Heat Treating Society
An Affiliate Society of ASM International

ASM Heat Treating Society's
1999 Research & Development Plan

R&D

ASM INTERNATIONAL

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A Letter from the Chairman

Dear Colleague,

I am pleased to present the ASM Heat Treating Society's 1999 Research & Development Plan. This Plan is the next logical step in work that has been ongoing since ASM International began in 1913 as the "Steel Treaters Club."

In 1994, ASM formed the Heat Treating Society (HTS), composed of members of the heat treating community. Since then, committees, such as Immediate Needs, R&D, Technology and Programming, and Education, have worked to meet member needs. The charter of the R&D Committee is "to identify future technical needs of the heat treating industry and develop the mechanisms to plan, fund, and implement R&D programs to meet these needs, and to transfer the results of these programs to industry."

The newly issued 1999 Research & Development Plan continues to support this charter. It builds on results of the Department of Energy/Office of Industrial Technology commitment to work with the Metal Treating Institute (MTI) and HTS to create a vision of the future, and to establish a roadmap of technology advances to achieve that vision. This commitment came as part of the DOE/OIT Industry of the Future program, intended to improve global competitiveness of the basic manufacturing industries in the United States, while at the same time reducing energy consumption and waste generation.

The program began with a February 1996 meeting of 20 leaders of the heat treating community, including commercial and captive heat treaters, manufacturers, and suppliers. Their ideas were summarized in the Heat Treating Industry Vision 2020, a representation of an ideal future for the industry and the problems that must be solved to ensure that future. It includes not only technical challenges, but also those involving profitability, the work force, government regulations, product liability, customer/industry relationships, and the structure of the industry.

A second group of industry representatives met in February 1997 and focused on the specific research and development activities that must be undertaken. The result of that meeting was the "Report of the Heat Treating Technology Roadmap Workshop." In this report, needs in three areas were identified: Equipment and Hardware Materials, Processes and Heat Treated Materials, and Energy and Environment. In each of these areas, technology challenges were ranked relative to potential payoff and risk. Many projects were identified — too many to take on at one time.

We recognize that projects must be prioritized to achieve the Vision 2020. Otherwise, it is unlikely that we will make the technology advances that will drive competitiveness and profitability. We recognize, too, the importance and power of collaborative efforts, as the heat treating industry combines forces with thermally dependent industries to leverage research activities. The 1999 R&D Plan is intended as a first step in these efforts. It attempts to focus on a subset of the technical research that will help us ultimately achieve the Vision 2020.

I am grateful for the efforts of members of the HTS R&D Committee, as well as the many persons outside the Committee who have unselfishly given their time to make this document possible, and hence, have been part of the effort to achieve the Vision 2020.

Robert J. Gaster
Chairman, HTS R&D Committee

The ASM Heat Treating Society 1999 Research & Development Plan

Executive Summary

The ASM Heat Treating Society 1999 Research & Development Plan was developed by the 1997-1998 Heat Treating Society (HTS) R&D Committee and is based on the HTS Roadmap and Vision 2020 documents. The HTS 1999 R&D Plan addresses the technological issues relating to achieving the Vision 2020 in an organized manner.

This document represents an implementation plan to achieve the high priority research items needed to accomplish the Vision 2020. It is intended that this plan will be updated and refined as new technologies emerge, as input is received from members, and as targeted research in this plan is completed.

This Plan does not address all the research issues identified in the Roadmap and Vision 2020 documents. It addresses only those that the R&D Committee felt would move the Heat Treating Industry closer to the Vision 2020 goals in the most expeditious manner possible. The priority research areas this plan addresses are:

Attain Higher Operating Temperatures

- Improved Heating Source Materials
- Improved Heating Source Configurations
- Improved Convection Sources
- Improved Insulation Materials

Develop Alternative Hardware

- Development and Application of Accelerated Heating Technologies
- Cost Reduction of Bath, Fluidized, and Vacuum Equipment

Develop Integrated Process Models

- Quenching Models
- Electromagnetic Models
- Mechanical Models
- Transformation Databases

Develop Real-Time Process/Predictive Sensors

- Sensors Controlling Systems with Multiple Chemical and Physical Inputs
- Integrate Quantitative Sensor Inputs
- Develop Real-Time Case-Carbon Sensors
- Develop Real-Time Sensors to Quantify Heat Transfer

Develop New Heat Treatable Materials

- For High Temperature Processing
- For Rapid Heat Treating Technology

Reduce Energy Consumption in Heat Treating Processes

- Map Energy Consumption of Commercial and Captive Heat Treating Facilities
- Increase Heat Transfer Rates, Reduce Process Times and Reduce Energy Losses
- Develop Low-Cost Heat Recovery Systems
- Develop Processes to Reduce Energy
- Develop Hybrid Gas/Electric Systems to Minimize Energy Consumption

