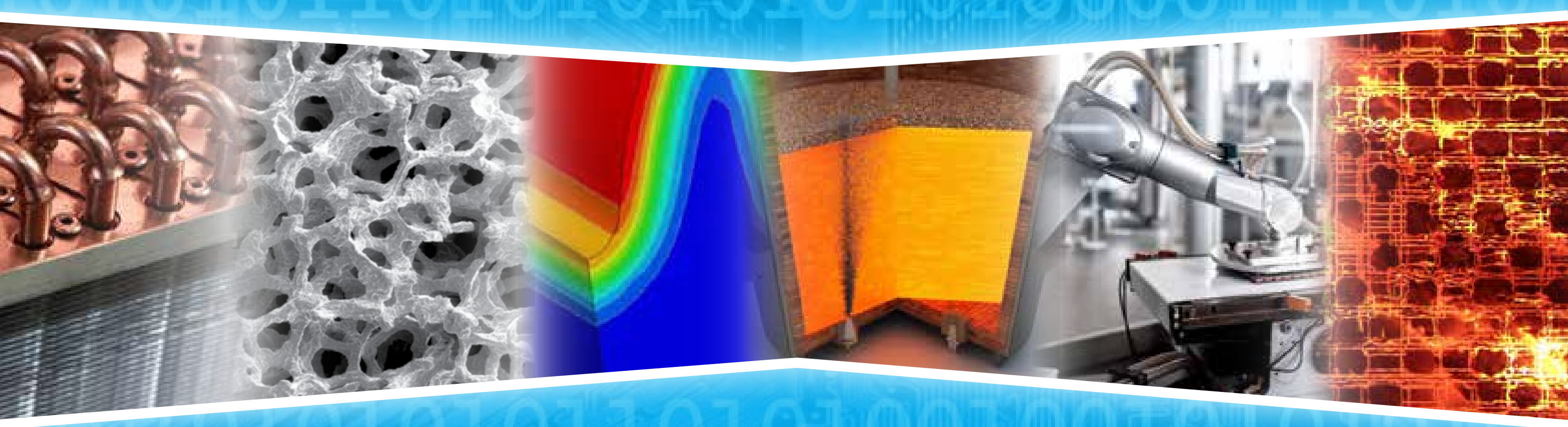
TMI ATC
THERMAL MANUFACTURING INDUSTRIES
ADVANCED TECHNOLOGY CONSORTIUM

ADVANCING THERMAL MANUFACTURING: A TECHNOLOGY ROADMAP TO 2020



Prepared by: ASM INTERNATIONAL NEXIGHT GROUP

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Acknowledgments

This roadmap was developed under the direction of Stan Theobald, Senior Director of Business Development at ASM International, and members of the Thermal Manufacturing Industries Advanced Technology Consortium (TMI ATC) Leadership Team. TMI ATC Leadership Team members represent important stakeholder organizations in the thermal manufacturing community, including the Association for Iron & Steel Technology (AIST), Forging Industry Association (FIA), ASM Heat Treating Society, Industrial Heating Equipment Association (IHEA), Center for Heat Treating Excellence (CHTE), Metal Treating Institute (MTI), and Oak Ridge National Laboratory (ORNL). Nexight Group supported the overall roadmapping process and prepared this roadmap; Sarah Lichtner, Warren Hunt, Ross Brindle, and Lindsay Pack are the primary contributors. The thermal manufacturing community experts who made vital contributions through workshop participation, phone interviews, survey input, and roadmap reviews are identified in Appendix B of this report.

About this Roadmap

In the 1990s and early 2000s, individual thermal manufacturing industry segments such as heat treating and metalcasting created technology roadmaps that identified significant technical challenges and called for research and development to overcome these challenges. However, because these individual industry segments were acting alone, they failed to attract the resources necessary to implement many of the actions identified in these roadmaps. Consequently, many challenges to developing and deploying advanced manufacturing technologies highlighted in these disparate roadmaps remain today, particularly for the small and medium enterprises that comprise 97 percent of all businesses in the thermal manufacturing sector. Further, many of the challenges defined in individual roadmaps are similar, suggesting a need for a more effective, coordinated approach that cuts across all thermal manufacturing industry segments for maximum impact.

ASM International recognized this opportunity for a more comprehensive roadmap to guide coordinated technology development and implementation efforts throughout the broader thermal manufacturing community and led the development of this roadmap, with funding from the National Institute of Standards and Technology (NIST) Advanced Manufacturing Technology Consortia (AMTech) program. This roadmap identifies common barriers that currently constrain the use of advanced technologies in thermal manufacturing and calls for action to develop, adapt, and implement these technologies in the next five years.

The development of this roadmap was informed by a variety of stakeholder inputs and the roadmapping team's extensive background research into the state of thermal manufacturing. To build upon previous work, the roadmapping team reviewed previous roadmaps developed by individual segments of the broader thermal manufacturing community (See Appendix D for a comprehensive list of roadmaps reviewed). ASM International also solicited input from key stakeholders across the thermal manufacturing community through online surveys, phone interviews, and two highly interactive, two-day technology roadmapping workshops organized to coincide with Materials Science & Technology (MS&T) 2014 and Furnaces North America (FNA) 2014.

The priority activities outlined in this roadmap will help inform the activities of the Thermal Manufacturing Industries Advanced Technology Consortium (TMI ATC), a broad consortium that will bring together many parts of the thermal manufacturing community. The ultimate vision of TMI ATC is to coordinate a national initiative to develop and deploy advanced manufacturing technologies across the broad thermal manufacturing community that will significantly increase sustainability and U.S. global competitiveness.

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Executive Summary

Many manufacturing processes in the United States use thermal energy to produce materials and downstream products—collectively referred to as thermal manufacturing in this roadmap.

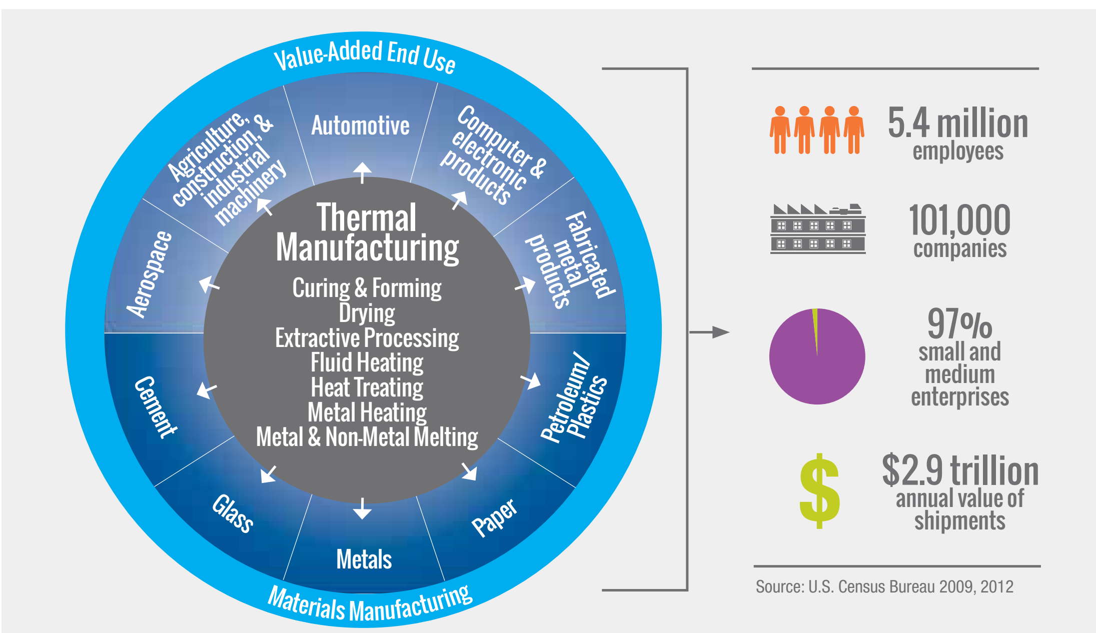
Including both material manufacturing and value-added end use businesses, more than 5.4 million people work in the 101,000 businesses involved in and impacted by the range of thermal manufacturing processes depicted in Figure ES1, generating almost $3 trillion in economic activity annually. Advanced manufacturing technologies can drive greater efficiency and productivity within these businesses, ultimately improving the sustainability and global competitiveness of U.S. thermal manufacturing while creating jobs and stimulating economic growth.

In the 1990s and early 2000s, individual thermal manufacturing industry segments created technology roadmaps that identified significant technical challenges and called for research and development to overcome these challenges. However, because these individual industry segments were acting alone, they failed to attract the resources necessary to implement many of the actions identified in these roadmaps. Consequently, many challenges to developing and deploying advanced manufacturing technologies highlighted in these disparate roadmaps remain today, particularly for the small and medium enterprises that comprise 97 percent of all businesses in the thermal manufacturing sector. Further, many of the challenges defined in these

What is Thermal Manufacturing?

Thermal manufacturing consists of processes that use thermal energy to alter the structure or properties of materials and products to achieve desired performance characteristics for a given application.

Figure ES1: U.S. Thermal Manufacturing Overview



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ASM International recognized this opportunity for a more comprehensive roadmap to guide coordinated technology development and implementation efforts throughout the broader thermal manufacturing community and led the development of this roadmap through funding from the National Institute of Standards and Technology (NIST) Advanced Manufacturing Technology Consortia (AMTech) program.

The Strategy for More Coordinated and Collaborative Technology Development and Implementation

This roadmap identifies common barriers that currently constrain the use of advanced technologies in thermal manufacturing and calls for action to develop, adapt, and implement these technologies in the next five years. Addressing these common barriers—including limitations of current technologies and processes, obstacles to achieving the needed capabilities of advanced thermal manufacturing technology, and widespread non-technical issues related to workforce development and training as well as resource and operational constraints—will require coordinated efforts across the thermal manufacturing community. This roadmap offers a two-fold strategy that combines focused technology development with activities designed to stimulate and support technology implementation. This strategy for more coordinated and collaborative technology development and implementation across the U.S. thermal manufacturing sector is depicted in Figure ES2.

Technology Development Pathways

The technology development pathways focus on achieving the needed capabilities of advanced thermal manufacturing materials and technologies. These pathways will help to enhance the development and selection of materials optimized for thermal manufacturing equipment and products, and will help improve understanding, prediction, monitoring, and control of thermal manufacturing processes.

The development, adaptation, and optimization of advanced technologies will require close coordination among equipment and technology suppliers, thermal manufacturing process implementers, and researchers and other supporting organizations. Through these collaborative efforts, process implementers can communicate their technology and information needs to equipment suppliers and research organizations, allowing these developers to better target their efforts toward addressing industry needs. The continuous exchange of experimental and real-world operating data between these stakeholders will also inform technology optimization.

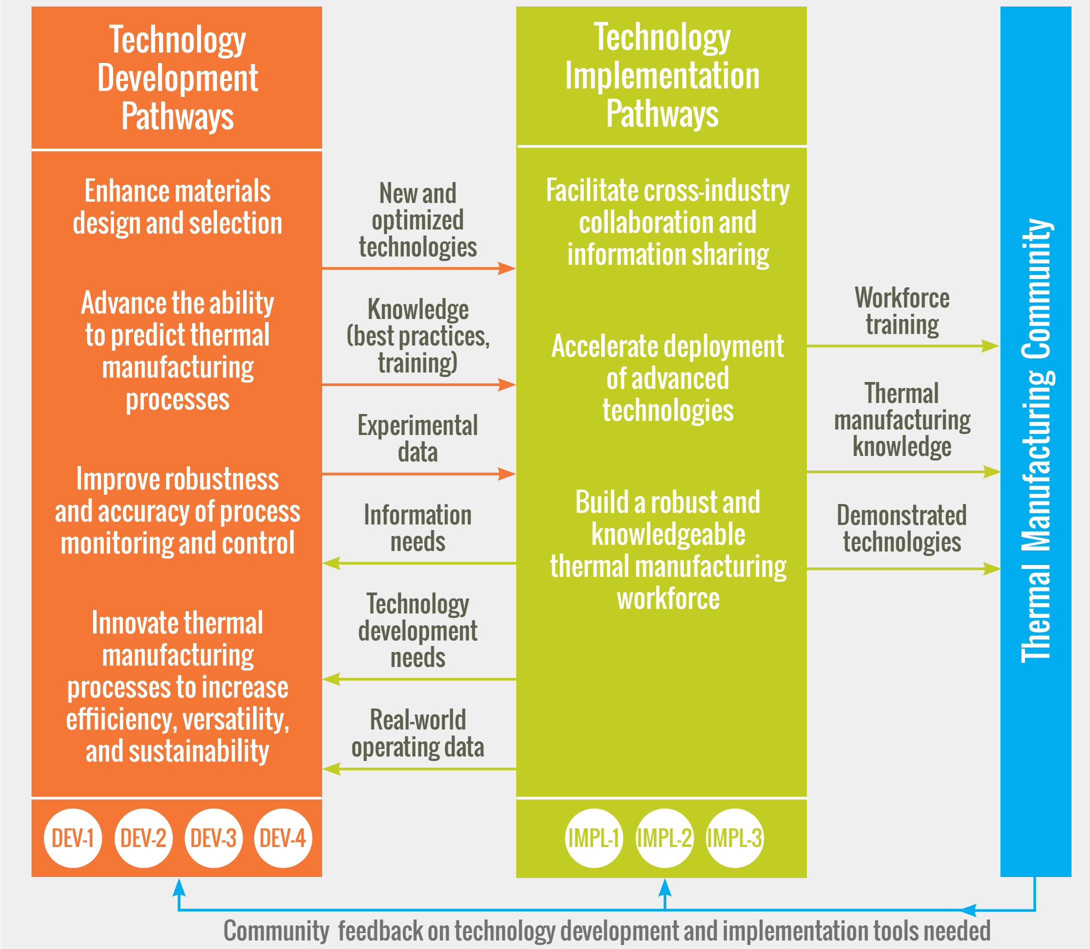
Technology Implementation Pathways

Even armed with advanced technologies tailored to their specific requirements, thermal manufacturing process implementers, particularly small and medium-sized companies with limited resources, may still be hesitant to implement these technologies in their operations. The technology implementation pathways, therefore, aim to stimulate the widespread acceptance and adoption of advanced technologies throughout the thermal manufacturing community. To do so, these pathways must establish stronger partnerships throughout the community; build a comprehensive knowledgebase of thermal manufacturing information; and provide the workforce with the knowledge and skills necessary to assess, implement, and operate advanced technologies.

The Benefits of a Coordinated Approach

This strategy can help the thermal manufacturing community to more effectively meet the growing demand for materials and products with lower cost, increased quality, and improved functionality. Coordination throughout the thermal manufacturing community and the increased implementation

Figure ES2: The Strategy for More Coordinated and Collaborative Technology Development and Implementation



Action Plans

- **DEV-1** Increase the robustness of materials used in thermal manufacturing equipment
- **DEV-2** Advance tools that model and simulate entire thermal manufacturing processes
- **DEV-3** Improve understanding of performance requirements and development needs of thermal manufacturing sensors
- **DEV-4** Identify and implement hybrid thermal processes and novel applications for existing thermal processes
- **IMPL-1** Establish a comprehensive thermal manufacturing knowledgebase
- **IMPL-2** Establish a thermal manufacturing demonstration facilities network
- **IMPL-3** Launch a thermal manufacturing workforce training program

of advanced technologies will also accelerate the widespread achievement of several important industry and national goals.

- **Improved productivity and global competitiveness:** Reduced production costs through improved manufacturing yields and efficiencies, increased labor productivity, and enhanced safety will not only help improve the global competitiveness of U.S. manufacturing companies, but can also help make their products more affordable to consumers.
- **Increased economic growth and employment:** A more globally competitive thermal manufacturing sector will stimulate U.S. investment, economic growth, and employment. Through effective collaboration and application of advanced manufacturing technologies, even a modest 2 percent increase in economic activity and employment translates into an additional $58 billion in value of shipments and more than 100,000 American manufacturing jobs.
- **Reduced energy intensity and emissions:** Reducing industrial energy intensity, which typically represents 2 to 15 percent of a manufacturer's total product cost,[1] will not only help decrease manufacturing costs but can also significantly cut greenhouse gases and other harmful emissions.
- **Enhanced product quality and value:** Manufacturing products with greater predictability, consistency, and more precisely tailored properties will improve product performance and reliability, delivering greater value to customers.

The Path Ahead

The future global competitiveness and sustainability of U.S. thermal manufacturing depends on action taken now to facilitate the coordination of a broader thermal manufacturing community. **Collaborative effort across thermal manufacturing industry segments and stakeholders is essential to accelerate the development, adaptation, and implementation of advanced technologies throughout the thermal manufacturing community in the next five years.** Implementation of this roadmap's critical actions and priority action plans will occur by bringing together key academic centers and departments; national laboratories; and industry trade associations and professional societies and their members through a newly formed Thermal Manufacturing Industries Advanced Technology Consortium (TMI ATC). Establishing and growing this broader thermal manufacturing community will serve as a call to action to the organizations involved in and impacted by thermal manufacturing and catalyze action in this nationally critical area. Ultimately, by working together through TMI ATC, the thermal manufacturing community can begin to realize the value of advanced manufacturing technologies in the next five years and for many years to come.

[1]Industrial Heating Equipment Association (IHEA) and U.S. Department of Energy (DOE), ***Roadmap for Process Heating Technology***, March 2001.

Defining Thermal Manufacturing

Thermal manufacturing is estimated to directly and indirectly employ 5.4 million people in the United States at more than 101,000 businesses.

These companies—97 percent of which are small and medium enterprises—annually produce $2.9 trillion in economic activity.[2] Figure 1 provides an overview of thermal manufacturing and the magnitude of its impact in select industry segments.

Figure 2 expands on the stages of materials processing—from raw materials to end products—of both the materials manufacturing industries and value-added end-use industries in Figure 1. It also depicts the specific thermal manufacturing processes applied at each stage to demonstrate the pervasiveness of thermal manufacturing and its impact in terms of overall energy use, U.S. employment, and economic activity.

What is Thermal Manufacturing?

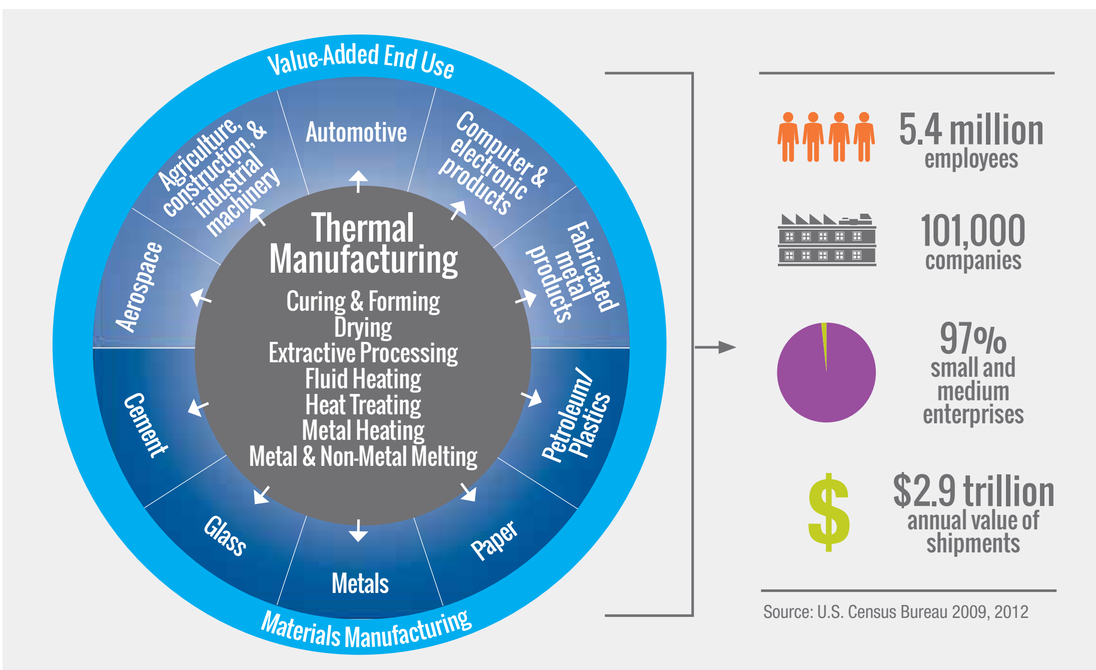
Thermal manufacturing consists of processes that use thermal energy to alter the structure or properties of materials and products to achieve desired performance characteristics for a given application.

