State of Advanced Manufacturing Technology and Process Developments in Thermal Manufacturing

Advanced technologies have the potential to improve the efficiency, productivity, and global competitiveness of a wide range of thermal manufacturing processes (e.g., drying, curing and forming, and heat treating) and various end-use industries (e.g., automotive and computer and electronic products). However, previous efforts to identify and pursue these technology advances have been done in isolation, rather than through collaboration across key stakeholders. Roadmaps were developed independently from one another by the different industries that rely on or supply thermal equipment and processes.

While much work to date has been conducted in isolation, a number of key technologies and process improvement areas cross-cut the different industries and processes that comprise the broad thermal manufacturing community. This state-of-the-art review aims to develop a foundation of the needs and opportunities for advanced thermal manufacturing technologies across relevant industries and involving all key stakeholders. To develop this overview, we reviewed previous industry roadmaps and pulled key needs and opportunities in thermal manufacturing, interviewed 20 experts in the thermal manufacturing community, and searched the websites of relevant organizations to provide an overview of recent or current work related to thermal manufacturing (see Bibliography for list of interviewees, roadmaps and documents, and organization websites).

The current needs and opportunities as well as the recent and current work being conducted in this area are categorized by the following high-level technology and process areas:

- Modeling and Simulation
- Sensors
- Heat Generation Methods
- Process Intensification
- Energy and Emissions Reduction
- Automation and Robotics
- Advanced Materials

While each of these areas provides value alone, advancing and implementing multiple technologies in parallel will have the maximum impact. Needs and opportunities as well as current and recent work have been categorized based on the technology and process area of most relevance; in most cases, one technology and process area enables or is dependent on another area of work (e.g., improved sensors could enable more advanced automation and facilitate improved data collection for modeling and simulation).
The increased use of modeling and simulation can help optimize manufacturing processes and products and save money by reducing trial and error approaches in materials and process development.

**Key Opportunities in Thermal Manufacturing**

- Improved 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

The following table outlines some of the current needs and opportunities for modeling and simulation in thermal manufacturing and the recent and current work being conducted in this area based on a selective literature review.

**Table 1: Current State of Modeling and Simulation in Thermal Manufacturing**

<table>
<thead>
<tr>
<th>Needs and Opportunities</th>
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<tbody>
<tr>
<td><strong>General Modeling Needs</strong></td>
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<tr>
<td>- Educate industry to better understand the economic value of modeling software and increase their willingness to buy software licenses</td>
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<tr>
<td>- Demonstrations of user-friendly modeling software packages (e.g., with auto-meshing capabilities) for non-experts</td>
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<td>- Increased communication between modelers and producers/processers</td>
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<td>- Through-process modeling that relates all processes in the manufacture of a product</td>
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<td>- Modeling software that includes thermal efficiencies</td>
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<tr>
<td>- Simulation software coupled with macroscale modeling software (finite element/difference) for property and microstructure prediction</td>
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<tr>
<td>- Life-cycle analysis models that relate structural properties to manufacturing processes to determine effectiveness of varying thermal manufacturing processes</td>
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<tr>
<td>- Process models that help generate material/microstructure specifications based on user-entered application-specific criteria (e.g., wear, forces, corrosion)</td>
</tr>
<tr>
<td><strong>Data Needs</strong></td>
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<tr>
<td>- Universal interface for exporting data</td>
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<tr>
<td>- Mechanical, thermal, and metallurgical data (e.g., thermal strains and transformation kinetics) as a function of time and temperature</td>
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<tr>
<td>- Consistent data for mold filling</td>
</tr>
</tbody>
</table>
• Steel transformation data and thermal strain information (e.g., heat treat with quench simulations)
• Diffusion data for specific alloys
• Stress-strain database as a function of phase, temperature, and strain rate
• Understanding of aluminum rheology, including liquid and plastic deformation characteristics
• Data to better understand intergranular oxidation concerns of carburization in protective atmospheres

Cast/Solidification Models
• Integration of CALPHAD in solidification codes
• Adequate models of turbulence in the casting process
• Ability to predict micro-structure as a function of composition and processing
• North American solidification models that account for centerline segregation and microsegregation
• Comprehensive heat transfer, fluid flow, and solidification models to define the thermal conditions in the growing shell and rotating roll and to enable in situ compensation or correction for roll distortions
• Advanced heat transfer and fluid flow models that include the free surface of liquid/liquid boundaries; slag emulsification; cast surface shape and position; inclusions or bubble distribution; and segregation patterns

Heat Treatment Modeling
• Full-load heat treat simulations to design the furnace process for optimal load density
• Computational fluid dynamics analysis for high-pressure gas quenching systems that includes phase changes
• Thermochemical models of atmosphere-material interactions during carburizing and nitriding
• Model for volumetric strains resulting from transformations during heating and cooling
• Heat-transfer coefficient database based on time-temperature data and scaling rules
• Computational fluid dynamics modeling of quench baths to predict flow patterns and cooling rates in loaded baths

Electromagnetic Modeling
• Methods to analyze 3-D problems in time frames that can be useful for individual runs
• Temperature-dependent electromagnetic material properties database

Phase/Precipitation Modeling
• Martensitic transformation modeling
• Temper kinetics of martensite modeling
• Modeling athermal transformation of retained austenite fraction in steel alloys
• Precipitation kinetics in micro-alloyed steel

Process Efficiency/Energy Modeling
• Modeling of thermal gradients in furnaces to optimize furnace design
• Modeling to design process flow path to meet final customer product requirements
• Predictive software that process implementers can use to compare and select thermal manufacturing equipment from different suppliers
• Coupled heat and mass transfer models to allow prediction of the effect of ladle metallurgy on chemistry and inclusion control
• A ladle model that would include heat transfer with the container and the slag, reaction between the steel and the slag, reheating, degassing, and refining
• Model that combines flow modeling and finite element thermal analysis to predict the location and rate of accretion in refractory materials
• Modeling of the electric arc furnace process with variable air infiltration, flexible charges, and variable degrees of post-combustion to benchmark the optimum process and improve design
• Plant layouts modeled with infrared imaging to develop more efficient plant process flow and better energy management