Attain Zero Environmental Impact

- Develop Pollution Prevention and Control Strategies
- Identify Alternative Quenchants to Oil
- Identify Alternative Salts to NO_2, NO_3, CN, Ba; and Alternative Solvent Cleaners
- Reduce CO and NO_x emissions

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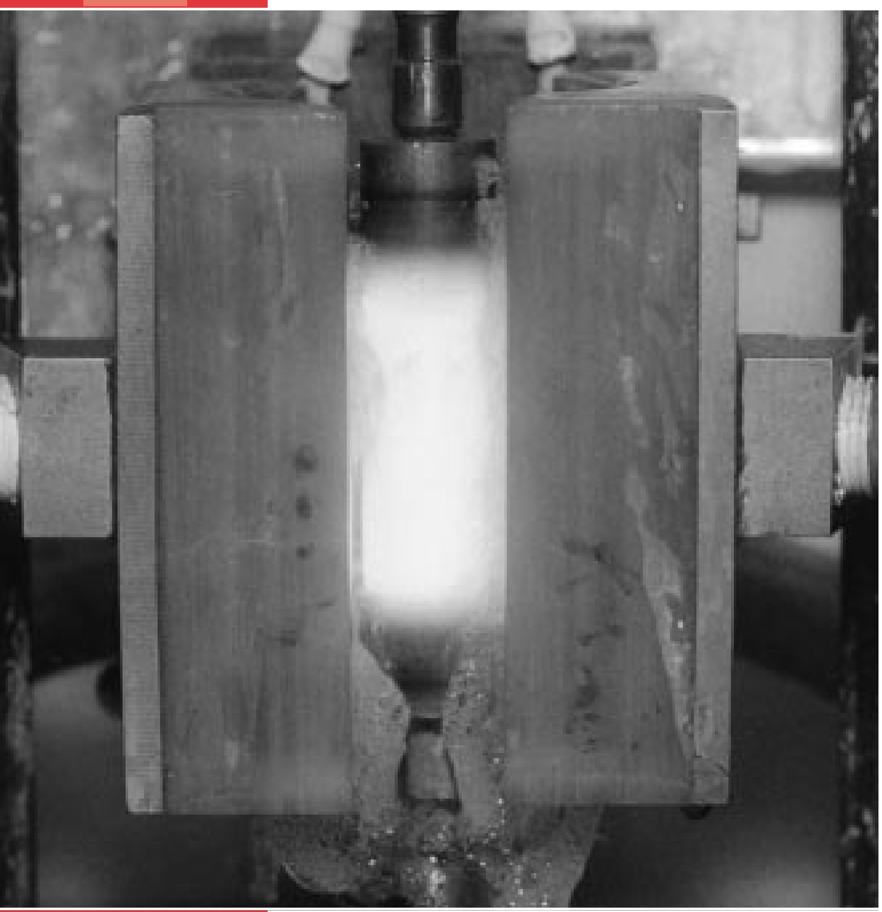
Approach

Heat treating is a vital process in the global effort to produce stronger, lighter, more durable parts at lower cost. The identification, quantification, and implementation of research to develop enabling technologies is critical to the success of the Heat Treating Industry 2020 Vision. ASM must proactively structure a framework for action with limited internal resources, and must leverage these through collaborative activities to reach our vision. The following steps are planned:

- *Implement* a comprehensive plan to define key technology goals: define and validate industry technology needs; establish a priority rating of R&D technology needs; and identify and review opportunities in existing R&D projects.
- *Review* other thermal manufacturing technology R&D activities for synergistic opportunities.
- *Define* cross-cutting collaborative opportunities at the working level to attract optimum industry support.
- *Deliver* results in a timely fashion to promote support from the heat treating industry and others.



A metal automotive part heats to a glow in an induction heating coil at Sandia National Laboratories, where a closed-loop, real-time process controller for induction hardening is being developed.

Photo courtesy of Sandia National Laboratories.

Background and Industry Needs

Prior to choosing, funding, and conducting relevant heat treating R&D projects, the needs of the heat treating industry must be determined. These needs have been identified on four occasions in recent years: the ASM Heat Treating Society Immediate Needs Committee surveys of 1995 and 1996, the ASM Heat Treating Society R&D Committee Survey of 1996, and the Heat Treating Technology Roadmap Workshop in 1997.

The industrial needs cited in this R&D Plan are the result of the needs identified on these four occasions, especially the Technology Roadmap Workshop.

HEAT TREATING INDUSTRY 2020 VISION

Prior to the Technology Roadmap Workshop, heat treating industry executives identified long-term technology needs and described their view of the ideal future. ASM International published the vision that resulted from those discussions as the *Heat Treating Industry Vision 2020.* It describes the changes in both the structure of the industry and in heat treating processes that will be required to reduce energy consumption, operating costs, and environmental impact by the year 2020.