In this roadmap, thermal manufacturing processes include:

- Curing and forming
- Drying
- Extractive processing
- Fluid heating
- Heat treating
- Metal heating
- Metal and non-metal melting

More information about these processes is provided in Appendix C.

Figure 1: U.S. Thermal Manufacturing Overview



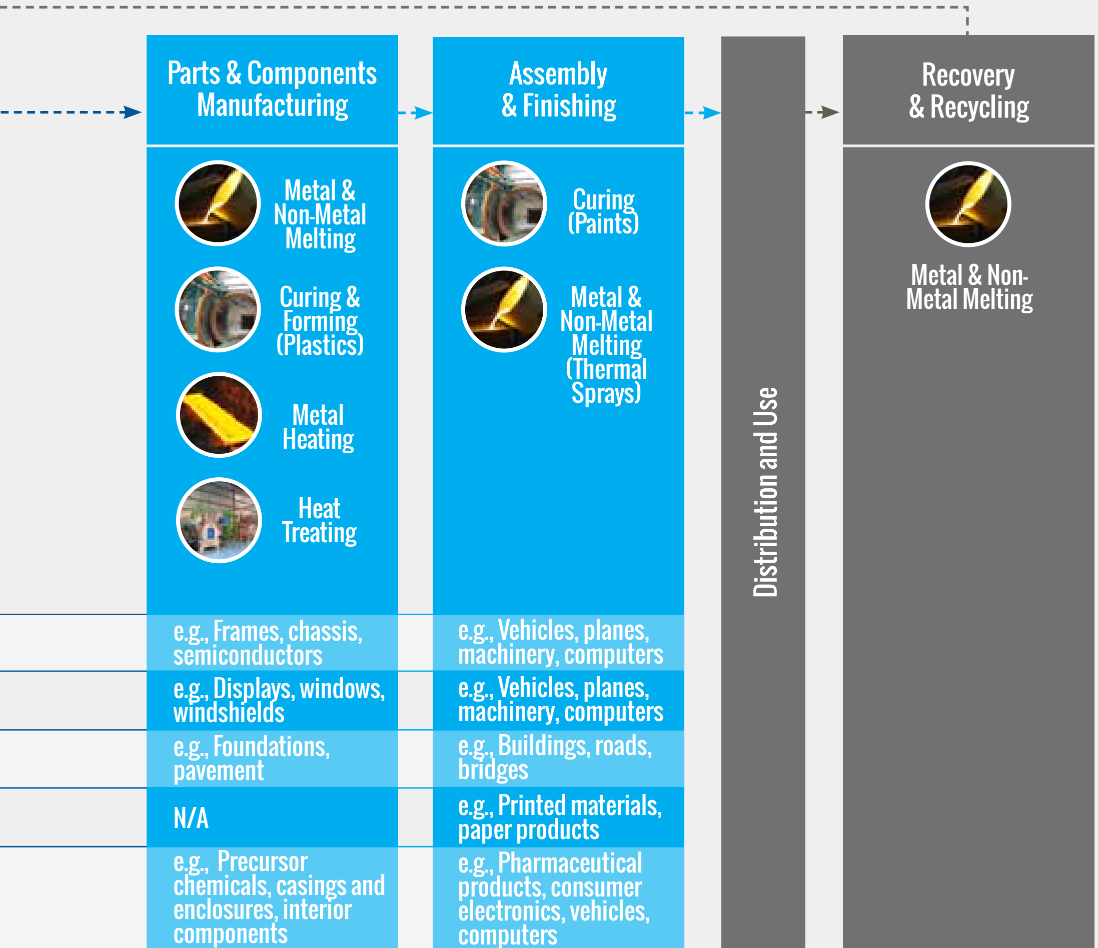
[2]United States Census Bureau, U.S. Department of Commerce, "Statistics of U.S. Businesses," Historical Data Tabulations by Enterprise Size-2012, NAICS codes 322, 324, 327, 331, 332, 333, 334, 336, http://www.census.gov/econ/susb/data/susb2012.html; U.S. Census Bureau, "The 2012 Statistical Abstract," Manufactures, http://www.census.gov/compendia/statab/cats/manufactures.html.

Figure 2: Thermal Manufacturing Value Chain

		Extraction/ Reduction/ Separation	Primary Processing	Secondary Processing
		Extractive Processing	Fluid Heating; Curing & Forming; Drying; Metal Heating; Melting & Non-Metal Melting	Heat Treating; Metal Heating; Curing and Forming (Plastics)
Metals	Minerals and ores	Raw metals/elements and coke processing	Ingots, billets	Semi-finished and finished shapes
Glass	Sands, minerals, and ores	Primary materials/ minerals	Semi-finished and finished shapes	Finished shapes (Cut, polished)
Cement	N/A	Primary materials/ minerals	Raw meal/clinker	Dry cement
Paper	Plant matter	Pulp	Paper	Coated and cut paper
Petroleum/ Plastics	Oil, oil sands, and oil shale	Crude Oil	Feedstocks and fuels	Refined fuels, semi-finished and finished plastic and polymer shapes and films

Energy Use Total: 10.3 Quadrillion BTU*	Cement: 246 TBTU Glass: 164 TBTU Metals: 1,610 TBTU	Paper: 2,110 TBTU Petroleum/Plastics: 6,140 TBTU
Employment Total: 1.1 million jobs	Cement: 170,000 Glass: 80,800 Metals: 394,000	Paper: 352,000 Petroleum/Plastics: 100,000
Value of Shipments Total: $1.36 trillion	Cement: $41.4 billion Glass: $20.4 billion Metals: $270 billion	Paper: $182 billion Petroleum/Plastics: $844 billion

*This figure represents total energy use in these industry segments. Energy used for thermal manufacturing is a portion of this figure.



Energy Use Total: 465 TBTU	Aerospace: 14 TBTU Agriculture, Construction, and Industrial Machinery: 149 TBTU Automotive: 66 TBTU	Computer and Electronic Products: 145 TBTU Fabricated Metal Products: 91 TBTU
Employment Total: 4.29 million jobs	Aerospace: 379,000 Agriculture, Construction, and Industrial Machinery: 1.06 million Automotive: 667,000	Computer and Electronic Products: 851,000 Fabricated Metal Products: 1.33 million
Value of Shipments Total: $1.57 trillion	Aerospace: $179 billion Agriculture, Construction, and Industrial Machinery:$408 billion Automotive: $302 billion	Computer and Electronic Products: $337 billion Fabricated Metal Products: $340 billion

Thermal Manufacturing Equipment and Processing Conditions

The specific objective of each thermal manufacturing process—like strengthening a material or removing water from it—varies, but all of thermal manufacturing shares a fundamental similarity: it uses thermal energy to alter materials and products to achieve desired performance characteristics for a given application. This similarity is illustrated by the overlap in the equipment and conditions of different thermal manufacturing processes, which provides opportunities for coordinated and collaborative development of advanced manufacturing tools and technologies.

The types of equipment used for different thermal manufacturing processes, and the optimal process temperatures and atmospheres, depend on the material undergoing thermal treatment and the thermal process needed to achieve the desired properties of the final product. Different types of equipment can best achieve these properties based on varying modes of operation (batch vs continuous), heat-producing energy sources, heating methods (e.g., radiant, convection, conduction), and operating atmosphere and temperature. Manufacturers carefully choose atmospheric conditions, including air composition and pressure, and operating temperature because these conditions can interact with materials and products positively or negatively, impacting product quality.

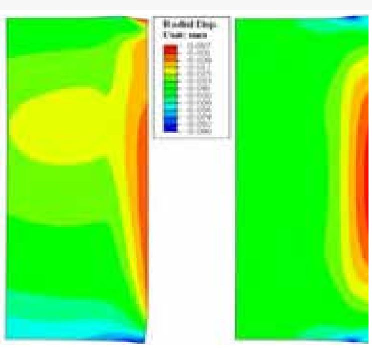
Thermal Manufacturing Stakeholders

A thermal manufacturing community that could foster collaboration has not previously existed. A coordinated effort across the following stakeholders in the industry segments that rely on or supply thermal manufacturing equipment and processes will help accelerate development and implementation of advanced manufacturing technologies.

Equipment and Technology Suppliers manufacture the furnaces, ovens, autoclaves, kilns, distillation units, heat exchangers, burners, dies, presses, rollers, refractory materials, and supporting equipment used in thermal manufacturing processes. This stakeholder group also includes tool developers such as modeling software and sensor providers targeting thermal manufacturing applications. Consisting of several large companies and thousands of small and medium ones, these stakeholders seek to implement advanced manufacturing technologies into their equipment to provide expanded capabilities to the process implementers.

Process Implementers are companies who use equipment and technology to conduct thermal manufacturing processes, creating a wide range of products and services. This

Heat Treating Stakeholders



Comparison of distortion after scan hardening (outer diameter)

The Heat Treating industry sector provides an example of the stakeholders in one segment of thermal manufacturing. More than 400 manufacturers provide equipment, including burners, furnaces, and supporting technologies. More than 270 commercial heat treating companies complement an extensive group of captive heat treaters. These businesses are supported by university-based research groups such as the Center for Heat Treating Excellence at Worcester Polytechnic Institute and national laboratories including Oak Ridge National Laboratory. Several trade associations and professional societies provide valuable support to the heat treating industry segment, including the ASM Heat Treating Society, Industrial Heating Equipment Association, and the Metal Treating Institute.

stakeholder group consists of large companies with in-house thermal manufacturing processes (often referred to as “captive” organizations) as well as many small and medium enterprises, many of which provide thermal manufacturing as a specialized service (often referred to as “commercial” organizations).

Research and Supporting Organizations conduct R&D and provide information, training, and education that supports equipment and technology suppliers and process implementers, typically focused within a specific industry segment. These organizations—including academia, national laboratories, contract and not-for-profit research organizations, as well as trade associations and professional societies—often develop new understanding, data, tools, materials, and other enabling technologies that then must be transferred to industrial applications. Several industrial consortia housed within universities or not-for-profit research organizations serve individual industry segments of thermal manufacturing, but none currently encompass thermal manufacturing as broadly defined in this roadmap.

State of Advanced Thermal Manufacturing Technologies

Advanced manufacturing technologies have the potential to improve the efficiency, productivity, and global competitiveness of a wide range of thermal manufacturing processes and various end-use industries.

Technologies with particular relevance to thermal manufacturing can be categorized as follows:

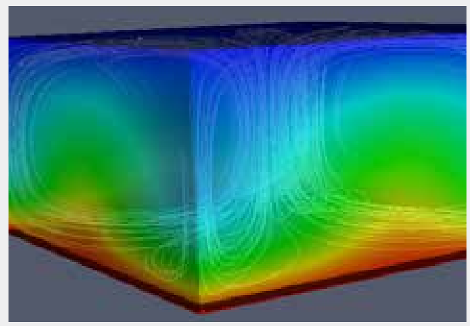
- Modeling and Simulation
- Sensors and Automation
- Heat Generation Methods
- Advanced Materials
- Energy Intensity and Emissions Reduction

While each of these areas provides value alone, advancing and implementing multiple technologies in parallel will have the maximum impact. While they have been categorized based on the technology of most relevance, in most cases, one technology enables or is dependent on another area of work (e.g., improved sensors could facilitate improved data collection for modeling and simulation). The following sections provide a high-level summary of the key opportunities in each of these technology areas based on an assessment of prior roadmaps as well as current information available through the literature and public websites.

Advanced Manufacturing

The President's Council of Advisors on Science and Technology defines advanced manufacturing as "a family of activities that (a) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or (b) make use of cutting-edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry, and biology. This involves both new ways to manufacture existing products, and especially the manufacture of new products emerging from new advanced technologies."

Report to the President on Ensuring American Leadership in Advanced Manufacturing, June 2011.



Simulation of a thermal distribution

Modeling and Simulation

The increased use of modeling and simulation has been shown to optimize manufacturing processes and products and save money by reducing trial and error approaches in materials and process development. Advanced manufacturing areas that support thermal manufacturing include:

- Enhanced decision-making tools
- More accurate models validated with real operating data
- Improved user friendliness of models that are adaptable for different processes
- More comprehensive and accurate materials properties and process databases
- Increased accessibility and affordability of data
- Improved computational speed that is consistent with data processing speed needs
- Advanced models that integrate all relevant characteristics that impact process optimization and product quality

Sensors and Automation

Improved sensor technologies can enable more accurate measuring and monitoring, and when coupled with automation technologies, can control thermal manufacturing process parameters and improve the quality and reliability of products. Some areas in which sensors and automation impact thermal manufacturing are:

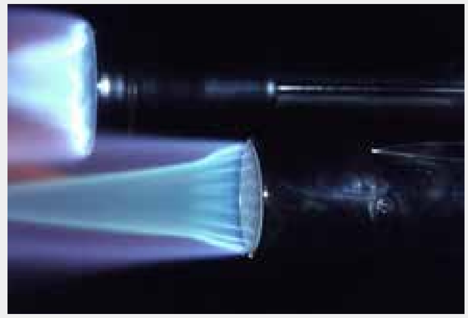
- Low-cost, real-time, non-intrusive sensors capable of measuring and monitoring multi-element emissions from the combustion system, process operation (e.g., temperature and atmospheric composition and pressure), and the physical properties of equipment and the product being heated
- Smart systems that can detect and diagnose product quality problems, predict process requirements and changes, signal maintenance activities based on operating conditions, and automatically adjust process variables for optimization
- Improved ability to measure and predict energy consumption, equipment degradation, and cycle and process management, and to better integrate controls, sensors, automation, and documentation technologies

Optical sensor

Heat Generation Methods

Due to the inherent energy-intensiveness of thermal manufacturing, there is a continuous need for more cost-effective, energy-efficient, and cleaner heat generation methods with improved heat transfer. Some areas where advanced manufacturing technologies are used in heat generation include:

- Improved indirect heating methods

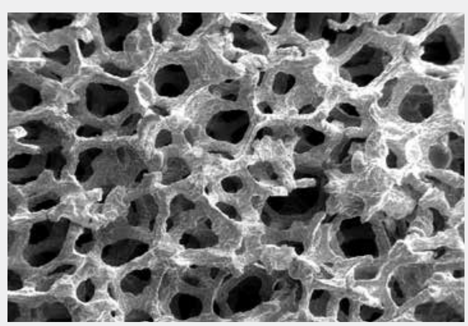


Open gas burner

- Hybrid heat generation methods that combine existing methods or couple a new method with an existing method to increase efficiency
- Advanced combustion methods with increased stabilization
- Reduced cost and improved purity of on-site oxygen production for oxy-fuel firing, including cogeneration
- Advanced electrical technology for heating and processing such as isothermal melting, electroforming, vacuum melting, electric discharge machining, and electron beam processing

Advanced Materials

By manipulating the composition of materials and the processing techniques with which the materials are created and formed, scientists can develop equipment as well as end-use product materials with optimized mechanical, chemical, and physical properties better able to withstand



Scanning electron microscope image of metal foam the harsh operating conditions of thermal manufacturing. Some impacts of advanced manufacturing in the advanced materials area are:

- More cost-effective materials that are more resistant to corrosion, heat, creep, pressure, shock, and abrasion for both equipment and end-use products
- More cost-effective equipment that requires less maintenance, lasts longer, is more efficient, and is more compact
- End-use products that are higher quality, lower cost, and have more homogeneous structures

Heat exchanger

Energy Intensity and Emissions Reduction Technology

More stringent environmental standards and regulations necessitate advanced energy intensity and emissions reduction technologies that can help improve the energy efficiency and cost effectiveness of thermal manufacturing processes while improving the environmental sustainability of manufacturing, as well as the health and safety of workers. Advanced manufacturing technology examples in this area are:

- Increased efficiency in the use of raw materials, energy, and water
- Lower-cost emissions measurement technologies and controls
- More effective heat exchanger technologies
- High-performance thermoelectric materials
- Embedded energy monitoring to provide detailed data for process optimization

Barriers to Technology Development and Implementation

While advanced manufacturing technologies hold great promise for the thermal manufacturing community, many barriers limit the development, adaptation, and implementation of these technologies in thermal manufacturing.

Specific technical barriers include materials limitations in harsh environments and a lack of data and tools needed to accurately predict and control thermal processes. In addition to these technical barriers, widespread non-technical issues—related to workforce development and training as well as resource and operational constraints—continue to hinder the awareness, acceptance, and widespread adoption of advanced technology in thermal manufacturing. The thermal manufacturing community must work together to overcome these barriers to realize the increased productivity, cost-effectiveness, and efficiency made possible by advanced manufacturing technologies.

Technical Barriers

While there are unique technical challenges related to each thermal manufacturing process and its resultant products, there are many similarities in equipment and conditions across thermal manufacturing processes. As a result, several technical barriers cut across all or most thermal manufacturing industry segments.

Equipment materials limitations in harsh operating conditions

The high operating temperatures and environments of thermal manufacturing are harsh on equipment materials. Some materials suited for thermal manufacturing equipment—with increased wear and impact resistance, longer operating lifetimes, and reduced reactivity—are available, but their use is often cost-prohibitive. Optimizing thermal efficiency and extending equipment life via lower-cost high-temperature materials, including insulation materials and coatings, could reduce energy intensity, lower production costs, and enhance product quality.

Limited understanding of the effects of thermal processes on end-use product performance

Accurate and reliable materials and process data is critical to understand the effects of thermal processes on the materials being produced. Because this data can be costly and time-consuming to generate and requires specialized testing and equipment, it is not adequately available. The data that does exist is not readily accessible throughout the thermal manufacturing community, as such data is typically considered to be proprietary by companies that have invested in its creation.

This lack of materials and process data makes it difficult to understand how to adjust thermal manufacturing process conditions to achieve desired materials properties. Further, many process implementers have an incomplete understanding of the materials they are producing, particularly regarding long-term materials performance. Access to improved data and models capable of simulating long-term materials performance could help process implementers select better materials and process conditions to optimize materials and product designs. Better data and prediction of long-term materials properties could help shorten product development time while also guiding process implementers as they seek to reduce processing times and lower operating temperatures without adversely affecting their products.

Limited tools for predicting and optimizing thermal processes

It can be difficult to control the precision and maintain the uniformity of thermal manufacturing conditions and operating

temperatures. Tools—such as models and sensors—that help predict and optimize thermal manufacturing processes need to be improved to further reduce energy intensity and emissions, lower production costs, and enhance product quality. Current modeling and simulation technologies are not adequately sophisticated to accurately and quickly predict all relevant materials and process interactions. Further, because current models typically require modeling experts to run, small and medium-sized companies rarely have the technical capabilities or resources needed to realize the value of these predictive tools.

Currently, sensor capabilities also lag behind their potential to reliably and accurately detect aspects of manufacturing processes in real time that negatively impact product quality, including equipment malfunctions, materials defects, non-uniform temperatures, and variations in atmospheric composition. The extreme environments of thermal manufacturing can also degrade sensing equipment, which limits sensor life and further reduces sensing accuracy. Next-generation models and sensors with advanced capabilities could increase process efficiency and productivity by reducing the need for trial-and-error decision making and could better ensure product quality by more closely linking process parameters with ultimate product performance.

Non-Technical Implementation Barriers

Even with the availability of cost-effective and robust materials, accessible and reliable process and materials data, and accurate and sophisticated sensors and modeling technologies, technology implementation is dependent on widespread knowledge and consistent action across the thermal manufacturing community. Working to overcome barriers related to workforce education and technology deployment is essential for the thermal manufacturing community to implement advanced manufacturing technologies.

Workforce development and training gaps

The future of thermal manufacturing depends on a highly skilled and forward-looking workforce with sufficient knowledge to consider and implement new technologies and process innovations. The thermal manufacturing community, however, currently lacks a common platform for workforce education. Additionally, some members of the thermal manufacturing workforce do not have a fundamental and mechanistic understanding of existing or forthcoming materials, equipment, and processes, particularly outside of their specific portion of the value chain. The lack of this holistic understanding limits opportunities to improve plant floor operations.