Recent or Current Work

General Modeling Needs
• CALPHAD thermal expansion database (National Institute of Standards and Technology)
• Integrated manufacturing process simulation framework that enhances understanding of what occurs as AA6111-T4 aluminum alloy sheets undergo shearing or trimming in preparation for the subsequent forming process (Ford Motor Company and Pacific Northwest National Laboratory)
• Method for predicting the stability and elasticity of certain alloys for millions of atomic configurations of the materials to help identify materials with optimized properties for an application (Hamburg University of Technology)
• Models for density and viscosity of crude oil and natural gas at high temperatures and high pressures (National Energy Technology Laboratory)
• Analytical and numerical models of specific top down and bottom up nanofabrication techniques and processes, as well as models and simulations of their associated metrology challenges (National Institute of Standards and Technology)
• Reference Architecture (RA) and Solution Stack (SS) for smart manufacturing systems to enable easy composition of solutions for the large, evolving, and heterogeneous systems in factories and production networks (National Institute of Standards and Technology)
• Measurement data and techniques to allow for accurate assessment of the thermal properties of insulating materials, including insulation meant for applications up to 250°C, microporous insulation, and phase-change materials (National Institute of Standards and Technology)
• Model to improve control of sheet reheating that considers temperature-dependent properties, sheet color, and operating conditions (McGill University)

Data Needs
• Energy landscape of glass that maps all possible energy positions of glass molecules to improve manipulation of properties and better control of glass aging (Duke University)

Cast/Solidification Models
• Composite element test modeling for the repair of commercial single crystal nickel-based superalloys to define processing parameters and the correlation between solidification conditions and microstructure (University of Birmingham)
• Electronic database for rapid selection of aluminum die casting alloys (Worcester Polytechnic Institute)
• Telluride Code Project: models and optimizes the gravity-pour casting processes which are currently ongoing at LANL foundries (Los Alamos National Laboratory)
• Use of high-energy protons to nondestructively image a large metal sample during melting and solidification (Los Alamos National Laboratory)
• Experimental methodology/apparatus to quantitatively measure and characterize hot tearing in aluminum cast alloys (Worcester Polytechnic Institute)
• Castability control in metal casting via fluidity measures (Worcester Polytechnic Institute)
Heat Treatment Modeling
- Predicting the response of aluminum casting alloys to heat treatment (Worcester Polytechnic Institute)
- Tools for prediction/control of distortion and residual stresses in heat treated components (Worcester Polytechnic Institute)

Electromagnetic Modeling
- Electromagnetic and thermal-stress modeling of induction scan hardening (DANTE)

Phase/Precipitation Modeling
- Using CALPHAD to increase understanding of multicomponent systems (e.g., phase changes, heating rates) (National Institute of Standards and Technology)
- Phase-field modeling of microstructure evolution during processing of cold-rolled dual-phase steels (RWTH Aachen)
- Alpha phase precipitation from phase-separated beta phase in a model Ti-Mo-Al alloy studied by direct coupling of transmission (Pacific Northwest National Laboratory)
- Data repositories for use with CALPHAD so relevant low-order (unary, binary, and ternary) systems can be re-assessed efficiently to develop new multicomponent descriptions (National Institute of Standards and Technology)

Process Efficiency/Energy Modeling
- Integration of Advanced Combustion GmbH’s Representative Interactive Flamelet mode with CONVERGE computational fluid dynamics software to model ignition, combustion, and emissions within a diffusion flame (Convergent Science)
- Publicly available combustion chemistry models for alternative fuels that are more sophisticated and detailed than commercially available computational fluid dynamics models (Argonne National Laboratory)
- Computer models based on Front-Tracking and Lattice-Boltzmann (LBM) techniques for direct numerical simulation of an internal combustion engine spray in the near-injector region (Argonne National Laboratory)
- Simulations and validation of two-phase flow experiments and the largest unstructured Large Eddy Simulation (LES) of combustors (CERFACS)
- Diagnostic capability that provides three-dimensional measurements of turbulent flame dynamics using high-repetition rate tomographic particle image velocimetry (Sandia National Laboratory)
Sensors

Improved sensor technologies can enable more accurate measuring, monitoring, and control of the high-temperature and corrosive operating environments of thermal manufacturing and can improve the quality and reliability of products.

Key Opportunities in Thermal Manufacturing

- Low-cost, real-time, non-intrusive sensors capable of measuring, controlling, 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

The following table outlines some of the current needs and opportunities for sensors in thermal manufacturing and the recent and current work being conducted in this area based on a selective literature review.

**Table 2: Current State of Sensors in Thermal Manufacturing**

<table>
<thead>
<tr>
<th>Needs and Opportunities</th>
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<tbody>
<tr>
<td><strong>General Process Control Sensors</strong></td>
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<tr>
<td>• Advanced microelectromechanical systems for embedded microsensors</td>
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<tr>
<td>• Improved understanding of the maintenance needs of sensors to ensure more accurate data</td>
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<tr>
<td>• Smart sensors that indicate in real time when they are not performing as designed and have the ability to self-calibrate</td>
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<tr>
<td>• Reliable basic oxygen furnace sensors to detect lance-to-steel bath distance and provide real-time feedback to improve the consistency of the process reaction path</td>
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<tr>
<td><strong>Physical Property Sensors</strong></td>
</tr>
<tr>
<td>• Real-time case-carbon quenching sensors to quantify heat transfer process variability</td>
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<tr>
<td>• Ultrasonic inclusion sensors or continuous-monitoring sensors to assist molten metal and glass analysis</td>
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<tr>
<td>• Increased use of non-contact laser ultrasonics to monitor the recrystallization of continuously cast strip prior to coiling</td>
</tr>
<tr>
<td>• Sensor to determine whether a part’s surface is clean enough to be correctly carburized</td>
</tr>
<tr>
<td>• In-line, real-time, operator-friendly, continuous non-contact sensor and method to identify and separate scrap</td>
</tr>
<tr>
<td>• A more sophisticated probe that addresses surface finish and geometry issues for quenching</td>
</tr>
</tbody>
</table>
### Gas/Electrochemical/Galvanic sensors
- Sensors to measure amount of carbon in the process atmosphere for carburizing and nitriding
- Laser-based immersion probe system that provides elemental analysis within a minute
- Oxygen sensors with improved resistance to carbon deposits

### Temperature/Infrared Sensors
- Better low-cost methods for measuring internal moisture and temperature in parts
- Measurement devices that can provide a 3-D thermal profile of the combustion space as well as the thermal velocity
- Sensors that can detect flame instability
- Hardware capable of making in-process temperature measurements to enable real-time fabrication of glass containers and tableware
- Improved understanding of glass composition effects on physical properties (e.g., as the Fe$_2$O$_3$ content in the glass changes, so does the emissivity) to improve the capacity for infrared sensors to detect temperature

### Force/Stress/Strain Measurement Sensors
- Incipient crack sensors
- Nondestructive method to detect residual stress
- Crack detection in unfinished parts