Performance Targets

Energy

- Reduce energy consumption by 80%
- Improve insulation (half needed for twice the capability)

Environment

- Achieve zero emissions

Productivity and Quality

- Reduce process times by 50%
- Reduce production costs by 75%
- Increase furnace life ten-fold
- Reduce the price of furnaces by 50%
- Achieve zero distortion and maximum uniformity in heat treated parts

Industry Performance

- Return 25% on assets
- Create ten-year partnerships with customers

The Technology Roadmap Workshop participants identified R&D project topics to move the heat treating industry toward vision goals. Topics were evaluated by priority, risk, benefit, and time for completion. These research needs are shown in the table that follows. The research topics described in the following sections of this Plan were developed based on these needs.

Research Needs Identified in Heat Treating Technology Roadmap Workshop, 6-7 February 1997

Heat Treating Processes

1. High-temperature carburizing processes (>1850° F, 1010° C) to shorten cycle.
2. Nitriding processes to shorten cycles.
3. Heat treatments that allow use of lower cost alloys.
4. Better understanding of aging and tempering processes.
5. New heat treating processes for advanced materials such as intermetallic materials and metal-matrix composites.
6. Accelerated-heating (high heat transfer) techniques and equipment.

Quenching Technology

1. Selective quenching methods.
2. Models for heat transfer behavior in quench baths that will ensure uniform cooling of a range of loads.
3. Water and inert-gas quenching methods to emulate salt and oil quenching.
4. Quenching media that are nonpolluting and safe to use.
5. Improved quenching systems for aluminum parts.
6. Probe for measuring heat transfer characteristics in production quench baths.

Heat Treating Equipment

1. Preventive maintenance models for heat treating furnaces and auxiliary equipment.
2. Improved systems for surveying furnaces to military specifications (MIL Specs).
3. Alternative heat sources for furnaces.
4. Improved burner designs for fuel-fired furnaces.
5. Improved methods and equipment for generating heat treating atmospheres.
6. Improved alloys that extend the life and operating temperature range of furnace hardware and fixtures.
7. Guidelines for the use of intermetallic materials in furnace hardware and fixturing applications.
8. Heat treating equipment for one-piece flow (batches of one) to support synchronous manufacturing.
9. Induction coils that make optimum use of the electromagnetic field distribution for heating.
10. New furnace insulation and furnace structural materials.

Heat Treatable Materials

1. Lower cost heat treatable alloys.
2. Alloys that enable some heat treating operations to be eliminated (to shorten cycle and/or save energy).
3. Alloys optimized for specific processes, such as high-temperature carburizing or induction hardening.

Process Control/Materials Inspection Instrumentation

1. Oxygen probes with improved resistance to carbon deposits (sooting).
2. Direct, real-time method of measuring carbon in the heat treated part.
3. Method to accurately, nondestructively, and economically measure residual stress after heat treating.
4. Sensor to determine whether a part's surface is clean enough to be correctly carburized.

Process Modeling

1. Life-cycle analysis model that evaluates the use of heat treatments.
2. How steel-mill processing affects material transformation kinetics.
3. Microstructure response models based on alloy composition, atmosphere, temperature, and time.
4. Models to predict distortion and residual stress profiles.
5. Database of thermal and mechanical properties up to and including heat treating temperatures.
6. Understanding of thermochemical boundary conditions in furnaces.
7. Models for continuous cooling transformations (CCT) of heat treatable alloys.
8. Models for continuous heating transformations (CHT) of heat treatable alloys.

Software Packages

1. User-friendly software for selecting materials and processes, including heat treating methods.
2. Predictive software that heat treaters can use to compare and select furnace equipment from different suppliers (a standard method of predicting furnace variability is incorporated).

Environment

1. Improved parts cleaning and degreasing methods, equipment, and media.
2. Cost-effective pollution control and waste treatment technology specific to the heat treating industry.

Energy

1. Low-cost technologies to recover low-grade heat.
2. Techniques that eliminate reheating or reduce the number of required reheating operations.
3. Improved high-temperature gas-recirculation systems.
4. Oxygen-enriched combustion developments.
5. A life-cycle approach to the calculation of energy losses due to scrap/rejects.

Clear general needs were often identified by several of the work groups. These include:

1. Heat treating processes that allow a shorter cycle and require lower-cost equipment and associated materials. This also includes alternative heat sources, more timely equipment maintenance, and more effective insulation.
2. Alternative quenching media that are more environmentally friendly, and that transfer heat more efficiently.
3. Improved process sensors, including those for carbon content, residual stress, and cleanliness. Also, more advanced controls that can fully exploit these and other sensors.
4. Enhanced computer modeling of processes, which includes composition, distortion, resultant microstructure, and final properties.
5. Additional ways to recycle heat, eliminate reheating where possible, and reduce heat losses.
6. More effective dissemination of solutions to specific problems.