The long history of thermal manufacturing has also created a widespread misperception of thermal manufacturing as a dirty and outdated industry, making it difficult to attract young employees. Additionally, new graduates are not commonly paired with senior employees when joining the workforce, which is critical for transferring knowledge of processes and technologies as many senior workers near retirement. A more diverse workforce and more robust education would help reduce human error and improve process efficiency through the integration of best practices and the latest technologies.

Limited cross-sector information sharing

To encourage technology acceptance and implementation, the thermal manufacturing workforce needs access to data on new equipment, technologies, and materials. However, because of the size and diversity of the thermal manufacturing community, no single comprehensive source of relevant thermal manufacturing data exists.

Additionally, due to the competitive nature of manufacturing, companies are typically unwilling to share certain types of information. Increased information sharing is needed to provide companies throughout the thermal manufacturing community, particularly small and medium enterprises, with opportunities to learn about the benefits of new equipment, technologies, and materials.

Resource constraints and risk averseness

While implementing advanced technologies and processes can deliver tangible benefits, many companies throughout the thermal manufacturing community—particularly smaller companies—lack the staff capabilities and financial flexibility needed to explore and implement new ideas. These companies are generally reluctant to accept new technologies unless the time and cost savings are recognizable, significant, and relatively easy to achieve in the short term. The reliability of some new technologies may also be less certain due to their lack of broad industrial use and track record, which introduces risk to the first few companies considering their adoption. Increased access to data and technology demonstrations could highlight the true costs, efficiency, effectiveness, and risks of new technologies and ultimately encourage more widespread adoption.

The Strategy for More Coordinated and Collaborative Technology Development and Implementation

To address the common barriers that currently constrain thermal manufacturing industry segments, this roadmap offers a two-fold strategy that combines focused technology development with activities designed to stimulate and support technology implementation.

These initiatives and the pathways for action outlined within them can guide coordinated efforts throughout the broader thermal manufacturing community over the next five years. This strategy for more coordinated and collaborative technology development and implementation across the U.S. thermal manufacturing sector is depicted in Figure 3. This figure demonstrates the close interrelationship and interchange of technologies, information, and needs between the technology development pathways, technology implementation pathways, and the thermal manufacturing community.

Defining Technology Development

In this roadmap, "technology development" includes activities necessary to develop new technologies and to adapt, optimize, and customize existing technologies for use in thermal manufacturing applications.

Technology Development Pathways

The technology development pathways focus on achieving the needed capabilities of next-generation thermal manufacturing materials, technologies, and tools. Because many advanced technologies that can improve thermal manufacturing already exist and only need to be refined to suit specific thermal manufacturing processes, this roadmap is intentionally focused on delivering an impact in the relative near term, through 2020.

This near-term focus calls for development, adaptation, and optimization of advanced technologies, an endeavor that will require close coordination among equipment and technology suppliers, thermal manufacturing process implementers, and researchers and other supporting organizations. Through these collaborative efforts, process implementers can communicate their technology and information needs to equipment suppliers and research organizations. As a result, developers will be able to better target their efforts to provide industry with new and optimized technologies and information tailored to their needs. The continuous exchange of experimental and real-world operating data among these stakeholders will also accelerate technology optimization. These technology development pathways will help to enhance the development and selection of materials optimized for thermal manufacturing equipment and products, and will help improve understanding, prediction, monitoring, and control of thermal manufacturing processes.

Technology Implementation Pathways

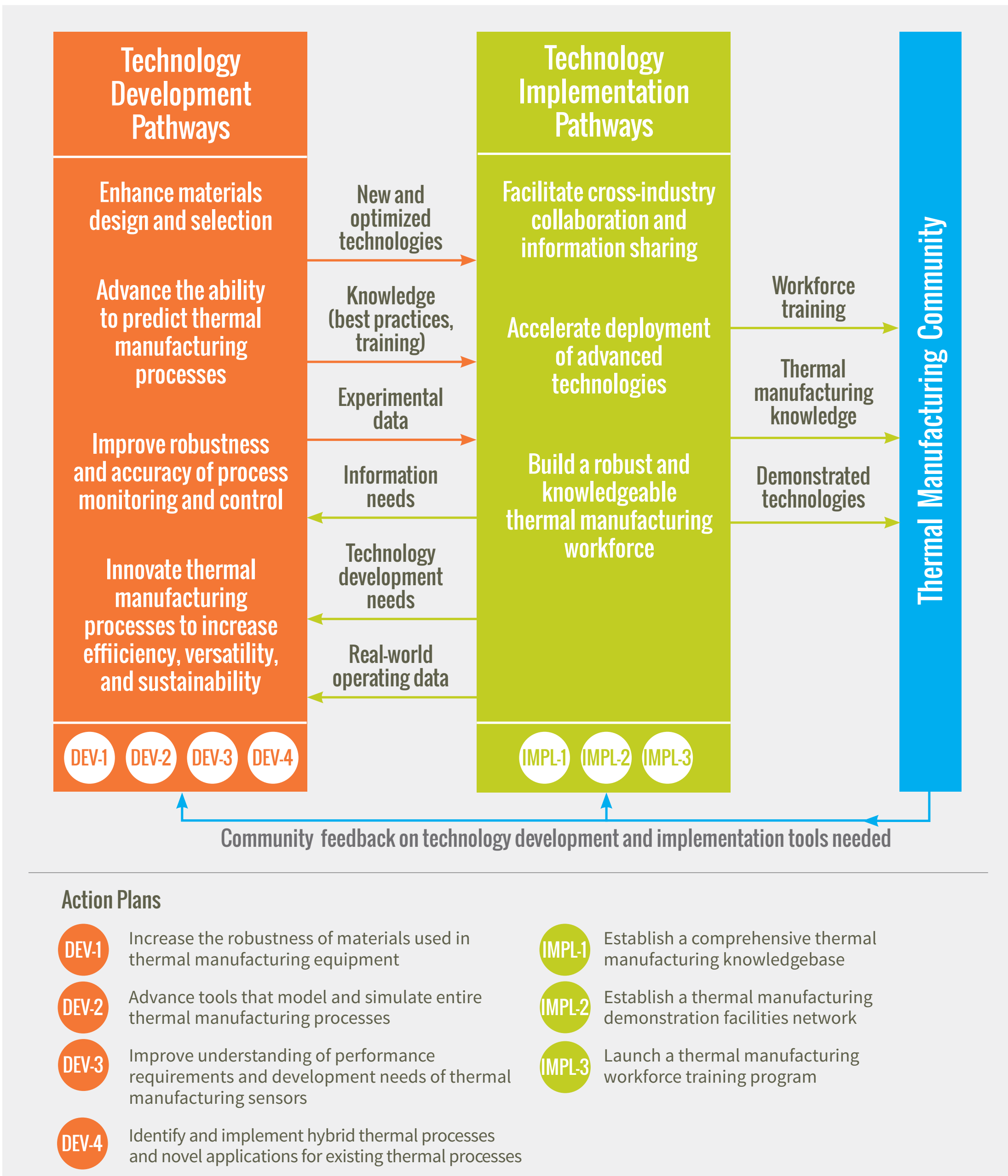
Even armed with advanced technologies tailored to their specific requirements, process implementers, particularly small and medium-sized companies with limited resources, may still be hesitant to implement these technologies in their operations. The technology implementation pathways, therefore, aim to stimulate the widespread acceptance and adoption of advanced technologies throughout the thermal manufacturing community.

These pathways will help establish stronger partnerships throughout the community; build a comprehensive knowledgebase of thermal manufacturing information; and provide the workforce with the knowledge and skills necessary to assess, implement, and operate advanced manufacturing technologies. In turn, the community will provide a valuable feedback loop to the technology development and implementation efforts, enabling enhanced focus and utility of the outputs of the work. Ultimately, greater adoption of advanced technologies throughout the thermal manufacturing community will help improve the productivity and global competitiveness of U.S. thermal manufacturing.

Near-Term Opportunities for Thermal Manufacturing Advancement

Implementing this strategy will require close

Figure 3: Thermal Manufacturing Strategy Overview



coordination and collaboration across the thermal manufacturing community at a magnitude that has previously not occurred. To provide immediate opportunities for advancement, this roadmap contains seven detailed action plans that focus on specific areas of activity that can accelerate the development or implementation of advanced manufacturing technologies throughout the thermal manufacturing community. These Priority Action Plans, which are listed at the bottom of Figure 3, present near-term opportunities that can significantly impact thermal manufacturing.

The Benefits of a Coordinated Approach

The thermal manufacturing community is too large, diverse, and complex, as evidenced by the 97 percent of small and medium enterprises within the community, to fully realize the benefits of advanced manufacturing technology without a coordinated approach. Through a collaborative, strategic effort as called for in this roadmap, the community can help one another improve the capabilities of advanced manufacturing technologies used in thermal manufacturing and accelerate their implementation. This collaborative effort will also accelerate the widespread achievement of several important industry and national goals.

Improved productivity and global competitiveness

The costs of raw material, energy, labor, and equipment required for thermal manufacturing can add up quickly. Reduced production costs through improved manufacturing yields, increased safety, and labor productivity via the use of robotics and automation, and similar advances will not only help improve the global competitiveness of U.S. manufacturing companies, but can also help make their products more affordable to consumers.

Increased economic growth and employment

A more globally competitive thermal manufacturing sector will stimulate U.S. investment, economic growth, and employment across the sector. Through effective collaboration and application of advanced manufacturing technologies, even a modest 2 percent increase in economic activity and employment translates into an additional $58 billion in value of shipments and more than 100,000 American manufacturing jobs.

Reduced energy intensity and emissions

Today's thermal manufacturing processes require a substantial amount of energy; 27 percent of overall U.S. industrial energy use is from thermal manufacturing processes, totaling approximately 4.0 quadrillion British Thermal Units.[3] Reducing industrial energy intensity, which typically represents 2 to 15 percent of a manufacturer's total product cost,[4] will not only help decrease manufacturing costs but can also significantly cut greenhouse gases and other harmful emissions.

Enhanced product quality and value

In addition to manufacturing cleaner and more affordable products, the thermal manufacturing community must develop and implement technologies, processes, and practices that lead to superior-quality products. Manufacturing products with greater predictability, consistency, and more precisely tailored properties will improve product performance and reliability, delivering greater value to customers.

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[3]U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program, *Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing and Mining*, December 2004; U.S. Energy Information Administration, U.S. Department of Energy, "AEO Early Release Overview," Delivered Energy Consumption by Sector, December 16, 2013, http://www.eia.gov/forecasts/aeo/er/early_consumption.cfm.
[4]Industrial Heating Equipment Association (IHEA) and U.S. Department of Energy (DOE), *Roadmap for Process Heating Technology*, March 2001.

Technology Development Pathways

The increased integration of advanced manufacturing technologies throughout the thermal manufacturing community has the potential to revolutionize the efficiency and productivity of thermal manufacturing processes.

Optimizing existing technologies and achieving the needed capabilities of next-generation thermal manufacturing technologies will require significant collaboration across the thermal manufacturing community. This collaboration should focus on the four technology development pathways in Figure 4 that crosscut all thermal manufacturing industry segments.

Figure 4: Overview of Technology Development Pathways

Enhance Materials Design and Selection

Increase the Robustness of Materials Used in Thermal Manufacturing Equipment
(Action Plan DEV-1)

- Design and test new alloys, coatings, and other materials (e.g., multimaterials or composite nanomaterials) to increase the robustness, lifespan, and inertness of furnace fixtures and refractory components **(D1)**
- Establish framework for improved high-temperature properties determination and materials selection **(D2)**
- Identify more environmentally friendly quenching media and quenching filtration systems
- Develop catalysts that enable lower-temperature combustion and help maintain flame stability

Maximize the Quality of End-Use Products

- Improve existing alloys within their broad specifications **(D3)**
- Conduct fundamental studies on phase transformation and communicate results along with existing phase transformation knowledge **(D4)**
- Improve techniques for materials joining
- Establish standards for documenting materials specifications
- Engineer paint and coating processes that allow for faster curing at lower temperatures
- Identify a method to control or analyze the introduction of contaminants into feedstocks sourced from recycled materials

Advance the Ability to Predict Thermal Manufacturing Processes

Increase the Widespread Use and Reliability of Thermal Manufacturing Modeling and Simulation Tools

- Simplify existing modeling and simulation software to make it accessible to different level users **(D5)**
- Generate benchmark data and validate models **(D6)**

Advance Tools that Model and Simulate Entire Thermal Manufacturing Processes
(Action Plan DEV-2)

- Develop models that will predict materials properties and performance in thermal manufacturing operating conditions **(D7)**
- Advance modeling and simulation tools for evaluating the thermal efficiency and energy use of thermal manufacturing processes **(D8)**
- Improve temperature uniformity models to optimize equipment design and processing consistency

Figure 4: Overview of Technology Development Pathways (cont.)

Improve Robustness and Accuracy of Process Monitoring and Control	**Improve Understanding of Performance Requirements and Development Needs of Thermal Manufacturing Sensors** (Action Plan DEV-3) • Identify and categorize currently available sensor technologies **(D9)** • Define thermal manufacturing sensor needs and metrics **(D10)** **Advance Ability to Non-Destructively Evaluate Product Quality** • Develop sensors capable of identifying when phase transformation takes place in various materials **(D11)** • Advance sensors that can provide in situ moisture and temperature profiles of products • Improve surface analysis sensors • Strengthen the ability to measure defects in thermally processed products **Improve Monitoring and Control of Process Parameters** • Implement mechanisms that enable more automated process control **(D12)** • Improve sensors that measure atmospheric constituents • Develop sensor arrays that measure and ensure consistency of process temperature and moisture
Innovate Thermal Manufacturing Processes to Increase Efficiency, Versatility, and Sustainability	**Optimize Thermal Manufacturing Processing Techniques** • Identify and implement hybrid thermal processes and novel applications for existing thermal manufacturing processes **(D13)** (Action Plan DEV-4) • Optimize thermal manufacturing equipment and processes to improve waste heat recovery and reduce emissions • Explore use of other innovative thermal manufacturing processing techniques

Enhance Materials Design and Selection

The future of thermal manufacturing demands more cost-effective and higher-performing materials—for both equipment used in thermal processes and the end products they create—that can better withstand the extreme operating conditions of thermal manufacturing. Many such materials already exist, but the thermal manufacturing community needs a better understanding of the effects of thermal manufacturing processes on these materials, better tools to help select the best materials for different applications, and pathways to reduced cost. In other cases, existing materials lack the needed mechanical, chemical, or physical properties. To develop materials with the desired balance of properties, materials scientists can manipulate the composition of existing materials and the processing techniques with which these materials are fabricated.

Integrating higher-performing materials into thermal manufacturing equipment and end-use products can yield significant benefits, both to the thermal manufacturing community

Graphs Depicting Cost and Impact of Priority Actions

The following sections include graphs that depict the cost of implementing the roadmap's high-priority critical actions relative to the impact that these actions can have on the thermal manufacturing community in the next five years. This information was provided by participants of the workshops that were held as part of the roadmap development effort.

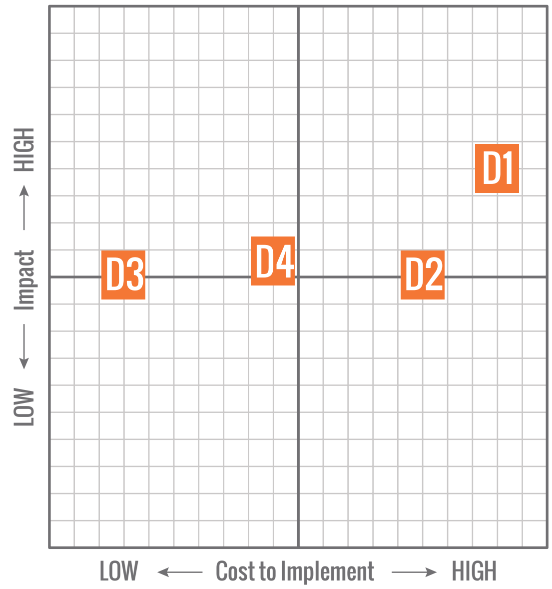
and to the end users of these products. Improved equipment materials can lower thermal manufacturing costs and increase process efficiency, while the use of advanced materials in thermally manufactured products can ensure their quality and consistent performance. To achieve these benefits, the thermal manufacturing community must work together to implement higher-performance materials into thermal manufacturing, ultimately improving the robustness of thermal manufacturing equipment and maximizing the quality of end-use products.

Increase the Robustness of Materials Used in Thermal Manufacturing Equipment (Action Plan DEV-1)

Thermal manufacturing equipment, including furnaces, dies, presses, and sensing equipment, must perform consistently and reliably when exposed to high temperatures—as high as 4,000°F—for long periods of time. The operating conditions of thermal manufacturing, however, are harsh on materials, and maintaining these environments requires significant amounts of energy. To reduce equipment maintenance and downtime, the thermal manufacturing community must design more robust equipment by implementing materials that react less with product materials and that are more resistant to wear, impact, corrosion, and strain. Additionally, more insulative equipment materials that can help maintain heat more efficiently and uniformly can reduce the energy intensity and emissions of thermal manufacturing processes. To increase the robustness of materials used in thermal manufacturing equipment within the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 5).

D1 Design and test new alloys, coatings, and other materials (e.g., multimaterials or composite nanomaterials) to increase the robustness, lifespan, and inertness of furnace fixtures and refractory components

Figure 5: Cost vs. Impact of Priority Actions D1-D4



For example, integrating advanced materials with lower heat capacities into holding technologies (e.g., ceramic ladles and carbon baskets) can make this equipment more insulative and reduce heat loss during materials transfer. Advanced surface engineering processes (e.g., carbonnealing) that coat inexpensive materials with more expensive ones with desired properties can reduce overall materials cost without sacrificing performance.

D2 Establish framework for improved high-temperature properties determination and materials selection

The ability to predict the long-term performance of materials in the high-temperature environments of thermal manufacturing can help materials scientists to identify and modify materials that are used in thermal manufacturing equipment, reducing materials development time and lowering manufacturing costs.

Identify more environmentally friendly quenching media and quenching filtration systems

Implementing alternative quenching media that are nonpolluting and safe to use (e.g., water and inert-gas quenching media to emulate salt and oil quenching) and developing filtration systems that continuously remove bacteria, fungus, and mold buildup from polymer quenchants can both improve the environmental friendliness of quenching and enhance the quality of quenched materials.

Develop catalysts that enable lower-temperature combustion and help maintain flame stability

Such catalysts can increase heating efficiency, extend equipment life, and reduce nitrogen oxide emissions.

Maximize the Quality of End-Use Products

The quality and reliable performance of end-use products is dependent on the properties of the end-use material and the consistency of thermal processing. To help ensure improved product quality, the thermal manufacturing community must better understand the impact of thermal processing on end-use materials, increase the accuracy and uniformity of these processes, and select materials with the desired functionality and properties for a given application. Additionally, to increase competitiveness of U.S. products, the thermal manufacturing community must identify and select lower-cost, but still high-performing, materials. These improved materials selection capabilities can help offset any issues with materials availability and cost fluctuations. To maximize the quality of end-use products within the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 5).

D3 Improve existing alloys within their broad specifications

Improving or altering existing materials instead of developing entirely new materials can significantly reduce product development time. For example, designing leaner alloy steels, specialized steel grades, and other high-performing alloys (e.g., 5xxx aluminum with strengths comparable to 2xxx and 7xxx aluminum) can reduce materials costs while meeting materials performance requirements. This improvement can be accomplished through better understanding of materials composition and processing effects on properties.

D4 Conduct fundamental studies on phase transformation and communicate results along with existing phase transformation knowledge

Understanding and pinpointing the moment when phase transformation takes place in a material is critical to operate thermal manufacturing processes more efficiently. To aid this understanding and increase process efficiency, the thermal manufacturing community must generate phase diagrams that define optimum phase transformation temperatures and processing times for various materials. In addition, the thermal manufacturing community should assess potential methods for accelerating phase transformations, including adding alloying elements that increase nucleation (e.g., microalloying), increasing vacancy concentrations and dislocations, and superimposing applied energy (e.g., with ultrasonics, laser radiation).