### Recent or Current Work

#### General Process Control Sensors
- Wireless sensors that form a network with one or more sensor interrogators, data concentrators, or processing nodes, and communicate the information generated by the sensors with a central operator or automated monitor (Pacific Northwest National Laboratory)
- Calibration methodology to address error readings due to sensor degradations (Argonne National Laboratory, Case Western University)
- Microelectromechanical systems fabricated from silicon and other materials to sense and react to environmental changes (Lawrence Livermore National Laboratory)
- In-line fluid analysis technology that provides real-time analysis data that indicates the condition of oils or other lubricants and detects contamination and metal wear content (Pacific Northwest National Laboratory)
- Semiconductor fabrication lines coupled with radio frequency interrogators and product identification tags to record processing steps for each wafer in a central database (Texas Instruments)
- Integrated methodology and protocols to enable, assess, and assure the real-time performance of secure wireless platforms in smart manufacturing systems (National Institute of Standards and Technology)
- Three-dimensional silicon sensors in which the n- and p-type electrodes penetrate through the entire substrate (SINTEF and Stanford Nanofabrication Facility)
- Technique to produce machines made of elastic materials and liquid metals by embedding a liquid-alloy pattern inside a rubber-like polymer to form a network of sensors to mimic the functionality of human skin (Purdue University)

#### Physical Property Sensors
- Method to monitor curing or cross-linking of adhesives and polymers to ensure proper processing (Pacific Northwest National Laboratory)
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- Integrated Micron-sized subwavelength structured photonic sensors that monitor critical thermomechanical phenomena (University of Illinois)
- Ultrasonic sensor that characterizes a fiber suspension to determine the degree of refining, making the refining process more efficient (Pacific Northwest National Laboratory)
- Rapid, non-destructive method to measure hardening depth and gradient of treated steel parts (Pacific Northwest National Laboratory)
- Microsensors designed and fabricated in the type of surface mount components (e.g., resistors and capacitors) and soldered directly onto networks for corrosion assessment of copper, aluminum, and wire-bonded chips (Sandia National Laboratories)

**Gas/Electrochemical/Galvanic sensors**

- Stand-alone, self-calibrating, high-temperature flue gas sensor capable of detecting nitrogen oxides, sulfur oxides, hydrogen sulfide, methane, carbon monoxide, carbon dioxide, water, hydrogen chloride, ammonia, phospine, toluene, and mercaptans (Georgia Institute of Technology)
- Process monitor featuring Raman and Coriolis/conductivity instrumentation configured for remote monitoring, MATLAB-based chemometric data processing, and comprehensive software for data acquisition/storage/archiving/display (Pacific Northwest National Laboratory)
- Method for amplifying signals in graphene oxide-based electrochemical sensors through a process called “magneto-electrochemical immunoassay” (Northwestern University)
- “Batteryless” nanosensor that can identify different chemical species in less than a second (Lawrence Livermore National Laboratory)
- Improved accuracy and durability of co-fired ceramic sensor elements and other ceramic components, for use in nitrogen oxides and particulate matter sensors (EmiSense Technologies LLC)
- Multifunctional chemical vapor sensors of aligned carbon nanotube and polymer composites (University of Dayton and Air Force Research Laboratory)
- Porous silicon-based conductometric gas sensor with a resistance of around 40 ohms that detects gaseous hydrogen chloride, ammonia, nitrogen oxide, and organic materials at concentrations of 10–100 parts per million (ppm) (Georgia Institute of Technology)
- Multifunctional metal oxide/perovskite-based in situ composite nanosensors for industrial and combustion gas detection at high temperature (700°C –1,300°C) (National Energy Technology Laboratory)
- Sensor that uses a resistively heated, noble metal-coated, micromachined polycrystalline silicon filament to calorimetrically detect the presence and concentration of combustible gases (Sandia National Laboratory, University of Utah, Massachusetts Institute of Technology, and University of New Mexico)
- Low-cost, high-sensitivity, wide-range oxygen sensor with a diffusion barrier, electrolyte material, and counter-electrode (Georgia Tech)
- BTU4400-NOx: portable flue-gas analyzer designed for emissions monitoring and maintenance as well as tuning of combustion processes (E Instruments International)

**Temperature/Infrared Sensors**

- Improved accuracy of infrared devices in measuring skin temperatures on furnace coils by studying emissivity of typical furnace coils (BASF)
- Active Millimeter Wave Pyrometer to determine the spatial distribution of the surface temperature of an object using non-contact methods (Pacific Northwest National Laboratory)
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- Temperature sensor with an outer wall of a conventional oxidization-resistant nickel alloy and an inner wall of a different nickel alloy that prevents contamination and can reduce drift by 80%–90% at 1,200°C –1,300°C (University of Cambridge)

**Force/Stress/Strain Measurement Sensors**
- Non-destructive ultrasonic method to detect stresses and damage not visually identifiable (Pacific Northwest National Laboratory)
- Miniaturized fiber-optical sensor system that can be fully embedded in a composite material and automatically monitor its structural health (Ghent University, imec, and SMARTFIBER)
- Micro-bead melt sensor that indicates the imposed strains of temperature and radial force strain as melt density “K” electro-motive force (emf) readout (Society of Plastics Engineers)
- System to monitor the effects of use-loading on structural members and detect failure precursors (Pacific Northwest National Laboratory)
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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 combustion methods with improved heat transfer.

Key Opportunities in Thermal Manufacturing

- Improved indirect heating methods (i.e., heat must be transferred from the heat source to the product via conduction, convection, or radiation)
- Hybrid combustion methods that combine existing methods or couple a new method with an existing method to increase efficiency
- Alternative fuels with increased energy flexibility
- Advanced combustion methods with increased stabilization
- Reduced cost and improved purity of on-site oxygen production for oxy-fuel firing, including cogeneration

The following table outlines some of the current needs and opportunities for combustion methods in thermal manufacturing and the recent and current work being conducted in this area based on a selective literature review.

