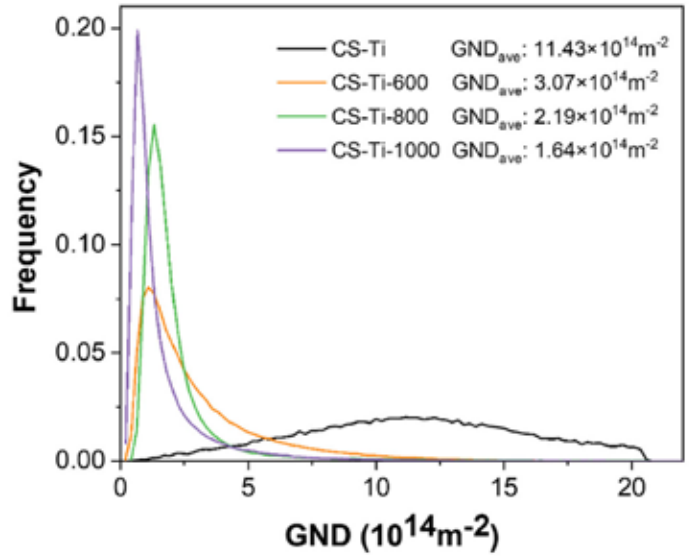


Figure 6: GND (geometrically necessary dislocation) curves of CSAM Ti at different conditions.

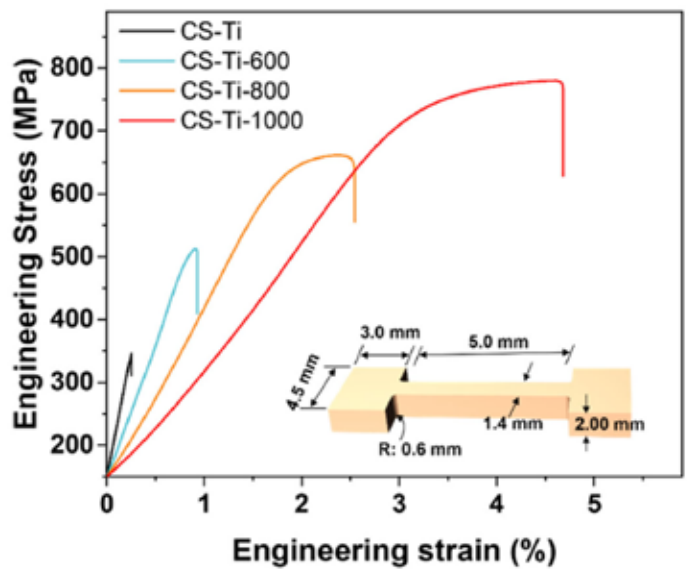


Figure 7: Engineering stress-strain curves of CSAM Ti at different condition.

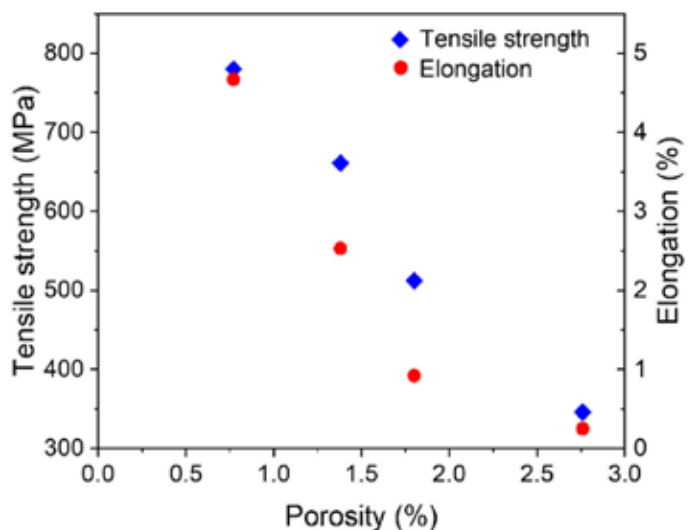
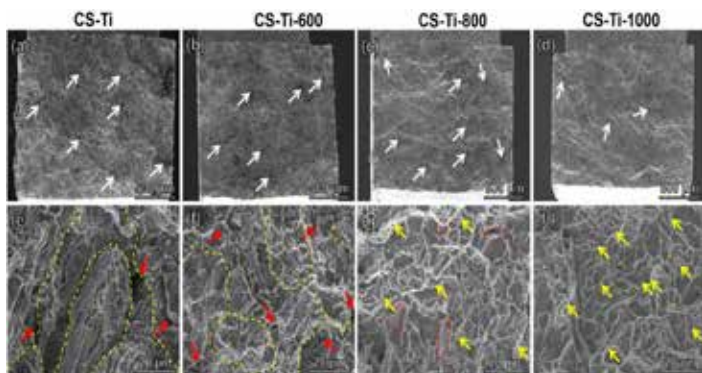


Figure 8: The relationship between porosity, tensile strength, and elongation.