1999 Technology Plan

The following technology plan is an outgrowth of the report of the Heat Treating Technology Roadmap Workshop in Concord, Ohio on 6-7 February, 1997. This workshop set the stage for future research by defining the status of the heat treating industry, its related needs, and the research and development necessary to meet those needs. Subsequent R&D Plans will follow strategies developed at this meeting to achieve the Heat Treating Industry Vision 2020. The specific goals of the Vision 2020 that this Technology Plan addresses are:

1. Reduce energy consumption by 80%
2. Reduce process time by 50%
3. Reduce production costs by 75%
4. Achieve zero distortion and maximum uniformity in heat treated parts
5. Increase furnace life ten-fold
6. Reduce price of furnaces by 50%
7. Achieve zero emissions

The research of the 1999 Technology Plan naturally falls into three areas: (I) Equipment and Hardware Materials, (II) Processes and Heat Treated Materials, and (III) Energy and Environment.

Proposed Research

I. Heat Treating Equipment and Hardware Materials

All seven targets of the Vision 2020 listed in this Plan apply, in varying degrees, to heat treating equipment. Several directly depend on furnace equipment. However, to identify the initial R&D effort research areas, which includes possible funding sources, plan objectives, and a meaningful timeline for completion, the focus must be on the greatest initial need. The Technology Road Map workshop identified furnace heating efficiency as offering the greatest payback, least risk and it falls into the mid-term time frame of 3 to 10 years. Taking this into account, the R&D committee selected the following areas for development of heating efficiency:

Goal A: Achieve Higher Operating Temperatures
Goal B: Develop Alternative Hardware

Equipment and Hardware Materials
Goal A: Achieve Higher Operating Temperatures Depends on the development of:
• Improved Heating Source Materials
• Improved Heating Source Configuration
• Improved Convection Sources
• Improved Insulation Materials

A. Achieve Higher Operating Temperatures

- *Improved heating source materials:* For decades, alloy radiant tubes satisfied the needs of the heat treating industry in protective atmosphere processes. In straight tube applications (which compete with "U" tubes having twice the surface area), a higher temperature material was needed to raise the heat flux. This drove the development of mullite as a straight ceramic tube material and demonstrated the potential of a higher temperature alternative. Because of its improved thermal shock resistance, silicon carbide displaced mullite/alumina/silica as the material of choice for both straight and "U" tubes. However, silicon carbide and its composites are fragile. They do not have the cold-toughness property of heat resistant alloys which is required for trouble free installation and furnace maintenance. In addition, the high cost of silicon carbide is an obstacle to wide-spread acceptance. Further research is necessary to find a suitable cost-effective material having the ductility, workability, and thermal shock resistance of heat resistant alloy, and the high temperature strength of alumina. A simultaneous effort is required to improve combustion efficiency to reduce fuel consumption at higher temperatures.
- *Improved heating source configurations:* As shorter process times drive heating rates and process temperatures up, reducing distortion from thermal stresses will become more difficult. At elevated temperatures, the predominant heat transfer mode is high-energy radiation. To reduce thermal gradients, heat flux profiles must be as uniform as possible. The traditional radiant tube (straight or "U" shaped) is unable to supply uniform radiant energy initially and at high load temperatures; they don't have the required heat transfer area required for rapid convection heating below 760°C (1400°F). Because of this restriction, a new radiant component probably will take on a shape that increases the overall heat transfer area. As the heat source area increases, the energy per unit area decreases, resulting in uniform heating even at accelerated rates. These new configurations will require new materials capable of withstanding high temperatures and thermal shock. New configurations also may require changes in current burner technology.
- *Improved convection sources:* As process times become shorter, heating uniformly becomes more critical. While radiation plays an important role, the initial heating portion of the cycle determines the temperature deviation within a load and in individual components. A circulating fan distributes hot gas through the load providing the source of heat at lower temperatures. At higher temperatures, in the production environment where loads are densely packed, the fan provides the difference between acceptable and unacceptable temperature uniformity. Today's alloys lack the high-temperature creep strength required to operate fans at the higher rpms needed to force the gas through dense loads. Furthermore, at

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higher carburizing temperatures, increased carbon-diffusion rates in steels necessitate increased gas flow through dense loads (these rates are currently unobtainable). Fan volume and efficiency also suffer because of the simple shape forced on manufacturers because of the low-strength alloys used for fans. New high performance fan materials are required to overcome these deficiencies.

- *Improved insulation materials:* As heat treating temperatures rise, energy requirements increase; providing thinner, more efficient insulation materials can alter this trend. Many new insulation materials exist today, but they are not cost effective enough to be used in the heat treating industry. New materials must have the following characteristics: low thermal conductivity, be non-carbon absorbent, non-hazardous, non-shrinking, and economical.