Table 3: Current State of Combustion Methods in Thermal Manufacturing

<table>
<thead>
<tr>
<th>Needs and Opportunities</th>
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<tbody>
<tr>
<td><strong>General</strong></td>
</tr>
<tr>
<td>- Increased use of oxygen/natural gas combustion process in glass furnaces</td>
</tr>
<tr>
<td>- Lower-cost technologies that can simultaneously reduce nitrogen oxides to low levels and achieve high thermal efficiency</td>
</tr>
<tr>
<td>- State-of-the-art combustion laboratories to validate computational fluid dynamics models</td>
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<tr>
<td>- Computational tools that contain validated, high-fidelity combustion models</td>
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<tr>
<td>- Method of direct heating that eliminates scale on metals</td>
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<tr>
<td>- Advanced boiler and combustion cycles (e.g., pressurized combustion systems, turbocharged combinations) with minimum operating conditions of 1,500 psi, 1,500°F, and 3:1 pressure ratio</td>
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<tr>
<td>- Combustion equipment for low heat-value fuels (e.g., waste fuels)</td>
</tr>
<tr>
<td>- Increased use of waste heat boilers that transfer heat from the byproducts of production to high-pressure steam for plant use or conversion into electricity</td>
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<tr>
<td>- Rapid-cycle regenerative systems</td>
</tr>
<tr>
<td>- Materials and designs that can withstand dirty, contaminated, unpredictable combustion flue gases</td>
</tr>
<tr>
<td>- Use of exhaust heat for absorption cooling</td>
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</table>
## Combustion Reaction Catalysts
- High-temperature catalyst materials
- Catalysts that help achieve flame stability and low nitrogen oxide at lower temperature
- A single, non-energy requiring biocatalyst for hydrocarbon and hetero-atom conversion

## Oxyfuel Combustion
- Better understanding of the impacts of oxyfuel technology on the clinker-burning process of cement manufacturing
- High turn-down, low-pressure-drop, variable geometry burner
- Unified code that accounts for burner-furnace geometry and includes emissivities and multi-flame interactions
- Adaptation of existing complex computational fluid optimization codes to burners

## Other
- Additional work in low-energy nuclear reactions, which could potentially be driven by waste heat
- Laser-based machining integrated in combustion equipment

## Recent or Current Work

### General
- Virtual Engine Research Institute and Fuels Initiative: first and only source in the world for high-fidelity, three-dimensional, end-to-end, combustion engine simulation/visualization, simultaneous powertrain, and fuel simulation, with uncertainty quantification (Argonne National Laboratory)
- Use of spinning gas near sonic velocities to achieve higher heating capacity and more closely reach the Carnot efficiency (Princeton Plasma Physics Laboratory)
- Two-minute production time to produce skutterudite compounds using microwave energy, improving methods of capturing waste heat (Oregon State University)

### Combustion Reaction Catalysts
- Research in how metal oxide surfaces interact with water to better understand and control chemical reactions in fields ranging from catalysis to geochemistry (University of Wisconsin-Madison, Aarhus University, and Lund University)
- High-activity de-alloyed platinum catalysts: durable high-activity catalysts show reduced cost by using various de-alloying techniques and mass activity that meets DOE targets after 30,000 voltage cycles (United States Council for Automotive Research)
- Catalytic pyrolysis technology to produce advanced lignocellulosic biofuels (Fortum, UPM, and Valmet)
- Lignin valorization through integrated biological funneling and chemical catalysis; conversion of lignin into a variety of renewable fuels, chemicals, and materials for a sustainable energy economy (National Renewable Energy Laboratory)

### Other
- High-intensity colorless distributed combustion for ultra-low emissions and enhanced performance (Ames Laboratory)
- Bionic liquids from lignin and hemicellulose that could realize a closed-loop process (e.g., in paper production) (Lawrence Berkeley National Laboratory)
Process Intensification

Process intensification involves engineering advances that decrease the size of equipment, increase energy efficiency, and reduce waste and emissions. The ultimate goal of process intensification is to reduce the time it takes for a product to progress from raw material to an end-use product, while reducing energy use and cost.

Key Opportunities in Thermal Manufacturing
- More flexible equipment that can be used for multiple processes
- Improved manufacturing plant layouts that reduce inefficiencies
- Shorter processing times and elimination of processing steps
- Retrofit equipment on existing capital equipment to increase efficiency while reducing the typical cost of integrating new equipment

The following table outlines some of the current needs and opportunities for process intensification in thermal manufacturing and the recent and current work being conducted in this area based on a selective literature review.

Table 4: Current State of Process Intensification in Thermal Manufacturing

<table>
<thead>
<tr>
<th>Needs and Opportunities</th>
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<tbody>
<tr>
<td>Alternate/Improved Heating Methods</td>
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<tr>
<td>- Heat treating equipment for one-piece flow (batches of one) to support synchronous manufacturing</td>
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<tr>
<td>- High magnetic field processing for development of ultralightweight metals with tailored microstructures and properties</td>
</tr>
<tr>
<td>- Impinging jets with good heat transfer coefficients that exert little force on products so as not to damage food and paper products</td>
</tr>
<tr>
<td>- High-temperature, high-pressure drying process that allows for vapor release without damaging food and paper products</td>
</tr>
<tr>
<td>- Alternative cell concepts to electrolytic reduction process, such as a combination of inert anode/wetted and drained cathode or systems approach for designing dimensionally stable cells</td>
</tr>
<tr>
<td>- Commercial-scale carbothermic reduction process</td>
</tr>
<tr>
<td>- Continuous, high-productivity, thin-strip casting process at lower gauge</td>
</tr>
<tr>
<td>- Water and inert-gas quenching methods to emulate salt and oil quenching</td>
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<tr>
<td>- Quenching media that are nonpolluting and safe to use</td>
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<tr>
<td>- New heat treating processes for advanced materials such as intermetallic materials and metal matrix composites</td>
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<tr>
<td>- Cleaner melting/pouring technologies</td>
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<tr>
<td>- Technologies capable of &quot;casting to shape&quot; by making better use of cavities</td>
</tr>
<tr>
<td>- In situ methods for melting and casting metals</td>
</tr>
<tr>
<td>- Environmentally friendly reactive flux gases for metal treatment</td>
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</tbody>
</table>
- Smart burners that adjust heat release profile
- More efficient radiant heater with uniform surface temperature
- Cost-effective, energy-efficient furnace modification packages that can be adopted by small companies
- Agglomeration process to form glass pellets or briquettes that achieves good thermal efficiency and minimizes dusting of the unmelted glass

### Processing Speed and Step Elimination
- More compact melting equipment with more flexible operation
- Paint/coating processes that allow for fast curing at lower temperatures to reduce energy consumption and allow for use of other materials that can’t handle as high of temperatures
- Processes capable of ramping up or slowing down quickly
- Advanced forming techniques to manufacture net shapes without intermediate processes
- High-temperature (>1,010°C) carburizing processes, including atmosphere and vacuum carburizing processes, to shorten cycles
- Die materials and coatings that eliminate the need for solder and heat checks
- Equipment that combines mass and heat transfer mechanisms and catalysis (e.g., catalytic distillation) to achieve the desired results more efficiently
- Bypassing the initial distillation of crude altogether through revolutionary new pathways, such as thermal cracking