**Figure 9: Fracture morphology of CSAM Ti after tensile test at different condition.**

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**COMPANY PROFILE ///**

**CLUSTER FOR INDUSTRIAL DECARBONIZATION (CDI)**

# ***WORKING TOGETHER FOR A CLIMATE- FRIENDLY INDUSTRY***

**NET  
ZERO**



# The Cluster for Industrial Decarbonization (CDI) supports the industrial transformation process toward climate neutrality by identifying and creating advanced solutions using science, business, and politics.

By **KENNETH CARTER**, Thermal Processing editor

**D**ecarbonization efforts are becoming a more urgent priority among heat-treat businesses, both big and small. Government directives guiding companies in Europe will eventually affect U.S. businesses that want to continue to work with their overseas customers.

In an effort to bring these carbon-reduction initiatives to the forefront, the Cluster for Industrial Decarbonization (CDI) is working with companies to identify ways they can make their processes more environmentally friendly.

“We’re German-based, but we’re also looking into international matters,” said Matthias Heck, cluster and network manager at CDI. “We have an international innovation group, which is a group of CDI partners who try to identify specific measures and activities, such as delegation tours or potential analyses of other countries and technologies. The focus is on knowledge transfer, supporting partners in tapping into international markets, and networking with international decarbonization players from research and industry.”

## FOUNDED IN 2021

CDI was founded in 2021 by an initiative of four entities from Cottbus, a town near Berlin. The founding partners include Brandenburg University of Technology (BTU) Cottbus-Senftenberg, the Institute of Low-Carbon Industrial Processes from the German Aerospace Centre, the Fraunhofer Research Institution for Energy Infrastructure and Geotechnologies (IEG), and the Competence Centre on Climate Change Mitigation in Energy-Intensive Industries (KEI).

They founded the CDI as an interdisciplinary network with the goal of driving solutions and innovations at the interface of science, business, politics, and administration. Its partners are companies from the energy intensive industries that have the opportunity to exchange cross industry concepts to tackle decarbonization. “We are funded by the federal German government and are part of the strategy to reach the German goal of carbon neutrality by 2045,” Heck said.

## FOCUS ON PROCESS HEATING

Although it doesn’t specifically work for the heat-treat industry, the aim of CDI is to look at energy-intensive industries including heat-treat as well, according to Heck.

“The heat-treat industry uses process heat that is fuel based just as other energy-intensive industries do,” he said. “Our partners are from all across the field of energy-intensive industries. We have a general strategy and try to work from the region. We’re rooted in the Lusatia region that’s situated southeast of Berlin and is, at the moment, transforming itself heavily because it used to be an open-cast coal mining region. Germany has been resolute to abandon coal energy by 2038. That’s why there’s a lot of action in the field of transformation in that region. We try to connect industries, science, and associations in a strong cooperative cluster.”

CDI’s goal is to represent cross-industry interests in an agile, interdisciplinary, and service-oriented manner through its 137-partner network, according to Heck.

“We are keen to strengthen knowledge transfer, promote cooperation, and offer guidance on decarbonization solutions within the framework of our innovation groups, our events, and policy papers that we publish,” he said. “These innovation groups are our core element, and they mark a protected space for exchange of our partners. Experts share insights on key topics, and we try to develop applicable solutions like our web tool. I coordinate the innovation group that covers process heat. Topics in this innovation group are, for example, decarbonization of industrial process heat as well as the technological solutions to replace fossil-fuel heat in general.”

## CDI’S WEB TOOL

CDI’s new web tool is designed to evaluate a company’s current situation in the field of process heat and help it to evolve and implement a decarbonization strategy, according to Heck.

“The idea of the web tool is rooted in the fields of our innovation group of process heat,” he said. “They started developing it two years ago. The main initiative has come out of that group, and 40 experts reviewed the tool during the development process several times. The web tool was released in February.” The web tool is designed to be easily accessible, according to Heck.