Equipment and Hardware Materials
Goal B: Develop Alternative Hardware **Depends on:** • **Development and Application of Accelerated Heating Technologies** • **Cost Reduction of Bath, Fluidized, and Vacuum Equipment**

B. Develop Alternative Hardware

- *Overall cost reduction in bath, fluidized, and vacuum systems:* Salt bath systems will benefit from materials development relating to environmental friendliness, allowing their integration into cellular manufacturing and a related reduction in energy use. Particulate research will help integrate fluidized bed systems into manufacturing cells. Finally, environmentally friendly vacuum equipment will benefit from lower cost insulation, lower cost woven carbon/carbon products, and more economical pumping systems. The vacuum furnace's adaptability to high pressure gas quenching will continue to grow. However, available steels with adequate hardenability limit the heat-treatable part size. Higher pressures can provide some near-term improvement, but additional development in hydrogen as a cooling gas to increase heat-transfer rates and lower operating cost and less expensive high-horsepower fan motors will require development before this technology will be widely accepted. Steel suppliers hold an important stake in high pressure gas quenching. To fully use the low-distortion advantage of this technology, steel suppliers must provide cost-effective higher alloyed steels.

- *Development and application of accelerated heating technologies:* There have been many recent advancements in rapid heating technology such as induction and laser hardening. Induction and magnetic pulse hysteresis technologies have widespread application in deep-case processing. Rapid heating technologies that provide substantial reduction in energy consumption typically are environmentally friendly processes and enable the use of synchronous manufacturing. Development and application of accelerated heating technologies is important in aluminum heat treatment, even though aluminum has a high thermal conductivity. The main issue usually is temperature uniformity to avoid overheating and melting. Reliable, uniform rapid heating processes would have a direct impact on productivity, capacity, and energy reduction for aluminum heat treatment. This is especially important in heat treating automotive alloys where capacity currently is limited. However, there still are obstacles to widespread use of these processes. The major barriers include high cost of equipment, inability to achieve the desired combination of properties in the case and core, and the often higher materials and manufacturing costs for these processes.

II. Processes and Heat Treated Materials

Key technology needs include integrated process models, the ability to model significant phases of heat treating processes, interactive process controls, and detailed knowledge of optimum structure for specific process conditions for both ferrous and nonferrous heat treating. The R&D committee selected the following as initial high-priority areas for proposed research in Processes and Heat Treated Materials:

Goal A. Integrated process models

Goal B. Real-time sensor technology and process control

Goal C. New materials

Processes and Heat Treated Materials
Goal A: Integrated process models **Depends on development of:** • **Quenching models** • **Electromagnetic models** • **Mechanical models** • **Transformation databases**

A. Integrated process models

Integrated models for the entire heat-treatment process for both ferrous and non-ferrous materials have been identified as a top priority. Currently, most heat-treating procedures are based on the experience of the heat treater. Trial-and-error methods typically are the basis of the selection of component design and material and processing parameters. Often this results in a component that is functional but not optimized.

Processes with the highest need for modeling include carburizing, nitriding, furnace hardening, induction hardening, precipitation hardening, solution treating, and quenching. Processes such as induction hardening have so many variables that optimization is nearly impossible through trial and error. Integrated process models would enable heat-treat practitioners, manufacturing engineers, and component designers to work together to optimize the process for case depth, hardness, residual stresses, and distortion.

During the past ten years, there has been a concerted, worldwide effort to develop process simulation tools based on the finite element method (FEM) and computational fluid dynamics (CFD). Simulations for induction heat treatment, furnace heat treatment, and quenching processes have been developed. They include simulation codes from Europe, Asia, North America, and South America. Common attributes that must be predicted for complete simulations are:

1. Predict heat-up parameters:

- Furnace gas circulation (to understand how part placement in furnace impacts heat up).
- Heat generated by the electromagnetic field applied during the induction process, and the subsequent temperature distribution in the component.
- Phase transformations as a function of time and temperature.
- Stress distribution and dimensional changes based on phases, volume changes from transformations, and thermally induced strains (expansion coefficient multiplied by temperature differential).

2. Predict carburizing, nitriding, and solutionizing behavior:

- Gas atmosphere potentials.
- Gas/solid reaction rates at the surface.
- Carbon and/or nitrogen distribution in the part and phase distributions during carburizing or nitriding.
- Dissolution of phases.

3. Predict cooling behavior:

- Varying surface heat-transfer coefficients for cooling across component model (usually a function of quenchant, temperature, location, and quenchant agitation).
- Temperature distribution in the component as a function of time.
- Phase distribution in the component as a function of time.
- Stress and strain distributions based on phase fractions, volume changes from transformations, and thermally induced strains (expansion coefficient multiplied by temperature differential).

4. Material databases and process inputs:

- Heat transfer coefficients (heating and cooling)
- Physical property data (thermal expansion, specific heat, thermal conductivity, density, etc.)
- Electrical and Magnetic property data (permeability, electrical resistivity, etc.)
- Mechanical property data (elastic constants, yield strength, etc.)
- Kinetic constants for gas reactions and gas-solid reactions, diffusivities, and chemical potentials
- Phase diagrams, TTT diagrams, heating transformation behavior, dissolution and precipitation, etc.