Improve techniques for materials joining

Advanced materials joining, particularly the joining of ceramic and metallic components, is critical to enhancing product functionality and robustness. As one example, the thermal manufacturing community should develop a melt infiltration technique for silicon-based eutectic alloys to join silicon and silicon carbide composite material.

Establish standards for documenting materials specifications

Improved materials standards can help create a common manufacturing language and ensure consistency in product quality.

Engineer paint and coating processes that allow for faster curing at lower temperatures

Lower-temperature paint and coating processes can reduce energy intensity and enable use of materials that are unable to withstand the higher temperatures of thermal manufacturing processes.

Identify a method to control or analyze the introduction of contaminants into feedstocks sourced from recycled materials

Improved control of contaminants (e.g., antimony, phosphorus, sulfur) can increase the use of recycled materials throughout the thermal manufacturing community and enhance the overall quality of end-use materials.

Advance the Ability to Predict Thermal Manufacturing Processes

The increased use of modeling and simulation tools could help companies, particularly small and medium enterprises, to more cost-effectively predict and improve thermal manufacturing processes. These tools reduce trial-and-error approaches to identifying and testing process improvements and can enable faster and more accurate prediction of the long-term properties of thermally manufactured products. The resulting improved understanding of materials properties and performance in response to thermal manufacturing can inform process improvements that increase the quality of the product delivered to the consumer.

Adopting thermal manufacturing modeling and simulation tools can help companies to shorten product development time, reduce thermal processing times, and lower operating temperatures, all of which increase the energy efficiency of thermal manufacturing processes. To achieve these benefits, the thermal manufacturing community must work together to simplify the functionality and enhance the capabilities of thermal manufacturing modeling and simulation tools, ultimately improving their widespread use, usefulness, and reliability.

Increase the Widespread Use and Reliability of Thermal Manufacturing Modeling and Simulation Tools

For modeling and simulation tools to be used more widely throughout the thermal manufacturing community, they need to be more accessible to non-modeling experts. While most small and medium enterprises do not have the resources to employ the help of a modeling expert, these companies could realize the benefits of modeling and simulation tools if these tools were more user friendly and affordable. Modeling and simulation tools must also be validated with actual operating data to ensure the accuracy and reliability of their predictions. To increase the widespread use and reliability of thermal manufacturing modeling and simulation tools within the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 6).

Figure 6: Cost vs. Impact of Priority Actions D5-D8

D5 Simplify existing modeling and simulation software to make it accessible to different level users

The thermal manufacturing community must develop publicly available, user-friendly, off-the-shelf modeling software packages (e.g., with auto-meshing capabilities) for the portions of the workforce without modeling expertise, including process implementers and non-experts in materials science and engineering. Open source building block models and the increased computational efficiency of modeling and simulation software could further increase the accessibility of these tools.

D6 Generate benchmark data and validate models

To generate data, the thermal manufacturing community should conduct round-robin data gathering activities (i.e., seven or more groups obtaining data in parallel using different instrumentation) directed by a standard methodology. This mechanism should be used to collect mechanical, thermal, and metallurgical data (e.g., thermal strains, transformation kinetics, and heat transfer coefficients) as a function of phase, time, temperature, and strain rate; diffusion data for specific alloys; rheological properties data of metals, including plastic deformation characteristics; and temperature-dependent electromagnetic materials properties data; as well as other data that would help aid understanding of the effects of thermal manufacturing on materials properties. Using this verified data, the thermal manufacturing community should then develop an integrated validation and verification plan for selected models.

Advance Tools that Model and Simulate Entire Thermal Manufacturing Processes (Action Plan DEV-2)

For modeling and simulation tools to be most effective, they must account for all of the factors that could impact the properties and performance of an end product. The ability to manipulate all of these factors using modeling and simulation tools could help companies pinpoint opportunities for maximizing process efficiency and could help avoid the sometimes inadvertent costly impacts of manufacturing decisions. To advance tools that model and simulate entire thermal manufacturing processes within the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 6).

D7 Develop models that will predict materials properties and performance in thermal manufacturing operating conditions

The thermal manufacturing community must develop life-cycle analysis models that relate the structural properties of end-use products to thermal manufacturing processes. Such models should include atmosphere-material interactions (e.g., during carburizing or nitriding), standards for determining boundary conditions and in-process thermophysical materials properties, and microstructure materials specifications that the model can generate based on user-entered application-specific performance criteria (e.g., wear, forces, corrosion).

D8 Advance modeling and simulation tools for evaluating the thermal efficiency and energy use of thermal manufacturing processes

Advanced modeling and simulation tools that simulate energy transformation based on first-principle calculations, evaluate thermal efficiency (e.g., using Sankey diagram and infrared imaging to account for flue loss, casing loss, and heat to work), and assess energy use at the point of use could enable more efficient plant process flows and better energy management of thermal manufacturing processes.

Improve temperature uniformity models to optimize equipment design and processing consistency

The thermal manufacturing community can help improve temperature uniformity models by conducting studies on furnace temperature uniformity influenced by shape, load, and volume, and by performing computational fluid dynamics modeling of thermal gradients in furnaces. Temperature uniformity models, coupled with validated, high-fidelity combustion models and burner-furnace geometry codes that include emissivities and multi-flame interactions, could help inform more efficient furnace designs.

Improve Robustness and Accuracy of Process Monitoring and Control

Improved sensing technologies can enable more accurate measurement, monitoring, and control of the high-temperature and corrosive operating environments of thermal manufacturing. The ability to control processes

CASE STUDY

Leveraging Process Data and Modeling for Industrial Heat Treatment Optimization

John Deere

Challenge

Heat treaters face many operating challenges—including the high variability of input materials and difficulty monitoring and controlling process variations—that impact process consistency and product quality. These inconsistencies often lead to costly rework and materials waste. As customers demand more stringent quality specifications, heat treating operations must be able to better monitor and control process parameters to improve the efficiency and cost effectiveness of their operations.

Innovation

Each year, heat treating operations generate significant amounts of data on input materials, process parameters, and product quality. While some of this data is used to audit processes and pinpoint issues with specific product batches, much of this data goes unused. Taking advantage of this available data, researchers at John Deere developed an analytical approach that builds on a typical closed-loop smart manufacturing process (i.e., generate data, analyze, model, apply lessons learned) and couples it with physics-based models that incorporate mass and energy conservation, laws of heat transfer, metallurgical thermodynamics, and chemical reactions and kinetics. The approach's synthesis of big data, data analytics, and data-based modeling can help heat treaters to more effectively optimize processes, ultimately improving process efficiency, increasing productivity, enhancing product quality, and reducing overall operating costs.

Results

John Deere applied its combined process analysis and modeling approach to three specific heat treating operations, helping these operations to make process adjustments that yielded the following results:

- **Industrial batch annealing operation in a secondary cold-rolling mill** — Reduced product rejection and downgrade rates for two major products by 44 percent and 60 percent, respectively, helping the mill to tighten product quality standards and reduce energy consumption.
- **Automated coil batch annealing in an integrated steel plant** — Improved overall productivity of the 1-million ton per year plant by 9 percent and significantly reduced energy costs.
- **Batch carburizing operation at a modern heat treating shop** — Projected a 12.5 percent increase in productivity, improved the methodology for recipe selection, reduced energy consumption, and reduced annual emissions by 90 metric tons.

Reference: Satyam S. Sahay, Goutam Mohapatra, Robert Gaster, and Hema Guthy, "Analytics, Modeling, and Optimization of Industrial Heat Treating Processes," *Advanced Materials & Processes*, March 2014.

with such accuracy is critical to ensure the robustness and repeatability of these processes, which facilitates the consistent quality and reliability of thermally manufactured products. Advanced sensing technologies could even allow the development of smart systems that can detect and diagnose product quality problems or inconsistencies in process conditions in real time and automatically adjust process variables for optimization.

Increased development and implementation of more robust, more accurate, and longer-lasting sensing technologies can improve the thermal efficiency of thermal manufacturing processes and reduce energy intensity and emissions. To achieve these benefits, the thermal manufacturing community must work together to advance the capabilities of sensing technologies for thermal manufacturing and encourage their adoption, ultimately advancing the ability to non-destructively evaluate product quality and improving the monitoring and control of process parameters.

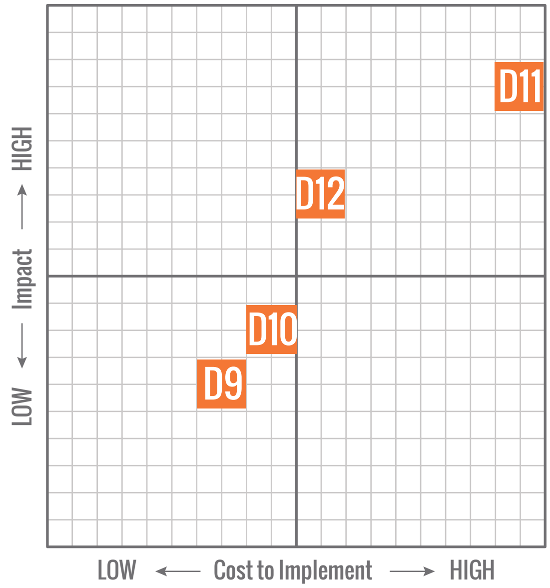
Improve Understanding of Performance Requirements and Development Needs of Thermal Manufacturing Sensors (Action Plan DEV-3)

While numerous sensing technologies currently exist, the thermal manufacturing community has not fully taken advantage of their potential. More effectively leveraging sensor capabilities will first require an assessment of the current capabilities of sensors used both within and outside of the thermal manufacturing community, followed by a gap analysis of needs that existing sensors cannot meet. To improve understanding of performance requirements and development needs of thermal manufacturing sensors within the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 7).

D9 **Identify and categorize currently available sensor technologies**

The thermal manufacturing community must catalog sensors currently used in thermal manufacturing, as well as available sensor technologies used outside of the thermal manufacturing community. They should then characterize thermal manufacturing operating environments and assess the availability of sensors capable of measuring parameters within such environments.

Figure 7: Cost vs. Impact of Priority Actions D9-D12



D10 **Define thermal manufacturing sensor needs and metrics**

The thermal manufacturing community needs cost-effective, robust sensors that remain stable in operating conditions above 2,500°F for years without drifting, or sensors that can be easily and cost-effectively replaced often. To inform the adaptation or development of such sensors, the thermal manufacturing community must first identify the needed performance metrics of sensing technologies, including precision, accuracy, and life (e.g., sensitivity coefficient [Kμ] and specific heat [Cp]). Meeting these needs could potentially require the identification of new sensor materials better suited for the harsh operating environments of thermal manufacturing.

Advance Ability to Non-Destructively Evaluate Product Quality

To evaluate the quality of an end-use product,

CASE STUDY

Combining Magnetic Field and Induction Heating for Innovative Thermal Processing

Eaton Corporation, Ajax-TOCCO Magnethermic Corp., and Oak Ridge National Laboratory

Challenge

Traditional thermal processes used to strengthen materials and improve performance have been developed and refined largely through empirical means. The primary concept is to expose materials to elevated temperatures in a controlled way to achieve desired properties—a process that relies on heat transfer mechanisms and associated kinetics. Reducing process times typically requires higher processing temperatures, which may have negative effects on product quality, energy efficiency, and cost.

Induction heating technology offers the ability to selectively focus and provide a highly controlled thermal profile within a part. This capability allows thermal processors to optimize the heat treating process to achieve maximum strengthening within the metal by enabling subsurface heat generation, an approach not possible through conventional heat treating. Heat distribution throughout the part can be carefully controlled to produce the desired metallurgical results. The ultimate value of induction heating is the ability to customize and optimize thermal processing to increase process efficiency while also improving properties and part performance.

Another technology of industrial relevance is high magnetic field processing (HMFP). A magnetic field alters the phase equilibrium diagram of materials by shifting phase-transition temperatures. Deformation behavior of a material may also be affected by high magnetic fields, a phenomenon known as magnetoplasticity. This mechanism provides potential opportunities to mitigate high- and low-cycle fatigue damage, enable superplastic behavior at ambient temperature, relieve residual stresses, and other novel effects.

Typically, however, induction heating and HMFP have not been considered together in order to obtain synergistic benefits.

Innovation

A new, industrial-scale facility was recently built at Oak Ridge National Laboratory to explore the synergies between induction heating and HMFP. The facility, which includes a HMFP facility with an integrated induction heating and quenching capability in a process termed induction thermal high magnetic field (ITHMF), will allow researchers to understand how this disruptive processing approach can be applied to improve material properties and better optimize thermal processes.

Results

Using coupled induction heat treatment with high magnetic field processing can produce alloys with improved performance while also delivering faster processing times and lower processing energy use. With this technology, lower-cost alloys could be substituted cost effectively for more exotic alloys while microstructure could be tailored for improved magnetic properties, wear resistance, or mechanical performance, as needed.

Results documented by Eaton Corporation and its partners demonstrated a 30 percent improvement in ultimate tensile strength (UTS) over the baseline carburized steels and a 43 percent decrease in retained austenite. The ductility improved by more than 100 percent. In high-strength steel, this novel approach resulted in 7 percent improvement in UTS, 10 percent improvement in yield strength, 90 percent improvement in elongation, and 40 percent improvement in wear, compared to the baseline. Finally, this work demonstrated that the tempering time in a magnetic field of a quenched and hardened steel decreased from two hours to ten minutes with uniform hardness.

References: George Pfaffmann and Aquil Ahmad, "Induction Coupled High Magnetic Field Expands Processing Envelope For Heat Treat Innovations," *Advanced Materials & Processes*, March 2014; Aquil Ahmad, *Prototyping Energy Efficient Thermo-Magnetic & Induction Hardening for Heat Treat & Net Shape Forming Applications*, Final Technical Report DE-FG36-08GO18131, July 2012.

it is critical to assess its mechanical, chemical, and physical properties throughout thermal processing. However, doing so accurately without compromising the product is extremely difficult. The thermal manufacturing community needs the ability to cost-effectively measure internal product temperature, moisture, and surface area and to detect product defects without disrupting the thermal manufacturing process. This ability to monitor product quality in real time can enable quick process modifications that can save significant amounts of time and money. To advance the ability to non-destructively evaluate product quality within the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 7).

D11 Develop sensors capable of identifying when phase transformation takes place in various materials

The thermal manufacturing community must develop non-contact, in situ sensing technologies—potentially using laser ultrasonics or electromagnetic technology—that accurately indicate when phase transformation of various materials (e.g., molten metals, steel, cast metal strips) is sufficiently complete.

Advance sensors that can provide in situ moisture and temperature profiles of products

High-temperature tools that can measure product temperature and moisture in situ are particularly critical for the manufacture of food, paper, and lumber.

Improve surface analysis sensors

Surface analysis sensors could have many applications in thermal manufacturing, including determining when a part's surface is clean enough to be correctly carburized and detecting surface finish and geometry issues that could reduce quenching effectiveness.

Strengthen the ability to measure defects in thermally processed products

The thermal manufacturing community needs a non-destructive method (e.g., ultrasonic inclusion sensors) to detect residual stress and cracks in unfinished products.

Improve Monitoring and Control of Process Parameters

In addition to advancing sensors that can non-destructively evaluate product properties, the thermal manufacturing community needs cost-effective sensors and systems that can reliably and accurately monitor and control thermal manufacturing process conditions. One small change in process temperature, atmospheric composition, or pressure, for example, could render a product unusable. To improve monitoring and control of process parameters within the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 7).

D12 Implement mechanisms that enable more automated process control

Advanced sensing technologies have the potential to increase process automation, which can optimize manufacturing productivity and improve worker safety. Opportunities for increased automation include process controls that better manage energy use and automatically control fuel options in response to energy spikes, fluctuations in electricity costs, and changes in process requirements; and smart sensors that detect and diagnose product quality problems in real time and automatically adjust process variables for optimization. To enable increased integration of process control and automation, however, some end-use industries (e.g., aerospace) must update their standards and specifications to include such systems.

Improve sensors that measure atmospheric constituents

The thermal manufacturing community needs high-temperature sensors that can measure and regulate concentrations of process atmospheric constituents, including carbon, nitrogen, and volatile organic compounds. Additionally, there is a need for a cost-effective and reliable technique for detecting leaks in pipes, valves, and equipment to reduce fugitive emissions (e.g., in petroleum refineries).

Develop sensor arrays that measure and ensure consistency of process temperature and moisture

The thermal manufacturing community must develop cost-effective sensing systems that can determine when one area of process heating equipment is not at temperature relative to surrounding sensors, enabling real-time decision making to increase process productivity.

Innovate Thermal Manufacturing Processes to Increase Efficiency, Versatility, and Sustainability

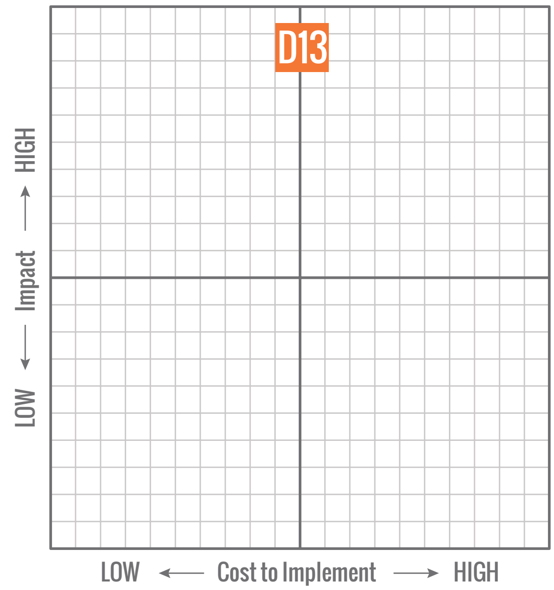
Due to the inherent energy intensiveness of thermal manufacturing, there is a continuous need for more cost-effective, efficient, versatile, and sustainable thermal manufacturing methods. The ability to integrate alternative fuels with increased energy flexibility, advanced combustion methods with better stabilization, and emissions control and waste recovery technologies could significantly reduce the environmental footprint of the whole thermal manufacturing community.

The resulting reductions in energy intensity and emissions could yield significant cost savings and improve profit margins on thermally manufactured products. Reducing the energy intensiveness of thermal processes could also free up the time and money of thermal manufacturing companies, allowing them to pursue other potential process improvements, which is of particular importance to small and medium enterprises with limited resources.

Optimize Thermal Manufacturing Processing Techniques

Hybrid thermal processes, new waste heat recovery options, and other innovative thermal manufacturing processing techniques hold significant promise in the longer term to increase the productivity, decrease the cost, and reduce the energy intensiveness of thermal manufacturing. To innovate thermal manufacturing processes to increase efficiency, versatility, and sustainability within the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 8).

Figure 8: Cost vs. Impact of Priority Action D13



D13 Identify and implement hybrid thermal processes and novel applications for existing thermal manufacturing processes (Action Plan DEV-4)

There are numerous combinations of energy sources (e.g., fossil fuels, electricity) and energy transfer mechanisms (e.g., induction, resistance, gas convection, infrared, ultraviolet, radio frequency, microwave, electron diffraction, plasma) that could be integrated into thermal manufacturing processes. Some of these energy transfer mechanisms are used in existing thermal manufacturing processes but could have novel applications elsewhere in the thermal manufacturing community (e.g., oxygen and natural gas combustion in glass furnaces, infrared and gas convection for powder curing). Other combinations would be new process hybrids, such as the use of indirect heating in calcination or the development of a high-temperature, high-pressure drying process (e.g., impingent jets) that allows for vapor release and an increased rate of heat transfer without damaging food and paper products. Applying existing thermal processes to novel applications

CASE STUDY

Using Infrared to Develop a Hybrid Drying System for Textile Coatings

Advanced Energy Corporation

Challenge

Many woven textile fabrics require a variety of coatings on both the finished side and the back side of the cloth. Typically, the finished-side coating is a type of stain guard and the back-side coating is designed to help the cloth adhere to the substrate (e.g., foam, wood) during final assembly. Due to the moisture content of the coating material, the textile plant in this case study had to run all double-coated cloth through their natural gas convection drying oven two times—once for each coated side. This process is time-consuming and expensive, requiring two overtime shifts on Saturday, extra run time for the drying oven, and double handling of the cloth, which increases the potential for cloth damage.