### Thermal Intensity/Uniformity
- Increased casting temperature consistency when pouring metals to make sure metal properties aren’t adversely affected
- Improved consistency and robustness of induction heat treating to ensure uniform part characteristics and properties
- Hybrid rapid infrared superheating furnace for treatment of aluminum alloys
- Induction coils that make optimum use of the electromagnetic field distribution for heating
- Improved high-temperature seal materials and seal designs
- Low-density, low-permeability insulation

### Enabling Support
- Demonstrations of infrared heating processes to increase understanding of how it works and its energy-saving abilities
- Guidelines for the use of intermetallic materials in furnace hardware and fixturing applications
- Understanding of the threshold conditions of fouling with the chemical composition of crude to determine the effectiveness of mitigation methods for various crude blending processes
- Better understanding of heat transfer limits in glass, both in the furnace and in forming

### Recent or Current Work

#### Alternate/Improved Heating Methods
- Industrial-scale high magnetic field processing and thermomagnetic field processing facility with an integrated induction heating and quenching capability (Oak Ridge National Laboratory)
- Advanced vacuum furnace design with a 15-bar quenching system and a full human-machine interface data retrieval control package to improve the hardness and corrosion resistance of stainless steel (Seco-Warwick Corp.)
<table>
<thead>
<tr>
<th>Technology</th>
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<tbody>
<tr>
<td>• Easycoil: flexible induction heating coil for large, oddly shaped parts that cannot be heated with a traditional copper coil (Ambrell)</td>
</tr>
<tr>
<td>• Laser surface modification techniques to enhance a material’s resistance to the detrimental effects of corrosion, abrasion, and wear (University of North Texas)</td>
</tr>
<tr>
<td>• Flash processing of steel to produce high strength and high ductility (Ohio State University, University of Tennessee, SFP Works LLC)</td>
</tr>
<tr>
<td>• Constant oxygen range across the entire firing range of a boiler using controls and sensors to improve efficiency (Cleaver-Brooks Inc.)</td>
</tr>
<tr>
<td>• Heat treating with diode lasers to enable lighter and stiffer constructions, reduced process steps, and high reproducibility (Laserline GmbH)</td>
</tr>
<tr>
<td>• In situ oxidation of precursor ferritic stainless steel powders using a unique gas atomization reaction synthesis technique (National Energy Technology Laboratory)</td>
</tr>
<tr>
<td>• Powder metal manufacturing technology to custom engineer novel titanium compositions and structures with new and useful combinations of properties, not producible by traditional melt processing (International Titanium Association)</td>
</tr>
<tr>
<td>• Foam injection molding using nitrogen and carbon dioxide as co-blowing agents to improve the morphology and mechanical properties of melts (University of Wisconsin)</td>
</tr>
<tr>
<td>• Using additives in the casting process to introduce characteristics to Nafion membranes that enable the fabrication of ionic polymer-metal composite actuators with high conductivity and output force (Xi’an Jiaotong University)</td>
</tr>
<tr>
<td>• Low-cost, energy-efficient, zero-emissions process for making magnesium (INFINIUM)</td>
</tr>
<tr>
<td>• Batch integral quench furnace technologies that maintain temperature uniformity and are designed to provide uniform quench flow velocities with minimum spread (Surface Combustion)</td>
</tr>
<tr>
<td>• Multilayer Feeder Furnace: energy-efficient modular furnace with automation for press hardening (AP&amp;T North America)</td>
</tr>
<tr>
<td>• Titanium-based catalyst that will enable a more efficient magnesium extraction process and should cut magnesium production costs in half (Pacific Northwest National Laboratory)</td>
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### Processing Speed and Step Elimination

<table>
<thead>
<tr>
<th>Technology</th>
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<tbody>
<tr>
<td>• Integration of heat treating directly into the machining production line using flat-panel radiators (ALD Vacuum Technologies)</td>
</tr>
<tr>
<td>• Three-step heat treat process to austenite condition, in situ cool, and bright age harden 17-7 precipitation hardenable (PH) stainless steel in a vacuum furnace without breaking vacuum (Solar Atmospheres)</td>
</tr>
<tr>
<td>• Vacuum induction degassing (VID) furnace that allows for meltdown, vacuum refining, and pouring under inert gas (ALD Vacuum Technologies)</td>
</tr>
<tr>
<td>• Increased use of radio frequency identification to drive efficiency and product quality (OATSystems)</td>
</tr>
<tr>
<td>• Torque amplification analysis program to help mills process tougher alloys, increase output with thicker slabs or higher speeds, protect against cold-end slabs, or mitigate torsional vibration (Emerson Power Transmission Solutions)</td>
</tr>
<tr>
<td>• Equipment that offers continuous quality control and repairing for reinforced thermoplastic pipes during the manufacturing process (Element Hitchin)</td>
</tr>
<tr>
<td>• Abrasive disc brushes that automate the deburring process while delivering an ideal surface finish to non-ferrous, cast iron, mild steel and ductile iron, stainless and alloy steels, titanium, and high nickel alloys (Orange Vise Co.)</td>
</tr>
</tbody>
</table>
- Contact elements designed to facilitate seamless plastics injection mold changes without typical sensor dismount or removal requirements, minimizing downtime and increasing throughput capabilities (Kistler)

**Thermal Intensity/Uniformity**
- Rotating process added to induction hardening process to provide uniform heating (Inductoheat)

**Enabling Support**
- Techniques that will lead to improvements in surface cleanliness of heat treated parts, surface cleaning equipment design, and in the development and use of alternative (green and cost effective) cleaning fluids and processes (Worcester Polytechnic Institute)
- Aging cycle optimization for aluminum alloys based on dimensional stability, yield strength requirements, and heat treatment costs (Worcester Polytechnic Institute)
- Plasma display panel recycling technologies that recover rare earth phosphors and indium (Worcester Polytechnic Institute)
Energy and Emissions Reduction Technology

More stringent environmental standards and regulations necessitate advanced energy 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.

Key Opportunities in Thermal Manufacturing

- 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

The following table outlines some of the current needs and opportunities for energy and emissions reduction technology in thermal manufacturing and the recent and current work being conducted in this area based on a selective literature review.