“You don’t have to have engineering skills to get started,” he said. “At first, you enter some general information about your company and about your industry, and the tool helps you to model your process heat streams and flows with an easy drag and drop menu. You just need to know your inlet and outlet temperature, your heat medium, and either your energy flow rate, volume flow rate, or mass flow rate to model your heat flows. When you finish modeling all of your flows, the tool does a pinch analysis and calculates the pinch temperature or the pinch range that marks the temperature or the temperature range from where the design of your heat system is most efficient. It can be used to reevaluate your heat streams as well as be the basis of a new design for your heating system. In the end, you will receive concrete recommendations for reducing the CO<sub>2</sub> emissions of your process heat, which can then be discussed with other departments in your company.”

## A WIDE RANGE OF INFORMATION

Web tool users also can get information about entities that work with process heat decarbonization that can provide pathways toward climate neutrality, according to Heck.

General information about process heat decarbonization is also available that can be used to individualize an action plan involving the use of excess heat and electrification or the reduction of energy waste by energy efficient measures.



CDI's new web tool is designed to evaluate a company's current situation in the field of process heat and help it to evolve and implement a decarbonization strategy. (Courtesy: CDI)



As CDI strengthens its connections beyond Germany, Matthias Heck, cluster and network manager at CDI (left), has hopes that other countries will see the market benefits in developing sustainable technologies and solutions. (Courtesy: CDI)

CDI sees the importance of worldwide decarbonization, which is why Heck emphasized the need for CDI's input.

"Process heat is one of the biggest emitters of carbon dioxide," he said. "In Germany, energy-intensive industries are responsible for around 22 percent of all carbon dioxide emissions, about two-thirds of which are from process heat production. As you can imagine, decarbonizing process heat is one of the biggest levers toward carbon neutrality. It's necessary to reach the goals of the Paris Climate Agreement, but not only for ecological reasons. The current war in Iran and the fossil energy crisis it has provoked have shown that industrial resilience for non-oil-and-gas producing countries can only be achieved by being independent from fossil fuels. Energy prices are really negatively impacting our economy, and that's why we need to change our dependence on that."

Heck also mentioned that the price for a ton of carbon dioxide will be rising eventually, which makes the reduction of emissions more profitable as well as a necessity for economic sustainability.



CDI's goal is to represent cross-industry interests in an agile, interdisciplinary, and service-oriented manner through its 137-partner network. (Courtesy: CDI)

“We at CDI are trying to help our partners lower their carbon emissions to have sustainable businesses both economically and ecologically,” he said.

**GROWING BEYOND GERMANY**

As CDI strengthens its connections beyond Germany, Heck has hopes that other countries will see the market benefits in developing sustainable technologies and solutions.

“That’s something that the German industrial branch will be looking out to do,” he said. “With sustainable energy prices being as low as they are and sinking further down, those applications with sustainable energy sources will be the most economical solutions in the future. Having these technologies and being able to sell them will be an advantage, and that’s something that will impact business cases in the future.

That’s why those technologies we’re looking into will be distributed worldwide.”

For U.S. companies, lowering emissions for their products or moving to a decarbonized model will help them when they are dealing with the European market, according to Heck.

“If U.S. companies want to sell products to Europe, CBAM — the carbon border adjustment mechanism — will have additional fees on some products they are importing, they will be charged with the carbon price that is applicable here in Europe,” he said. “That’s a reason why companies that want to target the European markets need to adjust to do so.”

**SUCCESSES AND MILESTONES**

In addition to its web tool, CDI has reached several other milestones in its short history that have helped to address decarbonization, according to Heck.

“We established a big conference in the Lusatia region — the Lausitzer Fachkonferenz Conference — that’s the leading conference on carbon neutrality in this region,” he said. “The foundation of our Advisory Board was

one of our key milestones. The members provide entrepreneurial and interdisciplinary expertise. In this way, they support the steering group in the customized development of the cluster into an innovative partner network for a greenhouse gas-neutral industrial future. The companies that are on this advisory board are ArcelorMittal, Cemex, Felix Schoeller, TRIMET Aluminium, Wiegand-Glas, and the ZINQ Group, as well as our four founding members. They are advising us so that our activities match the needs of the energy-intensive industries, and we’ve put out major projects including key studies.”

Heck also said it is important to engage a younger audience, and CDI recently established a decarbonization summer school for the second year in a row.