Innovation

When evaluating possible solutions to reduce the need to run the cloth through the drying oven twice, the plant operators and energy analysts identified the potential to add an infrared (IR) booster oven in-line between the two coating stations. After applying the first coating, the first coated side will pass through the IR booster oven and start drying, kick-starting the drying process before the second coating is applied. By adding an IR booster oven in-line between the two coating applicators, the cloth can be processed in one pass through the drying oven after both coatings are applied. This innovation will cut the coating drying time in half for all the double-coated products, significantly increasing the profit margins on this product.

Results

Adding the IR booster oven to the cloth coating and drying line is estimated to achieve the following results:

1. All weekend overtime shifts will be eliminated, leading to an estimated annual labor savings of $420,000.
2. The run time of the existing drying oven will be reduced by 1,335 hours per year, reducing annual electricity use by about 65,000 kilowatt-hours ($4,000) and natural gas consumption by 6,500 Dekatherms ($43,000).
3. Plant energy intensity in terms of kilowatt-hour per linear yard of cloth will be reduced by 12 percent.

These savings will enable a simple payback for this project, including the IR oven and installation, of just 0.33 years. In addition to these labor and cost savings, the increased process efficiency from the hybrid combination of an electric IR booster oven with a natural gas convection drying oven will help reduce the possibility of cloth damage by eliminating double handling, improve product quality from more consistent drying of the coatings, and increase the plant's capacity for processing coated cloth.

References: Michael L. Stowe, Advanced Energy Corporation of North Carolina, February 2015.

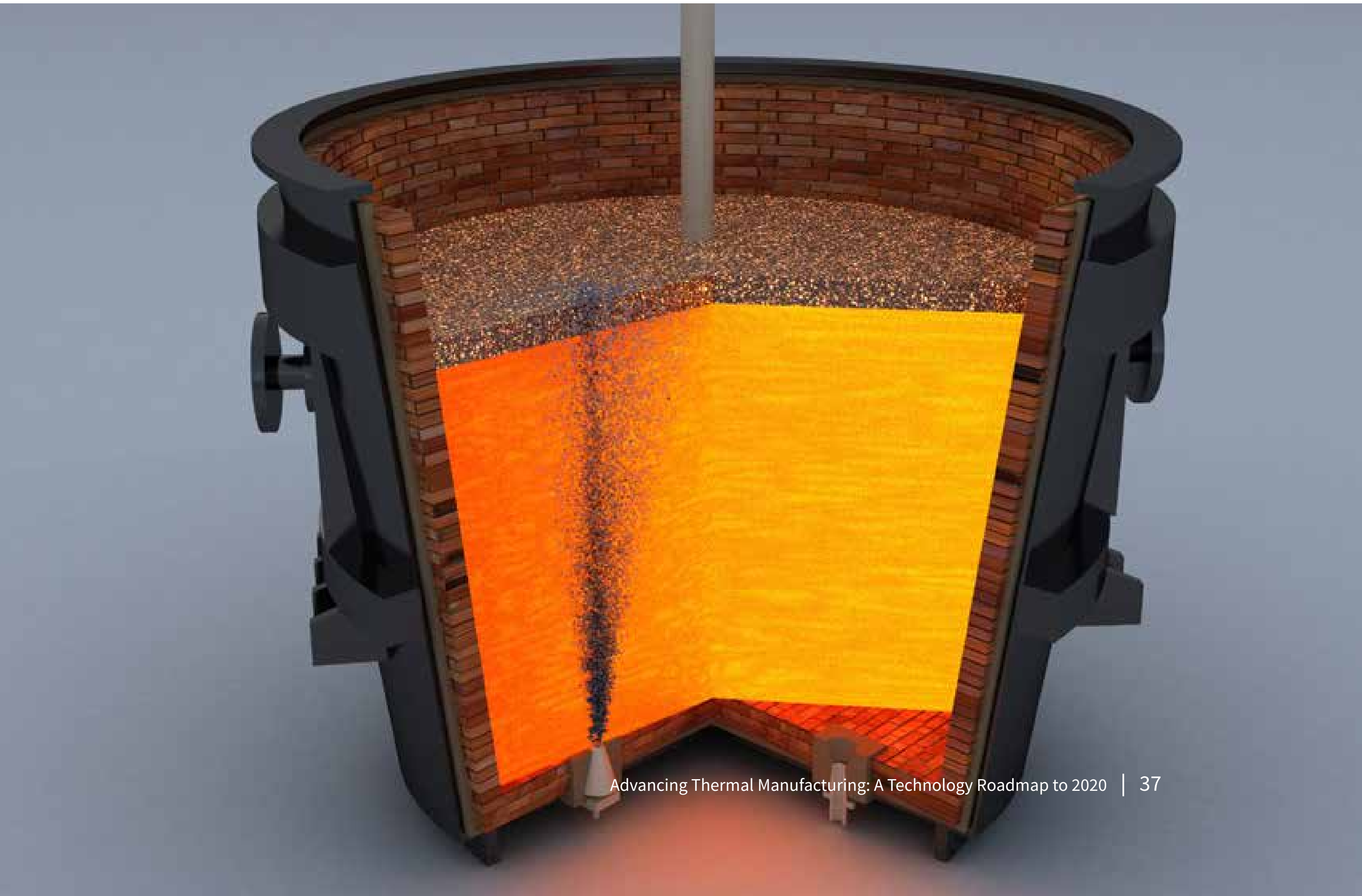
and identifying and implementing new, hybrid processes could help improve thermal efficiency and temperature uniformity, reduce thermal manufacturing processing time, and increase energy efficiency.

Optimize thermal manufacturing equipment and processes to improve waste heat recovery and reduce emissions

There are many potential technologies that the thermal manufacturing community could advance or develop to help recover waste heat and reduce emissions from thermal manufacturing processes. Examples include a thermal energy recuperation technology (e.g., high-temperature cascading heat pump) that removes pollutants (e.g., nitrogen oxide) from waste heat; waste heat boilers that convert heat from the byproducts of production to high-pressure steam for plant use or electricity generation; post-combustion chemical absorption and membrane technologies for controlling emissions, including fine particulates (<10 microns); and even improved seals on furnace doors, valves, and charging ports to reduce emissions.

Explore use of other innovative thermal manufacturing processing techniques

While it will be challenging to develop new processing techniques within the next five years, there are several techniques that could have a significant impact on thermal manufacturing processes. For example, the thermal manufacturing community should investigate the use of additive manufacturing (e.g., powder metallurgy, laser or electron beam), explore a method of direct heating that eliminates scale on metals, and assess the use of high magnetic field processing for developing ultra-lightweight metals with tailored microstructures and properties.



Technology Implementation Pathways

The widespread acceptance of advanced technologies in thermal manufacturing hinges on consistent action across the thermal manufacturing community.

However, many companies—particularly resource-limited small and medium enterprises—hesitate to take on the risk inherent with adopting new technologies. The thermal manufacturing community must collaborate on the technology implementation pathways in Figure 9 to help distribute and reduce this risk and build the business case for adopting advanced technologies.

Figure 9: Overview of Technology Implementation Pathways

Facilitate Cross-Industry Collaboration and Information Sharing	**Foster Stronger Partnerships within the Thermal Manufacturing Community** • Facilitate an intentional connection between universities, laboratories, and industry **(I1)** • Foster collaboration among various engineering disciplines • Promote idea exchange outside of the current thermal manufacturing community **Establish a Comprehensive Thermal Manufacturing Knowledgebase** (Action Plan IMPL-1) • Establish and lead a platform for information sharing across thermal manufacturing industry segments **(I2)** • Define the structure of a thermal manufacturing knowledgebase **(I3)** • Mine and catalog existing materials and technology data to assess data gaps **(I4)** • Develop standard equipment performance metrics and guidelines
Accelerate Deployment of Advanced Technologies	**Strengthen the Business Case for Adopting Advanced Technologies** • Develop case studies for new technology applications for each manufacturing segment or process **(I5)** • Create financial analysis tools to show the cost-benefits of new technology **(I6)** **Demonstrate the Benefits of Advanced Technologies and Processes** • Establish a thermal manufacturing demonstration facilities network **(I7)** (Action Plan IMPL-2) • Launch a low-cost equipment lease program • Organize small supplier problem solving events **Incentivize and Recognize Early Adopters** • Offer incentives to first adopters of new technologies **(I8)** • Develop a mechanism to encourage non-risk-averse companies to implement emerging technologies **(I9)** • Incentivize adoption of energy-efficient thermal manufacturing technologies
Build a Robust and Knowledgeable Thermal Manufacturing Workforce	**Launch a Thermal Manufacturing Workforce Training Program** (Action Plan IMPL-3) • Categorize existing workforce training initiatives and capabilities **(I10)** • Develop and distribute new training materials on existing and emerging technologies **(I11)** • Formalize a mechanism for transferring legacy knowledge to the younger workforce **(I12)** • Establish a certification program for thermal manufacturing workers **Attract the Future Thermal Manufacturing Workforce** • Attract K-12 students to fields related to thermal manufacturing **(I13)** • Establish STEM education programs at universities and community colleges **(I14)** • Support college internships that focus on gathering and validating data from shop floor operations • Promote a public campaign (e.g., via television or public figures) to attract students to engineering

Facilitate Cross-Industry Collaboration and Information Sharing

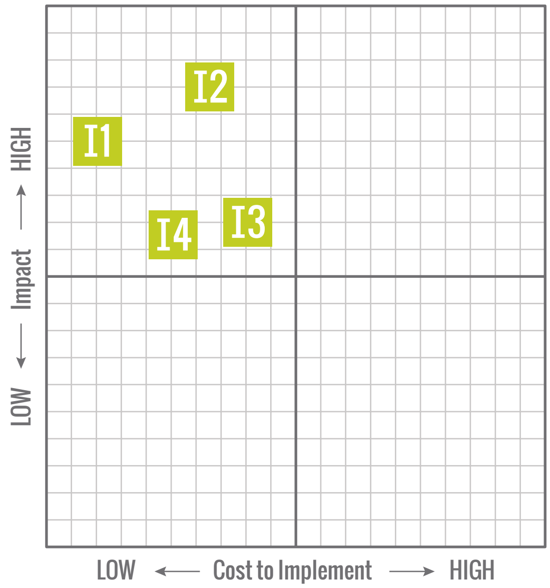
Increased collaboration and information sharing across the thermal manufacturing community is essential to reach the critical mass needed to address the common technical barriers, workforce development needs, and operational constraints that crosscut all thermal manufacturing industry segments.

Improved collaboration throughout the thermal manufacturing community will help build stronger partnerships across companies, disciplines, and industry segments that can help to more efficiently and effectively address the current barriers to thermal manufacturing. These partnerships can also facilitate the increased sharing and distribution of non-proprietary information to build a knowledgebase that will help educate the workforce and support the business case for implementing advanced technologies. To achieve these benefits, the thermal manufacturing community must foster stronger partnerships within the community and establish a comprehensive thermal manufacturing knowledgebase.

Foster Stronger Partnerships within the Thermal Manufacturing Community

Developing a structured framework for collaboration across companies, disciplines, and industry segments will reduce instances of unproductive duplication of efforts, ensure that the research and development community develops and improves the technologies that industry needs most, and better leverage technologies and knowledge throughout the thermal manufacturing community. To foster stronger partnerships within the thermal manufacturing community in the next five years, the community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 10).

Figure 10: Cost vs. Impact of Priority Actions I1-I4



I1 Facilitate an intentional connection between universities, laboratories, and industry

This intentional connection will help universities and laboratories better assess and address industry needs, maximizing the value of the resulting research and development throughout thermal manufacturing industry segments. One way to facilitate this connection

would be to develop a program through which PhD students work on the shop floor of thermal manufacturing plants to increase the practicality of their research.

Foster collaboration among various engineering disciplines

Many of the technical challenges currently limiting thermal manufacturing are interdisciplinary in nature, necessitating collaboration across engineering disciplines (e.g., metallurgical, chemical, mechanical, electrical, combustion, computer programming).

Promote idea exchange outside of the current thermal manufacturing community

Though collaboration across thermal manufacturing industry segments is most critical, the community could benefit from collaboration outside of the thermal manufacturing community to identify technologies for potential adaptation.

Establish a Comprehensive Thermal Manufacturing Knowledgebase (Action Plan IMPL-1)

To learn about new and existing thermal manufacturing equipment, technologies, and materials, the workforce requires access to reliable and comprehensive information. The thermal manufacturing community must catalog and build on information that is currently dispersed throughout the community to develop a centralized thermal manufacturing knowledgebase. This comprehensive knowledgebase, which must be easy to navigate and affordable for small and medium enterprises, would facilitate knowledge transfer from one thermal manufacturing industry segment to another, ultimately helping to optimize efficiency and productivity across the thermal manufacturing value chain. To establish a comprehensive thermal manufacturing knowledgebase within the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 10).

I2 Establish and lead a platform for information sharing across thermal manufacturing industry segments

To help facilitate information sharing, the thermal manufacturing community should provide forums through which thermal manufacturing industry segments can exchange knowledge (e.g., through short technology presentations), foster an open-source philosophy that encourages collaborative technology development, and gather experts from across these segments to define crosscutting technology development needs that will support the in-house goals of multiple companies.

I3 Define the structure of a thermal manufacturing knowledgebase

This mechanism could consist of centralized, stand-alone databases or a linkage of existing resources. As part of this activity, the thermal manufacturing community should also develop a tool to capture results, both positive and negative, of ongoing technology research and development efforts.

I4 Mine and catalog existing materials and technology data to assess data gaps

A better understanding of currently available thermal manufacturing materials and technology data can help the thermal manufacturing community to assess data gaps and determine a path forward for generating and validating this needed data.

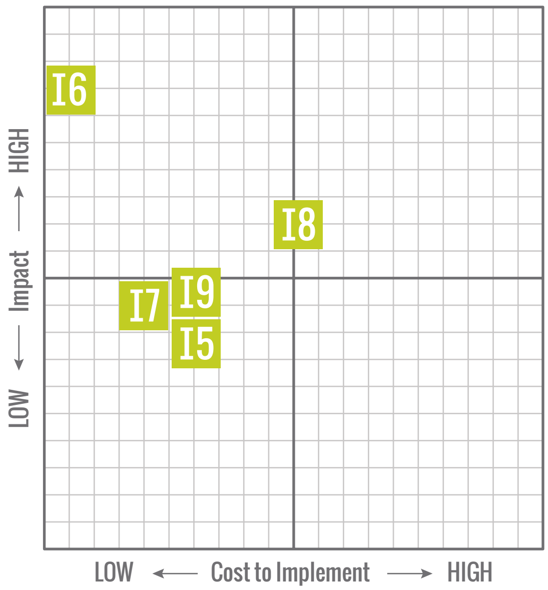
Develop standard equipment performance metrics and guidelines

The thermal manufacturing community must also work to establish best practices for operating thermal manufacturing equipment, which could increase the efficiency and productivity of thermal manufacturing processes.

Accelerate Deployment of Advanced Technologies

The benefits of adopting advanced thermal manufacturing technologies must be

Figure 11: Cost vs. Impact of Priority Actions I5-I9



recognizable, significant, and relatively easy to achieve in the short term. To make these benefits more obvious, the thermal manufacturing community must clearly present the advantages in terms of cost, productivity, and efficiency. Success stories from companies that have implemented these technologies and demonstrations that allow companies, particularly small and medium enterprises, to experience technology benefits firsthand can help convince companies throughout the thermal manufacturing community to adopt advanced technologies. To accelerate the deployment of advanced technologies, the thermal manufacturing community must strengthen technology business cases, demonstrate the benefits of advanced technologies, and incentivize and recognize early adopters.

Strengthen the Business Case for Adopting Advanced Technologies

Companies need to be able to justify investments in the equipment, software, and staff training necessary to implement advanced materials and technologies. To address this need, the thermal manufacturing community should develop clearly articulated and compelling case studies based on testimonials from companies that have adopted advanced technologies and real-world quantitative operating data. These case studies can help mitigate the risks of implementing new technologies—particularly for small and medium enterprises with limited resources—and continue to expand the valuable data available through the thermal manufacturing knowledgebase. To strengthen the business case for adopting advanced technologies within the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 11).

I5 Develop case studies for new technology applications for each manufacturing segment or process

For each business segment, the thermal manufacturing community should appoint an expert in charge of leading an effort to build clearly articulated and compelling business cases—including information about enhanced performance, reduced cost, and improved sustainability—of thermal manufacturing technologies and processes.

I6 Create financial analysis tools to show the cost-benefits of new technology

The information included in the thermal manufacturing knowledgebase would be even more valuable to companies, particularly small and medium enterprises, if they could calculate the cost-benefits of adopting advanced technologies in their particular application.

Demonstrate the Benefits of Advanced Technologies and Processes

One of the most effective ways to encourage companies to adopt new technologies is to provide them with platforms for viewing and interfacing with the technologies while in actual operation. Such demonstrations could take many forms, including physical demonstration sites, virtual facilities, or mobile demonstration exhibits. Regardless of the format, demonstrations are critical to convince companies that advanced technologies are right for their operation. To demonstrate the benefits of advanced technologies and processes within the next five years, the thermal manufacturing

CASE STUDY

Controlling Gear Distortion From Heat Treating Using ICME
Ford Motor Company

Challenge

Most gears used in industrial applications are carburized and quenched to meet requirements for surface and core hardness and overall fatigue strength. Increasing demand for lightweight vehicles with improved fuel efficiency has driven automakers to reduce the weight of transmission components, including gears. Thin transmission gears with tight dimensional tolerance requirements are more sensitive to distortion due to temperature non-uniformity during manufacture. Parts that do not meet these tighter quality specifications may require corrective measures like grinding, significantly increasing costs. Prediction of heat transfer during phase transformation has become increasingly important as gear manufacturers seek to optimize the quenching process while minimizing distortion.

Innovation

Using an advanced thermal process—low-pressure vacuum carburizing (LPC) combined with high-pressure gas quenching (HPGQ)—gear producers can better control the distortion of the final heat-treated product. Researchers and engineers at Ford Motor Company created a toolset, ICME-GearHT, to determine the optimal parameters for this process to deliver improved efficiency and effectiveness.

ICME-GearHT is a suite of software packages, including computational fluid dynamics (CFD), finite element analysis (FEA), and microstructure modeling, integrated to deliver a time-efficient, cost-effective way to optimize processing parameters. The ICME-GearHT model captures the key process variations in high-pressure gas quenching and is used to investigate and validate a new gas quenching process, thereby accelerating new process development and improved transmission gears. During this effort, Ford not only created the computational toolset but also validated the model experimentally, thereby increasing confidence in its predictions.

Results

Ford applied the ICME-GearHT model to two specific applications:

1. **Predicting the benefits of using carbon fiber composite (CFC) furnace fixtures rather than traditional alloy fixtures in the furnace** — Engineers expected that CFC fixtures could significantly improve temperature uniformity within the load and within individual gears, compared to a steel basket. Using the model, Ford predicted an improvement of 20 to 25 percent in temperature uniformity when using CFC fixtures.
2. **Evaluating a new cooling fan design** — Model results showed that a new cooling fan and stator design, coupled with velocity filtering, improves temperature uniformity by more than 20 percent.

Through this effort, Ford demonstrated the value of an advanced manufacturing technology—computational modeling—in quickly and accurately assessing the potential impact of process enhancements in thermal manufacturing.

Reference: Junsheng Wang, Xuming Su, Mei Li, Ronald Lucas, and William Dowling, "ICME Tools Can Help Control Gear Distortion from Heat Treating," *Advanced Materials & Processes*, September 2013.

community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 11).

I7 Establish a thermal manufacturing demonstration facilities network (Action Plan IMPL-2)

The thermal manufacturing community must identify an existing facility that can be used to demonstrate new thermal manufacturing technologies and processes. Additionally, setting up demonstration facilities on wheels or sponsoring equipment road shows could help make demonstrations more accessible to small and medium enterprises by eliminating or reducing travel expenses. A virtual demonstration facility could also be developed to link together and provide access to several sites.