Table 5: Current State of Energy and Emissions Reduction Technology in Thermal Manufacturing

<table>
<thead>
<tr>
<th>Needs and Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
</tr>
<tr>
<td>• Improved seals on oven doors and oven charging ports atop the battery to reduce gas emissions</td>
</tr>
<tr>
<td>• Cost-effective methods for filtering nitrogen from ambient air for combustion systems</td>
</tr>
<tr>
<td>• Processes to minimize solid waste and wastewater production</td>
</tr>
<tr>
<td>• Integration of a predictive emissions model with a process control model to allow both process optimization and emissions minimization</td>
</tr>
<tr>
<td><strong>New/Alternative Equipment</strong></td>
</tr>
<tr>
<td>• Cost-effective reliable means for detecting leaks in pipes, valves, and equipment in petroleum refineries to reduce fugitive emissions</td>
</tr>
<tr>
<td>• Alternative quenchants to oil</td>
</tr>
<tr>
<td>• Alternative to nitrogen dioxide and nitrates, copernicium and barium salts, and solvent cleaners</td>
</tr>
<tr>
<td>• Effective options for controlling fine particulate (&lt;10 microns) emissions for a wide variety of process stream conditions</td>
</tr>
<tr>
<td>• New low-cost sensing techniques and processes to reduce volatile organic compounds</td>
</tr>
<tr>
<td>• Heating technology and equipment with higher heat transfer rates including plasma and induction processing</td>
</tr>
<tr>
<td>• Use of high-velocity impingement to increase the rate of heat transfer</td>
</tr>
<tr>
<td><strong>Emissions Reduction Technologies</strong></td>
</tr>
<tr>
<td>• Post-combustion chemical absorption and membrane technologies</td>
</tr>
<tr>
<td>• Carbonate looping as a potential retrofit option in the cement industry</td>
</tr>
</tbody>
</table>
• Reuse of deactivated sorbents from power plants as a secondary raw material in cement kilns

Waste Heat Reduction or Recovery
• More compact heat exchanger technology
• Improved holding furnace technology to reduce heat loss during materials transfer
• More cost-effective Seebeck couples with a higher figure of merit
• A pollution control system for electric induction furnaces and gas-fired furnaces that separates out the pollution without sacrificing thermal energy, allowing heat to be recuperated for heating floors and water
• Heat sinks for small-scale, non-continuous food processing equipment
• High-temperature cascading heat pump to recover all energy

Recent or Current Work

New/Alternative Equipment
• Kiln technology that works in combination with lower-firing materials to cut energy costs for ceramics producers by up to 30% and reduce carbon emissions (Ceram)
• Continuous, zero-toxic-emission system that converts non-recycled plastics into crude oil and costs a quarter the price of other systems to run, while producing greater yields (Massachusetts Institute of Technology)
• Pure Oxygen Anode technology that enables three to five times higher production of aluminum per footprint than conventional processes, with virtually no emissions (Infinium Metals Inc.)
• Use of low-energy electron beams from particle accelerators to sterilize packaging, enabling lighter-weight and new packaging concepts, reducing waste, and reducing energy consumption during transport (Advanced Electron Beams)
• Passive high-temperature sealing device that acts as a high-temperature shutoff valve for pipes and ducts (Savannah River Nuclear Solutions)
• High-efficiency graphite hot zone (Solar Manufacturing)

Emissions Reduction Technologies
• Catalytic oxidation and catalytic reduction to control emissions by chemically transforming pollutants (American Institutes of Chemical Engineers)
• Bio-catalyst that strips carbon from liquefied gas (e.g., methane) and rearranges it into long chain plastic molecules (Newlight Technologies)
• New materials based on a pre-existing combination of copper, bipyridine \((\text{C}_5\text{H}_4\text{N})_2\), and hexafluorosilicate \((\text{SiF}_6^{2-})\) anions to capture carbon dioxide from combustion gases (University of South Florida and King Abdullah University of Science and Technology)
• Carbon Capture Simulation Initiative (CCSI): partnership among national laboratories, industry, and academic institutions to develop and deploy state-of-the-art computational modeling and simulation tools to accelerate the development of carbon capture technologies (National Energy Technology Laboratory)
• Single-component CO\(_2\)-binding organic liquids (CO2BOLs)—Alkanolguanidines and alkanolamidines—for post combustion CO\(_2\) capture (Pacific Northwest National Laboratory)

Waste Heat Reduction or Recovery
• High-performance thermoelectric materials that use liquid-like copper ions to carry electric current around a solid selenium crystal lattice (Chinese Academy of Science’s Shanghai Institute of Ceramics)
- Placement of nanocrystals of rock salt into lead telluride, creating a material that can more efficiently harness electricity from heat-generating items such as vehicle exhaust systems, industrial processes and equipment, and sun light (Northwestern University)
- Gravity-film heat exchanger to recover heat from wastewater (Doucette Industries)
- Microchannel heat exchangers that are smaller in size and have proven more effective than conventional clamshell and tubular heat exchangers (Pacific Northwest National Laboratory)
Automation and Robotics

Automation and robotics integrate mechanical engineering, electrical engineering, and computer science to streamline manufacturing processes and improve precision, processing speed, dexterity, and mobility.

Key Opportunities in Thermal Manufacturing

- Increased safety by reducing the need for humans to interface with hot equipment and materials
- Reduced human management and error
- 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

The following table outlines some of the current needs and opportunities for automation and robotics in thermal manufacturing and the recent and current work being conducted in this area based on a selective literature review.