From the above attributes, high priority research program areas have been identified as critical to the further development of these integrated process models. From an order of perceived importance, they would include quenching development, electromagnetic models, mechanical models, and transformation databases. Details for each of the areas follow:

Quenching models

- *Database and empirical relationships:* Heat-transfer coefficients are derived from temperatures measured at the surface and within the part. The values are affected by many parameters, such as agitation, quench fluid, quench temperature, part geometry, part orientation, load distribution, and surface finish.

It is very difficult to derive heat-transfer coefficients for three-dimensional components using inverse calculation methods. Because of these difficulties, few heat-transfer coefficients are available to model the quenching process. Furthermore, scaling rules are not available to estimate heat-transfer coefficients based on part geometry.

In practice, heat-transfer coefficients must be experimentally determined. Therefore, research is needed to develop robust methods to compute heat-transfer coefficients from time-temperature data, to develop detailed databases, and to compile scaling rules for quenching. Also, a more sophisticated probe is needed to address surface finish and geometry issues for quenching.

Development of improved methods to determine heat-transfer coefficients, heat-transfer databases, scaling rules, and sophisticated probes will enable users to perform virtual quench experiments for product and process development without the need for continually making real measurements. Today, the ability to model furnace heat treatment and quenching processes is severely hampered by a lack of heat-transfer data and scaling rules. Without these developments, heat-treatment simulation will be restricted to the very sophisticated user who has accumulated quenching data. Simulation is not likely to be extended to the process and design engineering communities.

- *Predictive quenching:* The current state of the art in quenching is the ability to use CFD modeling of quench baths to predict the flow patterns in unloaded baths. The larger analysis problem of a loaded bath at ambient temperatures can be solved, but it is very time consuming, even with the most advanced computers.

Currently, CFD is not applied to model quenching modeling because of the extremely large amount of computational time required to solve the transient-temperature problem which is necessary to calculate heat transfer coefficients at the component surface. In addition, CFD is not able to adequately deal with all the variables of boiling liquids (i.e., oils, water, and polymers). CFD codes, theory, and application methods need to be developed and advanced to be able to handle larger problems in quench baths without boiling, and to be capable of handling the boiling process in oil and polymer quenchants. This work will also need extensive material property databases for quenchants over the range of temperatures at the part/quench interface.

- *Benefits of research programs:* Heat treaters will gain the ability to use heat-transfer coefficients and CFD modeling to alter heat-transfer behavior, thus improving part performance in the process models. In addition, they will be able to determine which quenchant, flow, and quenchant temperature will provide the best balance between component performance and distortion without building hardware.

Experimental costs and the time required to develop heat-transfer coefficients for every new component will be reduced or eliminated. The process and design communities will have access to scaling rules for heat transfer coefficients. Advancing the CFD capabilities will benefit not only modeling of the quenching process, but also modeling of other areas of fluid flow that have problems with boiling phenomena.

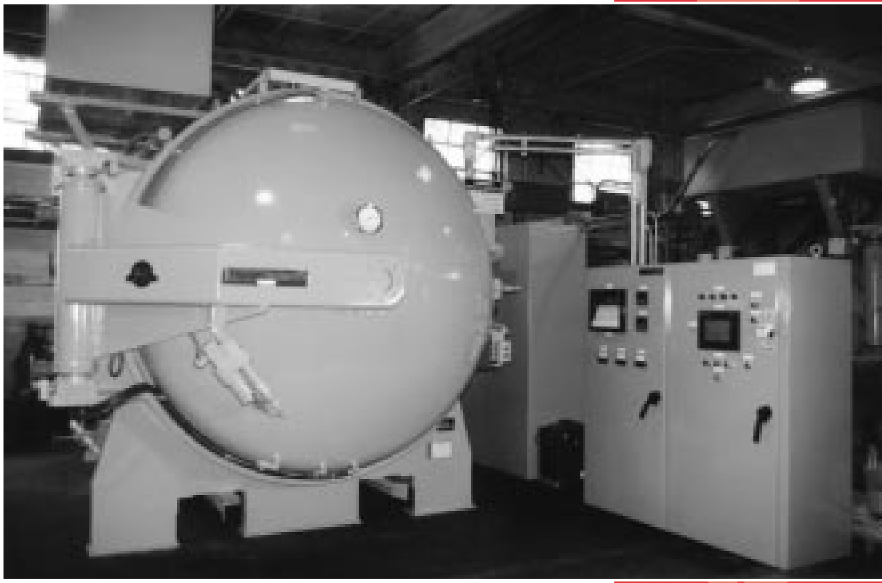
Electromagnetic (E-M) models

- *3-D analysis:* Several two-dimensional E-M models currently are available to predict temperature distributions in components. Three-dimensional analysis is too time consuming for practical application. Substantial work is needed to develop models and methods to analyze three-dimensional problems in time frames that can be useful for individual runs. Two-dimensional problems also need to run much faster to enable routine optimization of the coil-component-process parameter system.
- *Material databases:* A database of temperature-dependent electromagnetic material properties is needed for accurate simulations. These databases must include the effects of phases and chemical compostions.
- *Benefits:* The combinations of coil, workpiece, and process could be evaluated in a virtual environment in a few days compared with months currently required to experimentally determine process procedures. Temperature fields could be determined in complex three-dimensional shapes such as cross holes in shafts and longitudinal grooves, as well as in optimized process conditions. All potential processing parameters could be included for process optimization (programming power, time, scan rate, etc.).