Launch a low-cost equipment lease program

Providing a test bed service platform that allows companies to pay a fee to test technologies in real-world operating conditions could help companies to better experience technology benefits while also increasing the budget available for future thermal manufacturing research and development efforts.

Organize small supplier problem solving events

Sponsoring events that pair smaller companies with universities or other research entities could help address the challenges these smaller companies face in their operations.

Incentivize and Recognize Early Adopters

By nature, some companies are less risk averse and potentially more willing to implement new technologies. To further encourage these companies to adopt emerging technologies, the thermal manufacturing community should provide these companies with financial incentives and awards that recognize them as forward-thinking leaders in the community. Lessons learned from these early adopters are critical to further optimize new technologies, develop best practices for their operation, and ready technologies for widespread deployment throughout the thermal manufacturing community. To incentivize and recognize early adopters within the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 11).

I8 Offer incentives to first adopters of new technologies

Financial incentives can help reduce the financial risk associated with technologies that have not yet been widely commercialized. It will also be important to define the period of exclusivity to incentivize first adopters and developers prior to open source availability.

I9 Develop a mechanism to encourage non-risk-averse companies to implement emerging technologies

The thermal manufacturing community must establish a mechanism to share the risk and reward of adopting new technologies and processes, and should encourage trade associations to identify member companies that can spearhead technology adoption.

Incentivize adoption of energy-efficient thermal manufacturing technologies

The thermal manufacturing community could save significant amounts of energy and money by implementing more energy-efficient technologies and processes. The community could push to incentivize adopters of these more energy-efficient technologies in many ways, including through electric utility subsidies, a competition based on a best practice scoring matrix, a J.D. Power's award for innovative process heating, and a TMI ATC Energy Star award.

Build a Robust and Knowledgeable Thermal Manufacturing Workforce

To realize the value of a comprehensive thermal manufacturing knowledgebase, the workforce must be able to navigate, understand, and apply this materials and process information to their operations. A common platform for workforce training across the thermal manufacturing community can help arm

CASE STUDY

Implementing Advanced Sensor Technologies to Reduce Energy Use in Foundry Operations

Sensor Synergy and Cornell University

Challenge

Process implementers at foundries must provide their diverse sets of equipment with enough power to meet overall facility production requirements. However, many of these facilities lack the tools to determine the exact power input needed to meet this capacity, often resulting in excess energy consumption. Improving the energy efficiency of these operations requires sophisticated and customized approaches that focus on implementing advanced technologies as well as improving operating practices. To help process implementers more easily identify energy savings opportunities, advanced sensing systems must be able to correlate data from disparate sensors that measure different process parameters—including melt temperature, melt weight, and gas and electricity consumption—in a time synchronous manner. Additionally, for these systems to demonstrate the return on investment necessary to encourage companies to integrate them, they must be affordable and easy to use.

Innovation

Researchers at Sensor Synergy and Cornell University designed an advanced sensing system that provides real-time measurements to help pinpoint opportunities for improving energy efficiency in foundry operations. The team used a wide range of commercial off-the-shelf sensors and Ethernet-based networks to develop smart interface measurement systems capable of collecting data from eight diverse sensors at 2-second intervals. The system correlates power consumption data from transformers and voltage probes with data from sensors that measure other foundry process parameters, including pressure, flow, vibration, temperature, and humidity. A computer-based dashboard synthesizes the data in real time from each physical sensor and analyzes this data to help process implementers gain a better understanding of the whole processing system.

Results

When working with process implementers across several sectors, the Sensor Synergy and Cornell University researchers discovered that 80 to 90 percent of process implementers consume more electricity than necessary to meet their production requirements. Smart sensing systems that generate easily understood data about energy use and other process parameters in real time could help process implementers to determine the exact electricity input needed to meet their true process requirements. The researchers determined that the use of their advanced sensing system could help identify inexpensive process improvements with the potential to reduce total annual energy costs of a given operation by 10 to 40 percent.

Reference: J.J. Wiczer and M.B. Wiczer, "Improving Foundry Energy Efficiency through Analysis of Multi-Dimensional Process and Machine Measurements," Paper 13-1597, *AFS Transactions 2013* (Illinois: American Foundry Society, 2013).

the workforce with the expertise and skills necessary to efficiently implement and properly operate advanced technologies. Additionally, efforts to continuously attract new talent to the thermal manufacturing workforce can help ensure sustained industry advancements. To achieve these benefits, the thermal manufacturing community must train the existing workforce and conduct outreach that will attract the future workforce.

Launch a Thermal Manufacturing Workforce Training Program (Action Plan IMPL-3)

A consistent platform for workforce education could help provide workers with the required fundamental and mechanistic understanding of existing and forthcoming materials, equipment, and processes. To establish this education platform, the thermal manufacturing community must collect and catalog existing training materials, identify training gaps, and develop new training materials to address these gaps. Adopting a variety of effective workforce training delivery methods (e.g., manuals, videos, and webinars) would maximize reach throughout the community and ultimately encourage more widespread optimization and adoption of advanced technologies. To launch a thermal manufacturing workforce training program within the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 12).

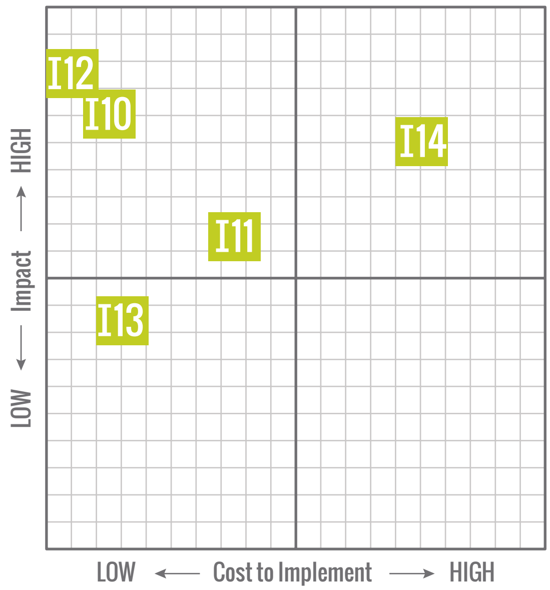
I10 Categorize existing workforce training initiatives and capabilities

Identifying additional workforce training needs will require gathering and organizing all existing thermal manufacturing training materials, evaluating these materials to assess content gaps for multiple workforce audiences (e.g., shop floor workers, engineers, managers), and proposing a pathway for addressing these gaps.

I11 Develop and distribute new training materials on existing and emerging technologies

Trade associations and professional societies within the thermal manufacturing community can help develop new training materials

Figure 12: Cost vs. Impact of Priority Actions I10-I14



(e.g., videos and web-based seminars) that provide basic information, including energy use, efficiency, heat transfer, and atmosphere control, about thermal manufacturing technologies and processes. Additionally, these associations can hold topical symposia at appropriate trade/technical conferences, encourage companies to add training to Employee Performance Measures, and expand regional training opportunities.

I12 Formalize a mechanism for transferring legacy knowledge to the younger workforce

With a large portion of the thermal manufacturing workforce nearing retirement, the thermal manufacturing community must formalize a mechanism for transferring knowledge from senior members of the workforce to the younger workforce, who can continue to build on this knowledge in future years.

Establish a certification program for thermal manufacturing workers

Identifying and evaluating potential training certification programs will help increase recognition and support of thermal manufacturing workforce training.

Attract the Future Thermal Manufacturing Workforce

With a large portion of the thermal manufacturing workforce nearing retirement, the thermal manufacturing community must act now to attract new people and ideas to the workforce of tomorrow. The community must partner with K-12 and undergraduate programs to engage students through science, technology, engineering, and mathematics (STEM) education programs; technology demonstrations; and internships. This targeted outreach to educational institutions, along with a more widespread public outreach effort to promote thermal manufacturing, will help motivate students to study disciplines and pursue careers related to thermal manufacturing. To attract the future workforce over the next five years, the thermal manufacturing community must collaborate on the following critical actions (priority actions are numbered and graphed in Figure 12).

I13 Attract K-12 students to fields related to thermal manufacturing

Mechanisms for attracting K-12 students to fields related to thermal manufacturing include developing virtual training modules about thermal manufacturing, establishing scholarships in thermal manufacturing-related fields, increasing the prevalence of materials camps, and expanding existing materials camps to include and emphasize thermal manufacturing.

I14 Establish STEM education programs at universities and community colleges

The thermal manufacturing community must develop educational initiatives and materials (e.g., internet-based short courses and materials simulation courses) at the college level that promote exciting, compelling, and sophisticated materials and thermal manufacturing processes, including a focus on the role of additive manufacturing in thermal manufacturing.

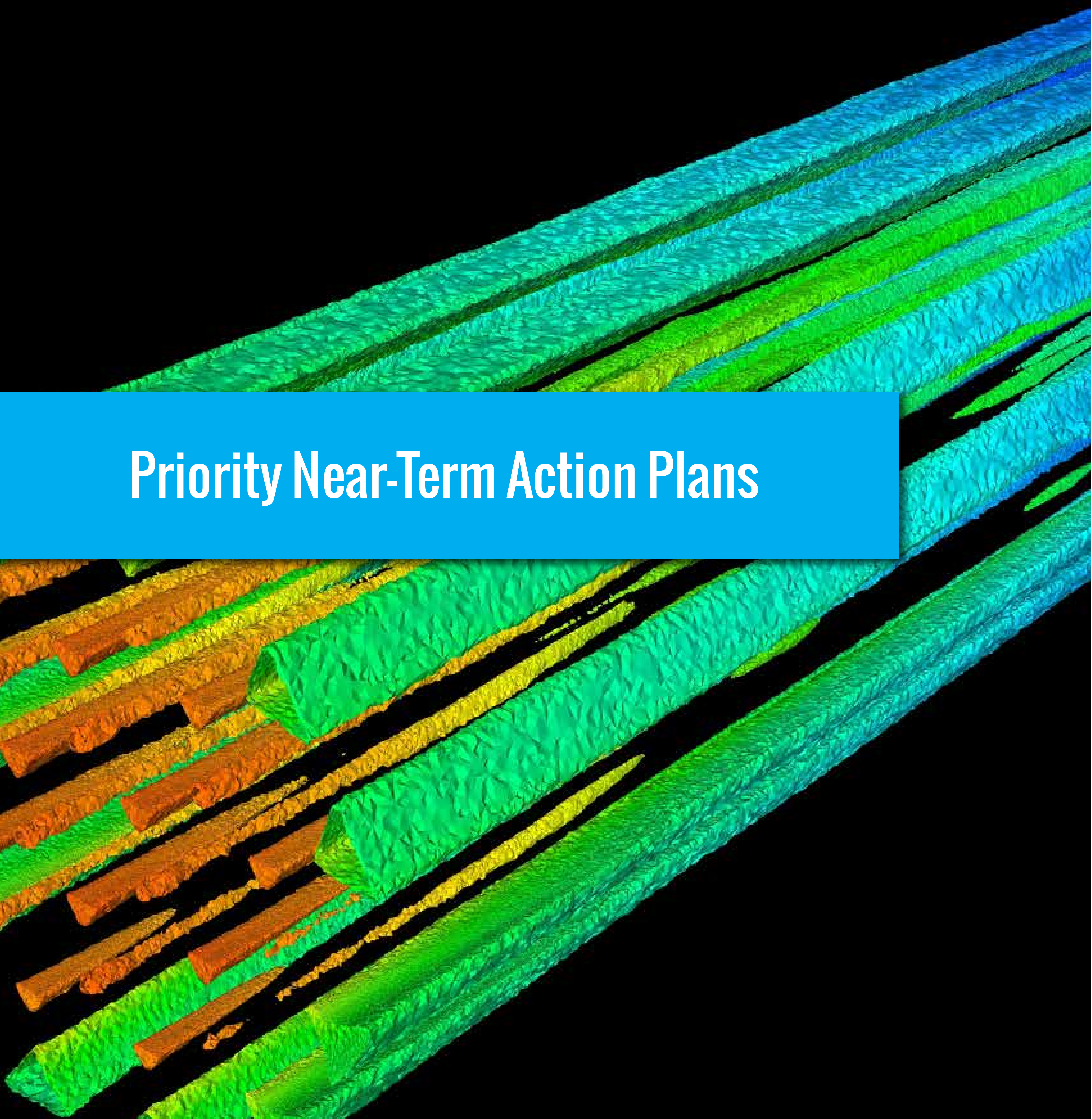
Support college internships that focus on gathering and validating data from shop floor operations

To help attract a younger workforce to thermal manufacturing, the community should promote industry-student mentorship programs.

Promote a public campaign (e.g., via television or public figures) to attract students to engineering

In addition to promoting thermal manufacturing through education, a more general public outreach campaign should aim to transform the public perception of thermal manufacturing, rebranding the field as a highly technical and critical aspect of U.S. manufacturing, especially among parents who have an important role in guiding their children into their future professions.

Priority Near-Term Action Plans



The thermal manufacturing community must begin to address the critical actions in this roadmap immediately to realize the full potential of a collaborative and more globally competitive U.S. thermal manufacturing sector.

Each detailed action plan within this section is directed at achieving an overarching goal that can accelerate the development or implementation of advanced manufacturing technologies throughout the thermal manufacturing community. These areas for action do not intend to capture all of the high-priority critical actions outlined in the roadmap. The thermal manufacturing community can launch these action plans in the near term, using the outlined sequences of tasks, project timelines, and roles and responsibilities of key thermal manufacturing community stakeholder groups as guidelines to execute the plans. Additional information about how this coordinated effort will progress in the near term is included in a later section of this roadmap titled “The Path Ahead.”

The following four Technology Development Action Plans in this section focus on the development of key technologies that can improve the efficiency and productivity of thermal manufacturing:

- Increase the robustness of materials used in thermal manufacturing equipment
- Advance tools that model and simulate entire thermal manufacturing processes
- Improve understanding of performance requirements and development needs of thermal manufacturing sensors
- Identify and implement hybrid thermal processes and novel applications for existing thermal manufacturing processes

The following three Technology Implementation Action Plans in this section aim to provide the resources necessary to encourage the workforce, particularly small and medium enterprises, to adopt these advanced technologies in their operations:

- Establish a comprehensive thermal manufacturing knowledgebase
- Establish a thermal manufacturing demonstration facilities network
- Launch a thermal manufacturing workforce training program

Collaboration on these priority action plans will help the thermal manufacturing community to make significant and immediate progress toward improving thermal manufacturing productivity and global competitiveness, increasing economic growth and employment, reducing energy intensity and emissions, and enhancing product quality and value.

DEV-1 Increase the robustness of materials used in thermal manufacturing equipment

Key Tasks

- Collect available materials data (e.g., on creep, thermal fatigue, and environmental effects) relevant to thermal processing applications
- Identify existing data and develop and implement a test plan for filling these gaps, including the use of accelerated test protocols
- Develop a platform for organizing and sharing available materials properties data
- Adapt and implement materials selection software that will allow companies to indicate needed materials performance characteristics and obtain options for existing materials that meet the performance requirements
- Identify needs for advanced materials in thermal manufacturing process applications and adapt or develop materials to meet these needs
- Demonstrate improved materials in select company operations throughout the thermal manufacturing community

Project Timeline

YEAR 1: Gather data and develop the platform for sharing it, including materials selection software

YEAR 2: Identify gaps in data and collect additional needed data

YEAR 4: Adapt and develop improved materials for use in thermal manufacturing applications

Targeted Outcomes

- Longer-life materials for use in furnace fixtures and other thermal manufacturing equipment
- Framework for new materials development that can be used by materials development companies

Roles & Responsibilities

TMI ATC

- Develop and house materials properties database
- Lead identification of gaps in existing materials data
- Analyze and deploy materials selection software to companies
- Coordinate adaptation and development of improved materials

Equipment and Technology Suppliers

- Contribute experience about needed materials performance requirements
- Provide demonstration sites for improved materials testing

Process Implementers

- Identify materials performance characteristics needed for thermal manufacturing processes
- Provide demonstration sites for improved materials testing

Research and Supporting Orgs.

- Provide data on current and emerging materials for thermal processing applications
- Provide materials selection software
- Adapt or develop improved materials

DEV-2 Advance tools that model and simulate entire thermal manufacturing processes

Key Tasks

- Create a catalog of current thermal manufacturing process modeling capabilities and tools
- Assess available benchmark data for use in thermal process models
- Identify critical needs for enhanced modeling use
- Initiate projects to address targeted areas of highest priority, such as melting and annealing
- Generate needed data for modeling
- Adapt modeling codes for use in key thermal processing areas
- Demonstrate modeling capabilities in select test sites and processes to validate utility and develop case studies
- Make software tools and data available to the thermal manufacturing community

Project Timeline

YEAR 1: Assess current state of the art in process modeling

YEAR 2: Identify targeted thermal manufacturing applications and initiate projects

YEAR 3: Identify demonstration sites and initiate demonstrations

YEAR 4: Complete and document demonstrations

Targeted Outcomes

- Cost reduction through quality improvement
- Cycle time reduction and productivity enhancements
- Broader application of modeling in the thermal manufacturing community

Roles & Responsibilities

TMI ATC

- Catalog existing modeling capabilities and benchmark data
- Develop the critical needs assessment for modeling
- Coordinate efforts to develop data and adapt models
- Identify demonstration test sites and facilitate demonstrations
- Document outputs and disseminate to the community

Equipment and Technology Suppliers

- Provide inputs on critical needs for modeling development
- Provide access to equipment for data generation
- Provide test sites for model demonstrations

Process Implementers

- Provide inputs on critical needs for modeling development
- Provide access to equipment for data generation
- Provide test sites for model demonstrations

Research and Supporting Orgs.

- Provide inputs on existing modeling and data as well as critical needs for modeling development
- Adapt modeling tools
- Participate in demonstration projects at user sites
- Support documentation and dissemination of outputs

DEV-3 Improve understanding of performance requirements and development needs of thermal manufacturing sensors

Key Tasks

- Conduct survey to identify and categorize sensors currently used in thermal manufacturing based on the process conditions they are designed to measure, including temperature, pressure, gas flow, eddy current, and gas composition
- Conduct survey outside of the thermal manufacturing community to identify additional sensors or novel methods for measuring characteristics of thermal manufacturing processes
- Identify other needed input, in-process, and output parameters that cannot currently be measured by any of the existing sensors identified through the surveys
- Identify development needs to integrate and implement these sensors and other novel measurement methods into thermal manufacturing applications
- Develop, adapt, and implement sensors in thermal manufacturing applications to address the identified needs
- Validate new or modified sensor performance at laboratory scale
- Conduct sensor trials at select companies throughout the thermal manufacturing community
- Analyze feedback from sensor measurements to adjust processing parameters using process controls

Project Timeline

YEAR 1: Conduct surveys to identify and catalog sensors used both in and outside of the thermal manufacturing industry

YEAR 2: Select sensors for further evaluation

YEAR 3-5: Develop and adapt the most promising sensors for thermal manufacturing

Targeted Outcomes

- Better understanding of thermal manufacturing processes from data obtained from sensors
- Increased development and implementation of sensors to improve process control
- Reduced processing time and temperature, which ultimately reduces overall manufacturing cost
- Increased process efficiency and productivity and improved product quality
- Improved prediction (i.e., health monitoring) of equipment failures

Roles & Responsibilities

TMI ATC

- Conduct surveys of sensor capabilities and needs
- Coordinate sensor adaptation and development work
- Facilitate demonstration of sensor technologies at companies or other sites

Equipment and Technology Suppliers

- Assist in determining advanced sensor and system integration needs
- Conduct trials and provide feedback on performance

Process Implementers

- Assist in determining advanced sensor needs
- Conduct trials and provide feedback on performance

Research and Supporting Orgs.