“We’re trying to form a motivated new generation that will help us fight our way toward carbon-neutral,” he said. ♣



**MORE INFO**

[www.cluster-dekarbonisierung.de/en](http://www.cluster-dekarbonisierung.de/en)

Web tool: [www.cluster-dekarbonisierung.de/tool](http://www.cluster-dekarbonisierung.de/tool)

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***“The inclusion of Tenova technologies in the INCITE platform confirms their alignment with both customer expectations and broader climate and industrial priorities.”***

### **What is the European Innovation Centre for Industrial Transformation Emissions (INCITE) web platform?**

The INCITE platform is a public digital initiative by the European Commission, developed by JRC in Seville under the EU Industrial Emission Directive (IED 2.0). Launched in 2024, it aims to identify, assess, and showcase innovative industrial techniques that improve environmental performance, particularly in energy-intensive sectors such as steel. Its results are expected to support and influence future updates of Best Available Techniques Reference Documents (BREFs).

INCITE evaluates technologies that are close to industrial deployment, focusing on measurable benefits such as decarbonization, reduction of air and water pollution, and improvements in energy and resource efficiency. The platform operates as a public, structured, and searchable database, where technologies are included only after a rigorous two-stage technical review carried out by JRC experts.

### **Why is it a major achievement for Tenova technologies to be featured on the INCITE platform?**

Inclusion in INCITE means that Tenova’s technologies have been recognized by an independent European body as mature, industrial solutions capable of delivering measurable environmental benefits. This validation highlights Tenova’s ability to contribute concretely to the decarbonization of the metals industry and to the production of green steel. At the same time, being featured on the platform positions these technologies as credible references for future regulatory frameworks, reinforcing Tenova’s role as a key technology provider aligned with European climate and industrial transition objectives.

### **Why is it important to identify and to evaluate these technologies committed to decarbonization?**

The steel industry is characterized by long investment cycles and highly capital-intensive assets, making decarbonization decisions particularly complex and exposed to risk. Choices made today in terms of technology and energy sources will affect competitiveness, regulatory compliance, and asset value for decades. For this reason, identifying and evaluating innovative solutions is essential. It ensures that regulators, investors, and industrial players share a common, evidence-based understanding of which technologies are technically feasible, environmentally effective, and economically viable. INCITE plays a key role by providing a reliable and transparent reference, helping align climate ambitions with industrial reality and reducing the risk of setting targets or regulations that cannot be realistically achieved.

### **What are some of Tenova’s technologies featured on the INCITE program?**

Among the technologies selected by INCITE is ENERGIRON, a process

for producing direct-reduced iron (DRI) that uses gas instead of coal. It can operate with natural gas, syngas, biogas, and up to 100% hydrogen, while also enabling CO<sub>2</sub> separation and potential reuse within industrial ecosystems. Another key solution is Consteel® and its latest evolution, Consteerr® , which enables pre-heating and continuous scrap charging in electric arc furnaces (EAFs). The integration of electromagnetic stirring improves energy efficiency, process stability, and operational flexibility. The Open Slag Bath Furnace is another innovative solution, designed for melting DRI, particularly when feedstock quality is variable, supporting more flexible and resilient low-carbon steelmaking routes. INCITE also includes in the platform innovative techniques for energy recovery systems such as Tenova iRecovery® and Heat Leap as well as technologies for polymer injection into EAFs, and it tracks the development of solutions for residual valorization and downstream processes, including hydrogen-ready furnaces, advanced pickling systems, and digital texturing technologies.

### **What has been the customer response to the technology Tenova’s offering that aids in the decarbonization process?**

Steelmakers are increasingly adopting Tenova’s innovative technologies at full industrial scale rather than limiting them to pilot applications. In Europe, several plants are already operating with Consteerr® combined with iRecovery®, while ENERGIRON-based DRI plants, already established worldwide, are now being commissioned even here. Recent geopolitical developments have accelerated a more pragmatic approach to decarbonization. It is no longer seen only as a regulatory or environmental obligation, but also as a strategic factor linked to energy security, industrial resilience, and long-term competitiveness. The inclusion of Tenova technologies in the INCITE platform confirms their alignment with both customer expectations and broader climate and industrial priorities, addressing not only CO<sub>2</sub> emissions but also efficiency, resource use, and overall environmental performance.

### **Anything else you’d like to mention that we didn’t talk about?**

Steelmaking is progressively shifting toward electric arc furnace (EAF)-based routes, including scrap and DRI charge and CCUS solutions that structurally reduce upstream emissions. This transition consequently increases the importance of downstream technologies, such as reheating and heat treatment, in achieving low-carbon steel production. Tenova has a strong tradition and expertise in these areas, with solutions designed to optimize energy efficiency, reduce emissions, and maintain product quality and operational flexibility. ♻️

**MORE INFO** [tenova.com](https://www.tenova.com)


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