Mechanical models

Mechanical models are required to predict the state of stress and the dimensions of components during stages of the modeling process. They must be able to predict the stress-strain response at all locations in the component as a function of phase, temperature, and strain rate. The outputs from the model are residual stresses, dimensional changes, and material strength. Typically, heat treatment processing problems are strain controlled. The strains introduced by thermal gradients and phase transformations must be accommodated elastically or plastically.

Plastic strains cause permanent dimensional changes and induce residual stresses. Whether strain is elastic or plastic depends on the stress-strain response of the phases at the local temperature and strain condition. The accuracy of these models depends on several factors:



HI TecMetal Group 10-Bar Turbo Treater™.
Photo courtesy of Walker Heat Treating.

- *Stress-strain databases:* Detailed stress-strain databases are needed for different alloys as a function of phase, temperature, and strain rate. This is particularly important for metastable phases such as low-temperature austenite.
- *Strain partitioning:* A general theory for partitioning of strain among all the phases also is necessary. This is very important when the flow behavior of the phases is unique. The ability to partition deformation strain is central to accurate predictions of both dimensions and residual stresses. This effect has a large impact on both prediction of residual stresses and the dimensional changes of components.
- *Transformation plasticity:* Transformation plasticity data must be generated. All current transformation plasticity calculations are based on a limited set of data. It has been

shown that this parameter can greatly influence prediction of component dimensions. To be truly predictive, the transformation plasticity must be incorporated as part of the base model. Detailed databases will enable models to be applied to a broad range of materials without individual users having to generate their own databases. Model accuracy is very dependent on the quality of the data. The current state of the art is for two-phase partitioning (e.g., between martensite and austenite). However, more than two phases are often present and a more general model is required. Unfortunately, current models are limited by transformation plasticity experimental values and by the calculated values available. These can be adjusted as a parameter in some models to fit experimental results.

Transformation databases

- *Quantitative transformation diagrams:* For most current transformation models, time-temperature-transformation (TTT) data and isothermal heating transformation (IHT) data are required to predict the transformation behavior along any given heating or cooling path. The accuracy of phase predictions is essential for the accuracy of all simulations. Phase transformations typically produce notable strain, and the mechanical response is phase dependent. Currently available TTT and IHT data are suitable for qualitative evaluations, but have not been developed for quantitative calculations. A very extensive set of transformation data is required to produce general models in which material chemistry and grain size are input parameters. Otherwise, this restricts users to material compositions that have been characterized.
- *Benefit of transformation data research programs:* An extensive database in transformation kinetics will enable users to have alloy composition as one of the variables that can be easily examined in performing virtual component and process development. It will enable chemistry ranges for applications to be determined analytically, rather than experimentally. The ability to predict microstructures at any composition also will have application in the area of heat treatment of products for machinability and forming operations. These research requirements are too extensive for a single company, but may be practical as a collaborative effort.

B. Real-time process sensors

The first level of sensor capability is a reactive response. In this case, when a parameter changes, the system reacts to the change. This mode is classed as inter-reactive. At a higher level of sophistication, the future goal is to implement an inter-proactive mode of operation. In this case, the sensor anticipates change, either by additional input information (such as hardenability index) or by the rate of change of a parameter. This is an inter-proactive response.

The application of sensors in batch type systems provides a substantial challenge because of the variations within the batch. Reduction in the number of items in the batch improves the effectiveness of a sensor system. In induction heating, the system essentially comprises batches of one. In these cases, sensors can be applied more effectively because they evaluate the process in an active, real-time mode, and have a much higher response resolution.

High-priority research program areas have been identified as critical to the further development of the development of real-time process sensors. They are as follows:

Processes and Heat Treated Materials

Goal B: Real-time process sensors/predictive sensors
Depends on development of:
- **Sensors controlling a system with multiple chemical and physical inputs**
- **Controlling algorithms to quantitatively integrate sensor inputs**
- **Real-time case-carbon sensors**
- **Real-time quenching sensors to quantify heat transfer**

- *Sensors controlling a system with multiple chemical and physical inputs:* Sensors operate by sending an electrical or mechanical signal that is proportional to a process variable; to a real-time closed (PID) or open loop control algorithm. These algorithms can be incorporated into stand-alone instruments, PLCs, and computers. Smart sensors have the algorithm software integrated into the sensor, making for a true distributed-control system. Thermocouples are one of the oldest real-time sensors that enable adaptive control of temperature. Pressure, rpm, and flow sensors also enable real-time process control.