- Develop and tailor sensors to specific thermal manufacturing process measurement needs
- Brainstorm new ideas for sensor adaptation, modification, and development
- Validate sensors at laboratory scale

DEV-4 Identify and implement hybrid thermal processes and novel applications for existing thermal manufacturing processes

Key Tasks

- Compile an inventory of cutting edge thermal manufacturing processes
- Engage process implementers and trade associations across the thermal manufacturing community to identify novel applications for these existing processes
- Suggest new hybrid thermal processes, including combinations of energy sources (e.g., fossil fuels, electricity) and energy transfer mechanisms (e.g., induction, resistance, gas convection, infrared, ultraviolet, radio frequency, microwave, electron diffraction)
- Conduct energy and financial analyses of alternate thermal processes to prioritize opportunities
- Adapt or develop the prioritized novel thermal manufacturing processes
- Implement the solutions at select companies throughout the thermal manufacturing community to assess their performance in real-world operations
- Report the results of implementation, develop case studies of success stories, and deploy solutions more widely across the thermal manufacturing community

Project Timeline

YEAR 1: Complete the inventory of cutting edge thermal manufacturing processes

YEAR 2: Identify new hybrid processes and conduct energy and financial analyses

YEAR 3: Adapt or develop high-priority, high-impact solutions

YEAR 4: Implement solutions in select companies

YEAR 5: Report results to facilitate wider implementation

Targeted Outcomes

- Improved performance, efficiency, competitiveness, productivity, and cost savings (e.g., cost of energy per pound, per ton, per linear yard)
- Increased access to novel thermal processing solutions that have been tested
- New equipment production and sales

Roles & Responsibilities

TMI ATC

- Develop the inventory of thermal processes
- Conduct energy and financial analyses
- Coordinate the adaptation and development of novel thermal processes
- Facilitate the demonstration of prioritized novel thermal processes
- Coordinate the evaluation of the test results and compilation into case studies

Equipment and Technology Suppliers

- Provide information about current novel thermal manufacturing equipment
- Provide input to the needs and opportunities for adaptation and development of novel processes
- Conduct applied research

Process Implementers

- Provide information about current novel thermal manufacturing processes
- Provide input to the needs and opportunities for adaptation and development of novel processes
- Conduct applied research
- Test and implement process solutions

Research and Supporting Orgs.

- Provide input on current state of the art of thermal processes
- Assist with energy and financial analyses
- Identify hybrid and novel process technology alternatives
- Conduct applied research
- Assist in analyzing test results

IMPL-1 Establish a comprehensive thermal manufacturing knowledgebase

Key Tasks

- Establish knowledgebase structure
- Populate knowledgebase with existing information about thermal manufacturing processes, technologies, and equipment
- Curate thermal manufacturing knowledgebase
  - -Add new information as it becomes available
  - -Regularly assess age and accuracy of knowledgebase content to ensure that content remains current
- Create products and services (e.g., a thermal manufacturing help desk or thermal manufacturing textbook) to facilitate use of the knowledgebase

Project Timeline

YEAR 1: Design the components, parameters, and the hierarchy of relationships within the knowledgebase structure

YEAR 2: Incorporate the first iteration of information into the knowledgebase

YEAR 3: Create a second-generation knowledgebase based on the experience with the first iteration

YEAR 3: Create and deploy tools to facilitate knowledgebase use

Targeted Outcomes

- Ability for industry, especially small and medium enterprises, to improve their operations, including reduced operating costs, improved productivity, and enhanced product quality, based on access to information about the latest thermal manufacturing technologies
- Reduced rediscovery and redevelopment of existing technologies and products
- Enhanced knowledge transfer to future workforce

Roles & Responsibilities

TMI ATC

- Design and maintain the knowledgebase
- Coordinate acquisition of knowledge from the thermal manufacturing community
- Provide products and services to facilitate use of the knowledgebase

Equipment and Technology Suppliers

- Provide information about thermal manufacturing equipment and the most modern applications for which this equipment is used
- Provide information, including cost data, to help develop business case studies

Process Implementers

- Provide process information for integration into the thermal manufacturing knowledgebase
- Provide information, including cost data, to help develop business case studies

Research and Supporting Orgs.

- Provide technology information for integration into the knowledgebase
- Provide supporting expertise (to TMI ATC) to facilitate use of the knowledgebase

IMPL-2 Establish a thermal manufacturing demonstration facilities network

Key Tasks

- Catalog existing facilities, both physical and virtual, that could potentially be used to demonstrate thermal manufacturing technologies and processes
- Coordinate with community partners to expand the list of prospective thermal manufacturing demonstration facilities
- Establish a thermal manufacturing demonstration facilities network—either a single facility at a national laboratory or multiple facilities in different locations—that covers the broad demonstration needs of thermal manufacturing industry segments and increases facility accessibility and testing convenience for companies throughout the thermal manufacturing community, particularly small and medium enterprises
  - -Identify needs for augmenting existing facilities capabilities for demonstration
  - -Establish legal and business agreements for demonstration facilities
- Develop technology transfer mechanisms to share demonstration outcomes with the broader thermal manufacturing community

Project Timeline

YEAR 1: Create catalog of existing facilities for thermal process demonstration

YEAR 2: Formalize and establish virtual network of thermal manufacturing demonstration facilities with full instrumentation and open source information exchange

YEAR 3: Carry out demonstration projects

YEAR 4: Communicate outcomes to thermal manufacturing community

Targeted Outcomes

- Opportunities for companies to compare and contrast alternative thermal manufacturing technologies, encouraging overall adoption of advanced manufacturing technologies
- Increased speed to market for new thermal manufacturing technologies or thermally manufactured products
- More effective use of existing equipment, staff, and energy

Roles & Responsibilities

TMI ATC

- Develop, expand, and maintain catalog of existing facilities
- Manage the demonstration facilities network

Equipment and Technology Suppliers

- Provide access to existing facilities where thermal manufacturing demonstrations can be conducted
- Support work and use shared equipment sites

Process Implementers

- Provide access to existing facilities where thermal manufacturing demonstrations can be conducted
- Support work and use shared equipment sites

Research and Supporting Orgs.

- Provide demonstration sites, including specific national laboratories
- Supply test equipment and tools (e.g., sensors) for demonstration

IMPL-3 Launch a thermal manufacturing workforce training program

Key Tasks

- Identify and catalog existing training initiatives and resources throughout the thermal manufacturing community
- Survey companies in the thermal manufacturing community to assess unmet workforce training needs
- Identify ways to address training gaps in thermal manufacturing, either through additions to existing seminars and courses or by developing new seminars and courses
- Develop training pathways and provide training courses for each thermal manufacturing job function category
- Identify and evaluate potential training certification programs to increase recognition and support of the thermal manufacturing workforce training program

Project Timeline

YEAR 1: Review available training resources and identify training gaps

YEAR 2: Modify existing training materials or create new materials to meet needs

YEAR 2: Roll out training programs for an initial set of thermal manufacturing job categories: Process Engineer, Control Engineer, and Maintenance Technician

YEAR 3: Identify needs and best approach for training certification

ANNUAL: Update surveys and training courses

Targeted Outcomes

- Increased competency of thermal manufacturing workforce
- Optimized efficiency and productivity of thermal manufacturing processes
- Reduced overall manufacturing costs

Roles & Responsibilities

TMI ATC

- Coordinate the development of the catalog of existing training resources
- Compile needs from survey and develop training development plan
- Facilitate the delivery of training to the thermal manufacturing community

Equipment and Technology Suppliers

- Complete the workforce training survey to help identify current industry education needs
- Provide access to existing training resources
- Provide initial trainees to help refine training program materials and courses
- Provide experienced course instructors

Process Implementers

- Complete the workforce training survey to help identify current industry education needs
- Provide access to existing training resources
- Provide initial trainees to help refine training program materials and courses
- Provide experienced course instructors

Research and Supporting Orgs.

- Provide experienced course instructors
- Provide existing training resources

The Path Ahead

The future global competitiveness and sustainability of U.S. thermal manufacturing depends on action taken now to facilitate the coordination of a broader thermal manufacturing community.

Collaborative effort across thermal manufacturing industry segments and stakeholders is essential to accelerate the development, adaptation, and implementation of advanced technologies throughout the thermal manufacturing community in the next five years.

Developing this roadmap achieves the first of three goals outlined by the Thermal Manufacturing Industries Advanced Technology Consortium (TMI ATC) AMTech project (see sidebar). To further the consortium's vision and maximize the value of this roadmap, ASM International will lead the implementation of this roadmap's critical actions and priority action plans by bringing together key academic centers and departments; national laboratories; and industry trade associations and professional societies and their members. Establishing this broader thermal manufacturing community will serve as a call to action to the organizations involved in and impacted by thermal manufacturing.

While leading initiatives that facilitate the development and implementation of advanced manufacturing technologies, ASM International and the TMI ATC Leadership Team will also work to fully launch the Consortium. The Consortium, which will consist of members from industry, academia, national laboratories, and trade associations and professional societies, will help to sustain the continued advancement of U.S. thermal manufacturing by identifying and addressing industry needs through pre-competitive efforts.

Thermal Manufacturing Industries Advanced Technology Consortium (TMI ATC) Vision

Coordinate a national initiative to develop and deploy advanced manufacturing technologies across the broad thermal manufacturing community that will significantly increase sustainability and U.S. global competitiveness.

TMI ATC Goals

1. Lead the development of a comprehensive R&D roadmap
2. Facilitate implementation of advanced manufacturing technologies in thermal manufacturing
3. Fully launch TMI ATC and create a sustainable consortium

The resulting improvements in process efficiency and productivity from the implementation of this roadmap's critical actions and the ongoing efforts of TMI ATC will help to reduce thermal manufacturing energy intensity and emissions, lower overall manufacturing costs, and increase the quality of thermally manufactured products. Ultimately, the increased development and implementation of advanced manufacturing technologies across the broad thermal manufacturing community will help to achieve TMI ATC's vision for a more globally competitive and sustainable U.S. thermal manufacturing sector. To maximize this potential for job creation and economic growth, the community must act today.

Appendices

Appendix A. Acronyms and Abbreviations

AIST	Association for Iron & Steel Technology
AMTech	NIST Advanced Manufacturing Technology Consortia program
BTU	British thermal units
CFC	carbon fiber composite
CFD	computational fluid dynamics
CHTE	Center for Heat Treating Excellence
CVD	chemical vapor deposition
FEA	finite element analysis
FIA	Forging Industry Association
FNA	Furnaces North America
HMFP	high magnetic field processing
HPGQ	high-pressure gas quenching
ICME	integrated computational materials engineering
IHEA	Industrial Heating Equipment Association
IR	infrared
ITHMF	induction thermal high magnetic field
LPC	low-pressure vacuum carburizing
MS&T	Materials Science & Technology
MTI	Metal Treating Institute
NIST	National Institute of Standards and Technology
ORNL	Oak Ridge National Laboratory
STEM	science, technology, engineering, and mathematics
TMI ATC	Thermal Manufacturing Industries Advanced Technology Consortium
UTS	ultimate tensile strength

Appendix B. Roadmap Contributors

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Appendix C. Thermal Manufacturing Processes

Thermal manufacturing consists of processes that use thermal energy to alter the structure or properties of materials and products to achieve desired performance characteristics for a given application. These processes—curing and forming, drying, extractive processing, fluid heating, heat treating, metal heating, and metal and non-metal melting—are used in many industry segments in the United States to produce materials such as metals, glass, and ceramics, as well as downstream products such as electronics, vehicles, and machinery. The following sections provide more in-depth overviews of these key thermal manufacturing processes.

Curing & Forming

Curing is the crosslinking of polymer chains in polymer-based materials. Crosslinking causes an exothermic reaction (generation of heat) that is further accelerated with the application of thermal energy. Curing is commonly applied in the fabrication of composites and ceramic and polymeric coatings. Forming is a process that shapes plastic resin, polymers, glass, or rubber into a variety of configurations (e.g., rolls, containers, automotive parts). In thermoforming, a thermoplastic is heated and forced against a mold until cooled. Curing & forming processes include Curing/Postcuring, Glass forming, and Thermoforming.

Equipment	Arc furnace	Autoclave oven	Continuous strip furnace	Conveyor furnace/kiln	Cupola furnace	Crucible furnace	Fixed-bed reactor	Fluid heaters/ boilers	Fluidized bed reactor	Induction furnace	Infrared oven	Packed bed reactor	Quench furnace	Radiant tube/coil furnace	Rotary hearth kiln/furnace	Vacuum furnace	Vertical shaft/blast furnace	Walking beam furnace
Curing/Postcuring			●							●	●							
Glass Forming											●							
Thermoforming											●							

Process Atmospheres	Air/Ambient	Ammonia	Carbon-based	Dry steam/air	Inert gas	Helium	Hydrogen	Hydrocarbon	Oxygen	Particle-free	Pressurized	Reducing	Salt bath	Sulfur-based	Vacuum
Curing/Postcuring	●				●										●
Glass Forming	●														
Thermoforming															●

Curing & Forming (cont.)

Process Temperatures	
Curing/Postcuring	
	Ceramic coatings: 266°F-752°F
	Polymers: 70°F-780°F
Glass Forming	
	Glass: 900°F-3,180°F
Thermoforming	
	Polymers: 260°F-720°F

0°F 1,000°F 2,000°F 3,000°F

Drying

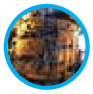
Drying is the removal of water that is not chemically bound to a material. It is most commonly used to reduce the moisture content of solvents and raw sand materials like clay, stone, and glass. Examples of drying include the use of direct-fired heaters to dry pulp at paper mills and the use of conveyer-type dryers to remove water from powder compounds in chemical and pharmaceutical manufacturing. Drying is also used during petroleum refining, textile manufacturing, and food production.

Equipment	Arc furnace	Autoclave oven	Continuous strip furnace	Conveyor furnace/kiln	Cupola furnace	Crucible furnace	Fixed-bed reactor	Fluid heaters/ boilers	Fluidized bed reactor	Induction furnace	Infrared oven	Packed bed reactor	Quench furnace	Radiant tube/coil furnace	Rotary hearth kiln/furnace	Vacuum furnace	Vertical shaft/blast furnace	Walking beam furnace
Drying			●	●					●		●				●			

Process Atmospheres	Air/Ambient	Ammonia	Carbon-based	Dry steam/air	Inert gas	Helium	Hydrogen	Hydrocarbon	Oxygen	Particle-free	Pressurized	Reducing	Salt bath	Sulfur-based	Vacuum
Drying	●														●

Process Temperatures	
Drying	
	Brick: 100°F-400°F
	Clay: 210°F-1,650°F
	Glass: 100°F-180°F
	Silica: 392°F

0°F 1,000°F 2,000°F 3,000°F



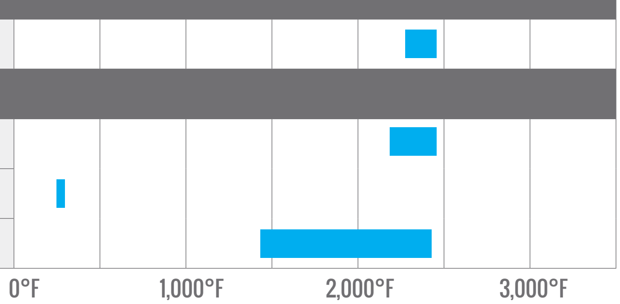
Extractive Processing

Extractive processing involves the conversion of mineral ores or inorganic materials to metals or other intermediate products. Three key extractive processes include agglomeration, calcining, and smelting. Agglomeration, also called sintering, is the grouping of smaller particles into a large cluster by applying pressure or heat below the melting temperature. Calcination is a thermal treatment performed in the presence of air or oxygen to remove chemically-bound water from a material (as opposed to free water removal, which is known as drying); this process is commonly used in the production of petroleum coke, lime, cement, wallboard, and pulp and paper. Smelting is a thermal or chemical treatment used to extract metal from ore; common smelting processes include steel, aluminum, and magnesium smelting.

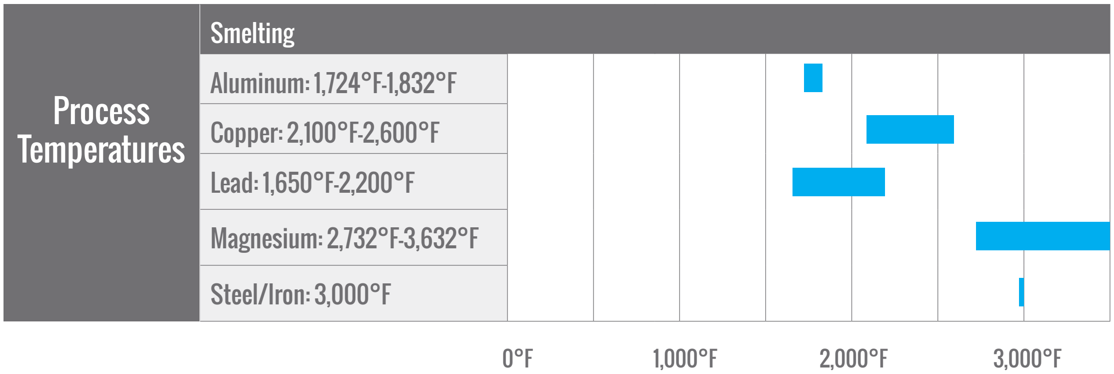
Equipment	Arc furnace	Autoclave oven	Continuous strip furnace	Conveyor furnace/kiln	Cupola furnace	Crucible furnace	Fixed-bed reactor	Fluid heaters/ boilers	Fluidized bed reactor	Induction furnace	Infrared oven	Packed bed reactor	Quench furnace	Radiant tube/coil furnace	Rotary hearth kiln/furnace	Vacuum furnace	Vertical shaft/blast furnace	Walking beam furnace
Agglomeration																	●	
Calcining									●						●			
Smelting	●														●		●	

Process Atmospheres	Air/Ambient	Ammonia	Carbon-based	Dry steam/air	Inert gas	Helium	Hydrogen	Hydrocarbon	Oxygen	Particle-free	Pressurized	Reducing	Salt bath	Sulfur-based	Vacuum
Agglomeration												●			
Calcining	●								●						
Smelting	●														●

Process Temperatures	
Agglomeration	
	Iron: 2,282°F-2,462°F
Calcining	
	Green coke: 2,192°F-2,462°F
	Gypsum: 250°F-300°F
	Limestone: 1,463°F-2,444°F



Extractive Processing (cont.)



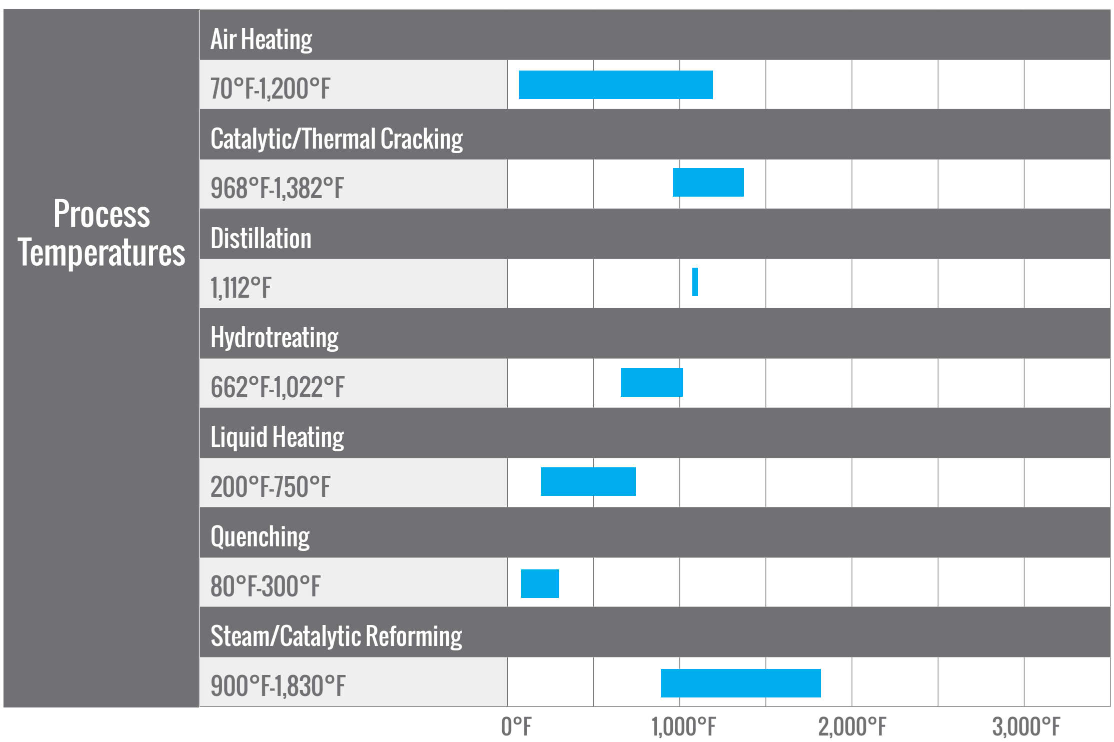
Fluid Heating

Fluid heating is the application of heat to a gas or liquid (i.e., thermal fluid) within a closed-loop system. These systems often rely on a series of heat exchangers, blowers, and pumps to apply thermal processing heat to a variety of products and materials. Examples of fluid heating include distillation of crude oil into separate components and heating of fluids in chemical manufacturing to achieve ideal processing conditions. Fluid heating processes include Air Heating, Catalytic/Thermal Cracking, Distillation, Hydrotreating, Liquid Heating, Quenching, and Steam/Catalytic Reforming.