Table 6: Current State of Automation and Robotics in Thermal Manufacturing

<table>
<thead>
<tr>
<th>Needs and Opportunities</th>
<th>Recent or Current Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Updated standards and specifications in end-use industries (e.g., aerospace) to enable increased integration of process control and automation</td>
<td>• EASYHEAT induction heating system with robotics (Ambrell Inc. and Nutek Industrial Systems)</td>
</tr>
<tr>
<td>• A wireless hub that can get real-time reporting to employees throughout a plant</td>
<td>• Vacuum heat-treating furnace-loading system that eliminates the need to disconnect the heating elements each time the system is used (Ipsen)</td>
</tr>
<tr>
<td>• Increased use of control systems that can better manage energy use and reduce energy spikes that result in electricity demand charges</td>
<td>• Robot automation systems for mold heat treatment with off-line programming (SAE International)</td>
</tr>
<tr>
<td>• Automation of forging lubricant application to improve environmental performance</td>
<td>• Miniature robotic bees that may be able to be produced cheaply by the thousands to take the place of a single expensive robot (Vibrant Research)</td>
</tr>
<tr>
<td>• Control system to allow equipment to assess and respond to changing process requirements and evaluate fuel options in real time</td>
<td>• Fast-response, closed-loop diecast shot cylinder controls</td>
</tr>
<tr>
<td>• Increased use of robotic analytical units on the floor and disciplined electrode changing practices for electric arc furnaces</td>
<td>• Increased use of control systems that can better manage energy use and reduce energy spikes that result in electricity demand charges</td>
</tr>
<tr>
<td>• Methods to relate surface quality measurements to the processing history of the material</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6: 3-D printing apparatus
• Arm sensors that read a human’s muscle movements, allowing robots to correct their own movements to improve manufacturing safety and efficiency (Georgia Institute of Technology)
• Automated Determination of Root Cause: uses a big data technique to determine the most likely root cause of upsets in a control loop and eliminate several costly and time-consuming steps in the problem-solving process (Metso Automation USA)
• Automated guided vehicles that serve as unmanned pallet trucks and tow tractors (American Society of Mechanical Engineers)
• Robotics-based laser cladding system that can apply welded deposits on multi-dimensional surfaces in a single cladding run (Sulzer Metco and MetroClad)
• E-Whisker tactile sensors from composite films of carbon nanotubes and silver nanoparticles that will give robots new abilities to “see” and “feel” their surrounding environment (Lawrence Berkeley National Laboratory and the University of California)
• Sensor and control system that can operate a highly articulated robotic arm without striking obstacles (Pacific Northwest National Laboratory)
• Sequential Modular Architecture for Robotics and Teleoperation (SMART): real-time control system coupled with commercially available robotic platforms to perform complex, cooperative behaviors (Sandia National Laboratories)
• Automated sorting of non-ferrous metals using X-ray and induction sensors (RWTH Aachen)
• Improved robot path accuracy by implementing real-time closed loop positional control of the robot end effector using a high-speed, high-accuracy metrology device (Manufacturing Technology Centre, England)
Advanced Materials

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

Key Opportunities in Thermal Manufacturing

- 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

The following table outlines some of the current needs and opportunities for advanced materials in thermal manufacturing and the recent and current work being conducted in this area based on a selective literature review.

Table 7: Current State of Advanced Materials in Thermal Manufacturing

<table>
<thead>
<tr>
<th>Needs and Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
</tr>
<tr>
<td>- Return on investment communicated in terms of weight reduction, longer product life, improved distortion, and energy savings</td>
</tr>
<tr>
<td>- Materials technologies that can be disassembled to allow critical non-renewable resources to be reused</td>
</tr>
<tr>
<td>- Method to control or analyze the introduction of deleterious elements or contaminants (e.g., antimony, phosphorus, sulfur) from recycled materials</td>
</tr>
<tr>
<td><strong>End Use Materials</strong></td>
</tr>
<tr>
<td>- Advanced surface engineering processes (e.g., carbonnealing) that coat inexpensive materials with more expensive ones with the desired materials properties</td>
</tr>
<tr>
<td>- Use of geopolymers (aluminosilicate base) in cement production to reduce the cost and carbon footprint of cement</td>
</tr>
<tr>
<td>- Paper that contains embedded phase-change materials that act as a heat source and heat sink during the drying process</td>
</tr>
<tr>
<td>- Aluminum and magnesium castings with corrosion-inhibiting properties and high-quality ductile iron castings</td>
</tr>
<tr>
<td>- Materials that adhere to dies and do not have to be replaced each cycle</td>
</tr>
<tr>
<td>- Metallic glasses and materials with ultra-fine structures for casting</td>
</tr>
<tr>
<td>- Phase diagrams of rapidly austenitized materials</td>
</tr>
<tr>
<td>- High-temperature (1,850°F) carburizing steels with grain growth resistance</td>
</tr>
</tbody>
</table>

Figure 7: Scanning electron microscope image of metal foam
State of Advanced Manufacturing Technology and Process Developments in Thermal Manufacturing

- Fine powders for metal injection molding (MIM) and micro-MIM
- More compact powders for electrical and electromagnetic applications
- New types of iron ore pellets more suitable for blast furnaces with high levels of coal injection
- Alloys and composites that will enable stronger and thinner-wall castings

Materials Handling & Process Heating Equipment

- Baskets and racking (e.g., carbon baskets) with lower thermal mass to decrease energy use and cost
- Ceramic ladles that are more insulative and have a lower heat capacity to reduce heat loss when transferring or pouring metals
- Pulp/paper presses with moisture-absorbing materials, decreasing the amount of moisture that needs to be removed during drying
- Food processing belts with embedded phase-change materials to improve efficiency of the corresponding drying process
- Improved temperature control of ceramic refractory shells used for stainless steel investment casting
- Material surfaces that withstand high surface temperatures and do not react with glass volatiles
- Stirring and sheathing materials for sensors and camera shields that can withstand furnace environments for 10+ years
- Improved glass mold materials for container manufacturing, improved lehr roll materials that are self-lubricating and do not stain the glass surface, and blades used in shearing operations that do not require lubrication
- New non-metallic pattern materials for casting applications
- Sand molding or core systems with low or no emissions
- Tundish and mold fluxes that achieve the proper fusing temperature and fluidity and are not corrosive to the refractories, while providing protection from reoxidation and the ability to capture inclusions
- New materials for medium-temperature thermal storage, between 100°C and 300°C, such as phase change, sorption, and thermochemical materials
- New sorption material coatings for heat exchanger surfaces and new heat and mass transfer systems
- Refractory-coated tubes to enable more robust, continuous monitoring of molten metal temperature

Recent or Current Work

General

- Multi-agency initiative designed to create a new era of policy, resources, and infrastructure that support U.S. institutions in the effort to discover, manufacture, and deploy advanced materials twice as fast, at a fraction of the cost (Materials Genome Initiative)
- New thermoelectric material that can convert 15% to 20% of waste heat to useful electricity (Northwestern University)
- High-velocity laser-accelerated deposition using advanced lasers to produce protective coatings with ultra-high-strength, explosively bonded interfaces that prevent corrosion, wear, and other modes of degradation in extreme environments (Lawrence Livermore National Laboratory)
- Portable aluminum deposition system (PADS) that uses newly developed ionic liquid electrolytes and a novel electrolyte dispensing mechanism to deposit aluminum, allowing
manufacturers to safely conduct aluminum deposition in open atmosphere (Oak Ridge National Laboratory)

End Use Materials

- **P x n–type transverse thermoelectric (p-cross-n) with p-type Seebeck in one direction and n-type orthogonal: a narrow gap semiconductor with both electrons and holes carrying comparable magnitudes of orthogonally directed heat currents (Argonne National Laboratory)**
- **Aluminum-based die casting alloys with either 8-10% higher yield strength or 20-30% higher elongation than A380 aluminum alloy so as to produce a 10-12% improvement in the alloy’s quality index (Worcester Polytechnic Institute)**
- **Carbon fiber from C-lignin, a linear polymer found in plants (University of North Texas)**
- **Designing new cobalt superalloys (National Institute of Standards and Technology)**
- **Alternate eutectic systems other than aluminum-silicon for aluminum casting alloys (Worcester Polytechnic Institute)**
- **Using a corrugated, specially formulated paper-derived carbon-based template to easily and flexibly obtain a ceramic honeycomb topology through a number of thermochemical routes (Georgia Tech)**
- **Thermoplastic composite materials for aerospace structural metal replacement in complex-shape applications (Greene, Tweed, and Aerolia)**
- **Alloy design for high-density metallic glasses/composites with high toughness (Case Western University)**
- **Curing functional inks with a toolset that delivers intense pulses of light from large flashlamps for short periods of time (Novacentrix)**
- **Double-sided tin nanowires array for high performance thermal interface materials (Georgia Tech)**
- **Advanced nanomaterials**
  - Chemical anchoring of carbon nanotube structures (Georgia Tech)
  - Nano-additives that incorporate time-release attributes similar to those used in pharmaceutical drug formulation and design to reduce friction and wear and prevent scuffing (Argonne National Laboratory)
  - Carbon nanotube arrays that yield extremely high thermal properties and can be configured in vertically aligned multi-walled, double-walled, few-walled, or single-walled carbon nanotubes (Oak Ridge National Laboratory)
  - Aluminum nanocomposites for elevated temperature applications (Worcester Polytechnic Institute)
- **Advanced composites**
  - Self-healing 3D vascular system that allows fiber-reinforced plastic composite materials to heal autonomously and repeatedly (University of Illinois)
  - 3D woven composites for metallic and 2D composite materials substitution (CFM International)
  - Multidimensionally crosslinkable rigid-rod benzobisazole polymer fibers with high tensile strength and modulus (Georgia Tech)
  - AlMgB14-based composites with high-wear resistance through powder metallurgy processing (Ames Laboratory)
  - Titanium/graphene composite with a greater range of applications than titanium alone produced using advanced powder metallurgy (Oak Ridge National Laboratory)
  - Metallosupramolecular polymers capable of becoming a supple liquid that fills crevasses and gaps left by scrapes and scuffs when placed under ultraviolet light for
less than a minute and then resolidifying (University of Arizona and Rensselaer Polytechnic Institute)

**Materials Handling & Process Heating Equipment**

- Stability enhancement of paraffin/exfoliated graphite nanoplatelet composites for latent heat thermal storage systems (Georgia Tech)
- Low-stress conformal coatings for microelectromechanical-system-based multi-chip module encapsulation systems (Georgia Tech)
- Innovative corrosion inhibitors for electrically conductive adhesives on lead-free surfaces (Georgia Tech)
- Hydrophobic coating material to improve efficiency of steam condensation (Massachusetts Institute of Technology)
State of Advanced Manufacturing Technology and Process Developments in Thermal Manufacturing

Bibliography

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- Bill Disler, AFC-Holcroft
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- Bob Gaster, John Deere
- Dan Herring, The Herring Group
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- Peter Hushek, Phoenix Heat Treating
- Joseph Pickens, Consultant
- Anoush Poursartip, University of British Columbia
- Tom Prucha, American Foundry Society
- Philip Ross, Glass Industry Consulting International
- Steve Sikirica, DOE Advanced Manufacturing Office
- John Speer, Colorado School of Mines
- Michael Stowe, Advanced Energy
- David Williams, ASI International
- Jamal Yagoobi, WPI
- Chenn Zhou, Purdue University Calumet

Roadmaps and Sources for Needs and Opportunities


State of Advanced Manufacturing Technology and Process Developments in Thermal Manufacturing


### Relevant Organizations Searched for Current or Recent Work

- Advanced Research Projects Agency – Energy
- Aluminum Association
- Aerospace Industries Association
- Alliance of Automobile Manufacturing
- American Ceramics Society
- American Chemistry Council
- American Coatings Association
- American Composites Manufacturers Association
- American Forest and Paper Association
- American Fuel & Petrochemical Manufacturers
- American Gear Manufacturers Association
- American Institute of Chemical Engineers
- American Iron and Steel Institute
- American Society of Mechanical Engineers
- ASM International
- ASM International Heat Treating Society
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Association for Iron and Steel Technology
Association for Manufacturing Excellence
Association of Equipment Manufacturers
Case Western Reserve University
Chemical Coater Associations International
Colorado School of Mines
Advanced Steel Processing and Products Research Center
Defense Advanced Research Projects Agency
Fabricators & Manufacturers Association, International
Farm Equipment Manufacturers Association
Food Processing Suppliers Association
Forging Industry Association
Georgia Tech
Glass Association of North America
Industrial Heating Equipment Association
International Federation for Heat Treatment and Surface Engineering
International Titanium Association
Investment Casting Institute
Manufacturing Institutes
Materials Genome Initiative
Medical Device Manufacturers Association
Metal Treating Institute
National Association of Manufacturers
National Center for Manufacturing Sciences
National Glass Association
National Laboratories
  • Ames Laboratory
  • Argonne National Laboratory
  • Brookhaven National Laboratory
  • Idaho National Laboratory
  • Lawrence Berkeley National Laboratory
  • Lawrence Livermore National Laboratory
  • Los Alamos National Laboratory
  • National Energy Technology Laboratory
  • National Renewable Energy Laboratory
  • Oak Ridge National Laboratory
  • Pacific Northwest National Laboratory
  • Princeton Plasma Physics Laboratory
  • Sandia National Laboratory

National Marine Manufacturers Association
National Network for Manufacturing Innovation
National Science Foundation
National Institute of Science and Technology
Rubber Manufacturers Association
RWth Aachen
Society for Advancement of Materials and Process Engineering
Society for Modeling & Simulation International
Society of Automotive Engineers
Society of Plastics Engineers
Steel Manufacturers Association
Technological Association of the Pulp and Paper Industry (TAPPI)
The Minerals, Metals and Materials Society
United States Council for Automotive Research
University of Illinois at Urbana-Champaign
World Steel Association
Worcester Polytechnic Institute - Center for Heat Treating Excellence (CHTE), Advanced Casting Research Center (ACRC), Center for Resource Recovery and Recycling (CR³)