Equipment	Arc furnace	Autoclave oven	Continuous strip furnace	Conveyor furnace/kiln	Cupola furnace	Crucible furnace	Fixed-bed reactor	Fluid heaters/ boilers	Fluidized bed reactor	Induction furnace	Infrared oven	Packed bed reactor	Quench furnace	Radiant tube/coil furnace	Rotary hearth kiln/furnace	Vacuum furnace	Vertical shaft/blast furnace	Walking beam furnace
Air Heating								●										
Catalytic/Thermal Cracking									●									
Distillation												●						
Hydrotreating							●											
Liquid Heating								●	●									
Quenching													●					
Steam/Catalytic Reforming							●											

Fluid Heating (cont.)

Process Atmospheres	Air/Ambient	Ammonia	Carbon-based	Dry steam/air	Inert gas	Helium	Hydrogen	Hydrocarbon	Oxygen	Particle-free	Pressurized	Reducing	Salt bath	Sulfur-based	Vacuum
Air Heating	●										●				●
Catalytic/Thermal Cracking	●										●				
Distillation	●														●
Hydrotreating											●				
Liquid Heating											●				
Quenching	●										●				●
Steam/Catalytic Reforming											●				



Heat Treating

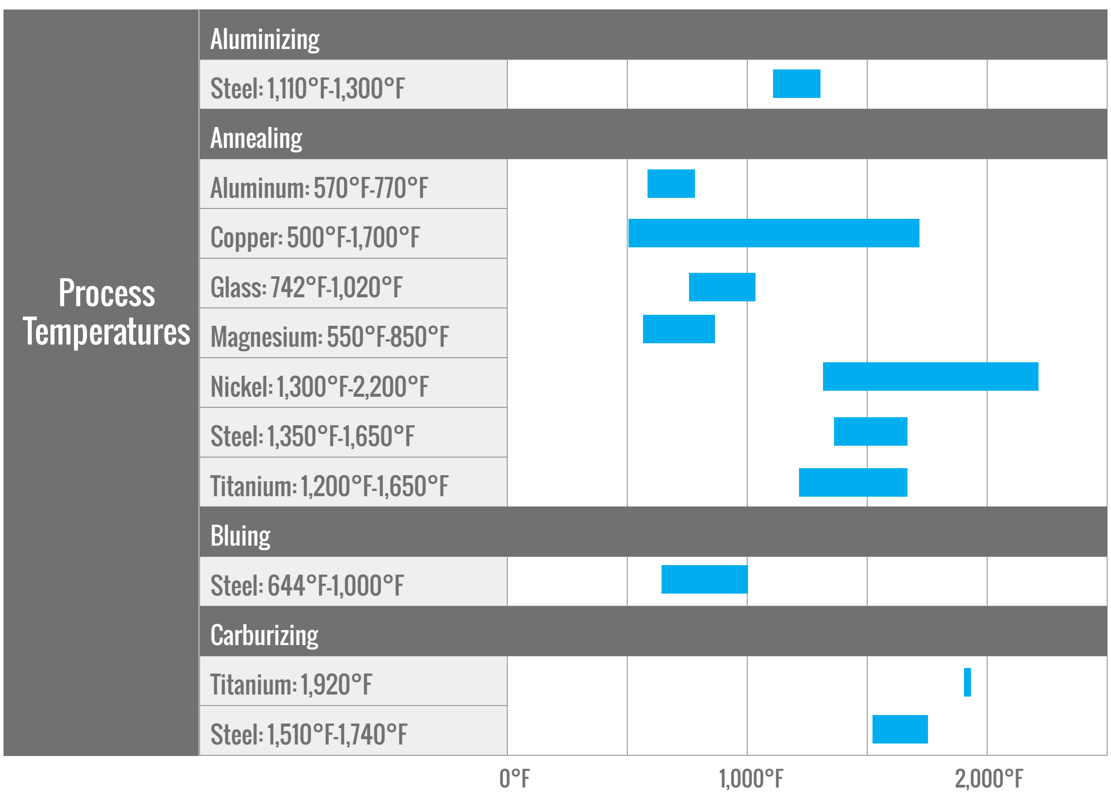
Heat treating is the application of thermal energy to change the microstructure of a material. This alteration then changes the material's mechanical properties—strength, ductility, hardness, toughness, and elasticity. Heat treating processes include Aluminizing, Annealing, Bluing, Carburizing/Recarburizing, Decarburizing, Homogenization, Nitriding, Precipitation Hardening, Solution Heat Treating, and Tempering.

Equipment	Arc furnace	Autoclave oven	Continuous strip furnace	Conveyor furnace/kiln	Cupola furnace	Crucible furnace	Fixed-bed reactor	Fluid heaters/ boilers	Fluidized bed reactor	Induction furnace	Infrared oven	Packed bed reactor	Quench furnace	Radiant tube/coil furnace	Rotary hearth kiln/furnace	Vacuum furnace	Vertical shaft/blast furnace	Walking beam furnace
Aluminizing				●		●				●						●		
Annealing			●	●						●					●	●	●	
Bluing				●														
Carburizing/ Recarburizing				●									●	●		●		
Decarburizing				●										●				
Homogenization			●							●					●		●	
Nitriding				●										●				
Precipitation Hardening			●	●						●					●	●	●	
Solution Heat Treating			●	●						●					●	●	●	
Tempering			●	●						●					●	●	●	

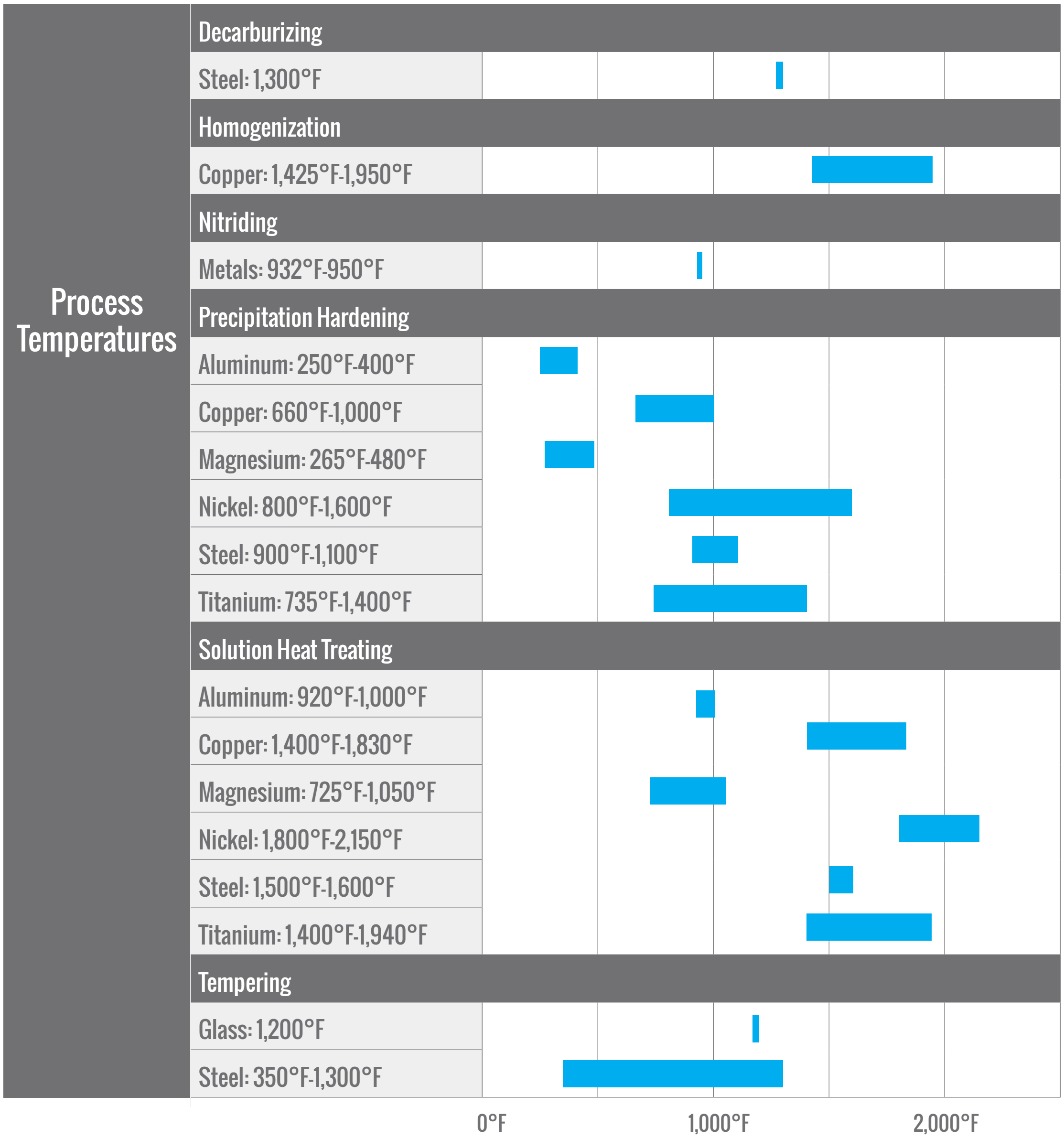
Process Atmospheres	Air/Ambient	Ammonia	Carbon-based	Dry steam/air	Inert gas	Helium	Hydrogen	Hydrocarbon	Oxygen	Particle-free	Pressurized	Reducing	Salt bath	Sulfur-based	Vacuum
Aluminizing			●		●										
Annealing		●	●	●	●		●	●		●			●	●	●

Heat Treating (cont.)

Process Atmospheres	Air/Ambient	Ammonia	Carbon-based	Dry steam/air	Inert gas	Helium	Hydrogen	Hydrocarbon	Oxygen	Particle-free	Pressurized	Reducing	Salt bath	Sulfur-based	Vacuum
Bluing				●											
Carburizing/ Recarburizing			●		●						●				●
Decarburizing							●		●						
Homogenization	●														●
Nitriding		●													
Precipitation Hardening		●	●	●	●	●	●						●	●	●
Solution Heat Treating		●	●	●	●									●	●
Tempering					●					●					●



Heat Treating (cont.)



Metal Heating

In contrast to heat treating, metal heating primarily refers to the heating of metals to establish ideal fabrication conditions in shaping processes. This application of heat increases the malleability of metals to prevent them from fracturing during cold- and hot-working processes such as forging, extraction, and rolling. In addition to shaping metals, metal heating is required in coating processes such as galvanization and chemical vapor deposition (CVD).

Metal Heating (cont.)

Equipment	Arc furnace	Autoclave oven	Continuous strip furnace	Conveyor furnace/kiln	Cupola furnace	Crucible furnace	Fixed-bed reactor	Fluid heaters/ boilers	Fluidized bed reactor	Induction furnace	Infrared oven	Packed bed reactor	Quench furnace	Radiant tube/coil furnace	Rotary hearth kiln/furnace	Vacuum furnace	Vertical shaft/blast furnace	Walking beam furnace
CVD Coating														●				
Cold-Working															●			●
Galvanizing			●															
Hot-Working										●					●			●

Process Atmospheres	Air/Ambient	Ammonia	Carbon-based	Dry steam/air	Inert gas	Helium	Hydrogen	Hydrocarbon	Oxygen	Particle-free	Pressurized	Reducing	Salt bath	Sulfur-based	Vacuum
CVD Coating					●										
Cold-Working	●				●										
Galvanizing	●														
Hot-Working	●				●										

Process Temperatures

Chemical Vapor Deposition Coating

Metals: 1,470°F-2,010°F

Cold-Working

Metals: 70°F-450°F

Galvanizing

Metals: 850°F-1,436°F

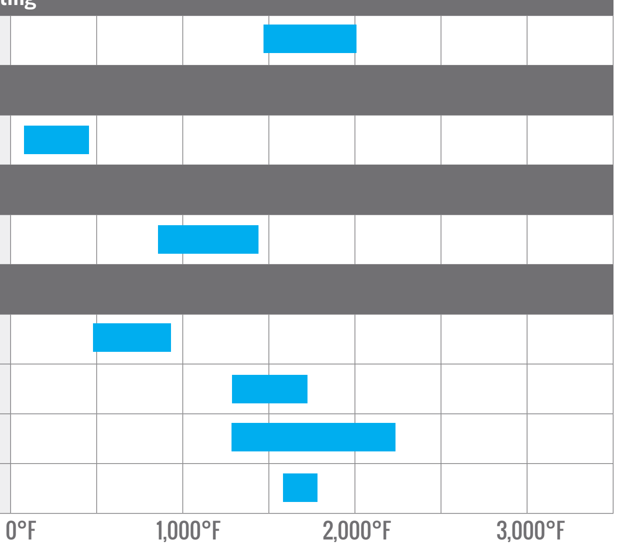
Hot-Working

Aluminum: 500°F-950°F

Copper: 1,300°F-1,740°F

Steel: 1,300°F-2,250°F

Titanium: 1,600°F-1,800°F



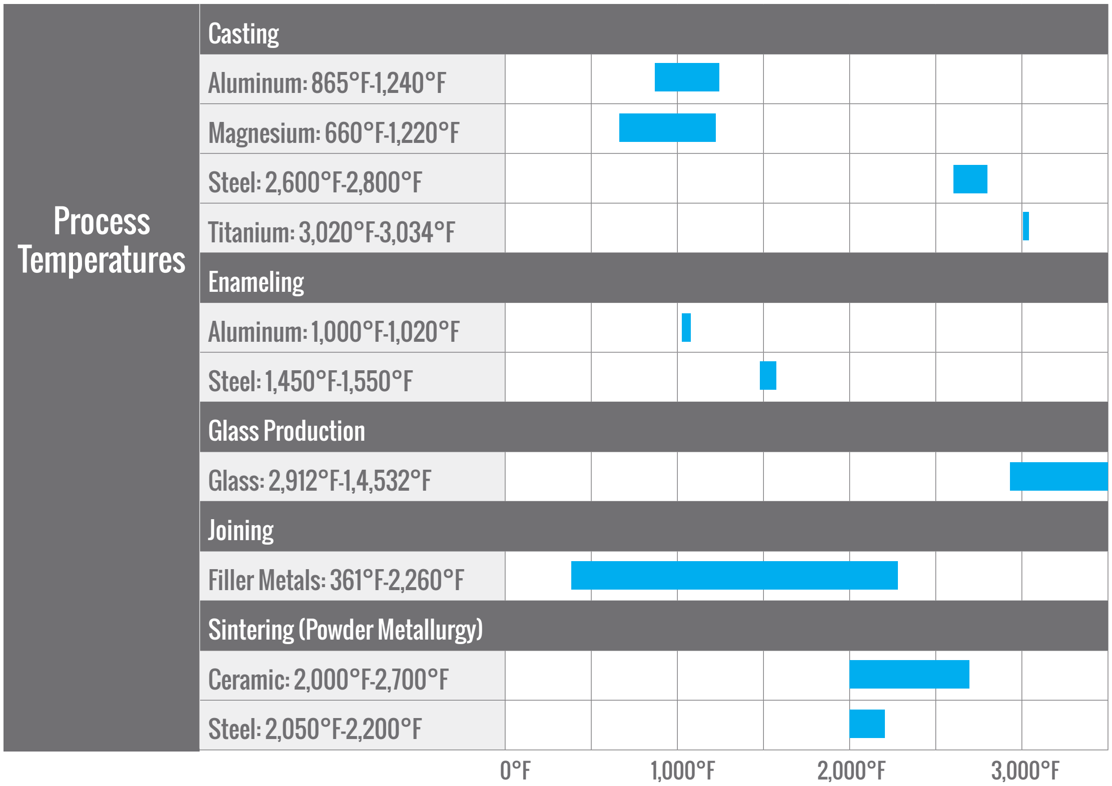
Metal & Non-Metal Melting

Melting is a standard procedure used to convert a material from a solid to a liquid by applying heat (also known as “molten”). It is commonly used in the metals industry to convert bulk ingots to finished or semi-finished castings. Non-metal melting is also used in the production of glass. Metal and Non-Metal Melting processes include Casting, Enameling, Glass Production, Joining, and Sintering (Powder Metallurgy).

Equipment	Arc furnace	Autoclave oven	Continuous strip furnace	Conveyor furnace/kiln	Cupola furnace	Crucible furnace	Fixed-bed reactor	Fluid heaters/ boilers	Fluidized bed reactor	Induction furnace	Infrared oven	Packed bed reactor	Quench furnace	Radiant tube/coil furnace	Rotary hearth kiln/furnace	Vacuum furnace	Vertical shaft/blast furnace	Walking beam furnace
Casting					●	●				●						●		
Enameling				●														
Glass Production				●														
Joining										●	●					●		
Sintering (Powder Metallurgy)	●			●						●	●					●		●

Process Atmospheres	Air/Ambient	Ammonia	Carbon-based	Dry steam/air	Inert gas	Helium	Hydrogen	Hydrocarbon	Oxygen	Particle-free	Pressurized	Reducing	Salt bath	Sulfur-based	Vacuum
Casting	●														●
Enameling										●					
Glass Production	●														
Joining	●				●										●
Sintering (Powder Metallurgy)		●			●		●				●				●

Metal & Non-Metal Melting (cont.)



Appendix D. Previously Developed Thermal Manufacturing Roadmaps

The Aluminum Association. *Aluminum Industry Technology Roadmap*. February 2003.

American Iron and Steel Institute. "Chapter 2: Process Development." *Steel Technology Roadmap*. December 2001.

ASM Heat Treating Society, an ASM International affiliate. *An R&D Plan for the Heat Treating Community*. 2001.

ASM Heat Treating Society, an ASM International affiliate. *1999 Research & Development Plan*. 1999.

Cast Metal Coalition of the American Foundrymen's Society, North American Die Casting Association, and Steel Founders' Society of America. *Metalcasting Industry Technology Roadmap*. January 1998.

European Commission Ad-hoc Industrial Advisory Group. *Factories of the Future PPP: Strategic Multi-Annual Roadmap*. 2010.

Forging Industry Educational and Research Foundation. *Forging Industry Technology Roadmap: 2008 Update*. June 2008.

Glass Manufacturing Industry Council and U.S. Department of Energy. *Glass Industry Technology Roadmap*. April 2002.

Industrial Heating Equipment Association and U.S. Department of Energy. *Roadmap for Process Heating Technology*. March 2001.

International Energy Agency. *Technology Roadmap: Solar Heating and Cooling*. 2012.

International Energy Agency and World Business Council for Sustainable Development. *Cement Technology Roadmap 2009: Carbon Emissions Reductions up to 2050*. 2009.

Metal Powder Industries Federation. *2012 PM Industry Roadmap, Technology Update for the Powder Metallurgy Industry*. 2011.

Metal Powder Industries Federation and U.S. Department of Energy, Office of Industrial Technologies. *PM2 Industry: Vision and Technology Roadmap, Powder Metallurgy and Particulate Materials*. September 2001.

U.S. Department of Energy. *Industrial Combustion Technology Roadmap*. April 1999.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. *Technology Roadmap for the Petroleum Industry*. February 2000.

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, and the Industrial Heating Equipment Association. *Improving Process Heating System Performance: A Sourcebook for Industry*. 2004.