In heat treating, sensors have been applied to furnace and quench oil temperature control, atmosphere control (CO_2, CO, CH_4, dew point, oxygen, and gas flow), and quench agitator rpm. Although monitoring of the heat-treating furnace atmosphere began decades ago, the industry has yet to develop a workable and reliable real-time sensor to actually measure surface carbon content in annealed, hardened, and carburized parts. Many attempts have been made to develop such a sensor, mostly in Asia, but they have all been unsuccessful. Furthermore, these efforts have attempted to measure carbon in wires, not in a representative component.

- *Controlling algorithms to quantitatively integrate sensor inputs:* Heat-treatment process sensing is a major challenge because of the great number of process variables involved. Some are interrelated and some are not. To address this multivariant situation, it usually is necessary to have a matrix system of several sensors. A suitable structure for analytical summation based on order of relevance is needed also. A valuable tool in working in these systems is failure mode effects and criticality analysis (FMECA, or simply FMEA), together with a suitable dynamic-control plan. Process modeling will be helpful to establish where sensors are required to meet the most critical needs, and provide a methodology for sensor design and application-output requirements. One objective is to develop fruitful coordination between the activities of the modeling and sensor groups.

Considerable research is being done in the area of induction heating. Since the induction system operates with batches of one, the distinct opportunity exists to monitor/control the process in a real-time mode. Also, because induction heating uses electrical power, it can take advantage of the more sophisticated technologies available for electrical energy driven processes. State of the art induction heating interrogates the part to determine whether or not the applied process is producing the necessary results or reaction.

- *Real-time case-carbon sensors:* Indirect sensors such as the electronic dew pointer and the oxygen probe have been developed. However, these sensors do not allow the heat-treat practitioner to measure carbon concentration as it diffuses into the steel surface, and the results achieved to date have not been adequate. Real-time adaptive case-carbon sensors will become necessary as even higher quality gains become the norm and part nonconformity of any degree becomes unacceptable.
- *Real-time quenching sensors to quantify heat transfer:* Process variability in quench baths is a major problem that needs improvement and/or solutions. This variability impacts distortion and part performance. As mentioned previously, quenching models will provide an improved understanding of the process. However, because of the many variables involved in bath-quench operations, such as part density loading, variability in agitation, and others, additional quantification of these variables by suitable sensors is needed. Limited work has been done in Europe on these types of sensors. However, additional research is required to monitor and improve the predictability of the quenching operation. This is another example of the need for cooperative work in modeling and sensor development.

Heating and quenching processes, and resultant distortion control and prediction, will require R&D funding on several fronts including a coordinated program on sensors. At this time, most, if not all of the effort is concentrated on predictive computer modeling. This on-going development will most likely result in the eventual need for sensors to monitor process-dependent outputs, not presently considered sufficiently robust for use in industrial applications. These could include on-line residual stress analysis using X-ray (currently used in a production environment at a major European automotive manufacturer) and integrated nonevasive sensing techniques, such as eddy current and Barkhausen noise either as predictive or complimentary input to matrix systems. For example, CFD models could establish finite fluid velocities to meet predicted thermal transfer requirements. These could be validated using a suitable, robust fluid-velocity sensor.

- *Benefits of real-time sensors:* In the future, smart sensors will automatically reduce variability with an adaptive feedback control to maintain predefined limits. Substantial work is being done in many different areas in this technology. In view of the critical need for development and implementation, it is apparent that existing activities would benefit from better coordination and interaction.

However, sensor development and design improvement, particularly of the smart sensor type, stretches the resources available in the equipment industry. This effort incorporates a number of sophisticated engineering disciplines. In addition to a robust product for heat treating environments, it is necessary to incorporate the latest innovations in electronics, microprocessor capabilities, software design, and an understanding of materials science and physics. Because of resource limitations in the heat-treating industry and the interdisciplinary nature of sensor development, collaboration may be the best avenue to accomplish these objectives.

Processes and Heat Treated Materials
Goal C: New materials need to be developed for: • **High-temperature processing development** • **Rapid heat-treating technology than radiant tube to distribute heat more uniformly**

C. New materials

In order to implement the process improvements outlined, advances are required not only in the furnace materials, but also in the materials to be heat treated. Materials need to be developed for higher temperature processing, rapid heat-treating technologies, as well as for improved surface treatments.

This *Technology Plan* addresses the design and development of materials that optimize performance, and minimize the use of heat-treat energy. One example is carburizing at the highest possible temperatures, while maintaining the proper microstructural characteristics to allow for optimal performance. Another example is the design of materials for optimal response to short time heat-treatment processes such as induction heating, laser heat treating, and electron beam heat treating. This requires material that austenitizes quickly, hardens deeply, has a narrow austenite-ferrite phase field temperature range, and can be tempered to have excellent high hot hardness characteristics.

Materials could be designed to have the proper balance of performance and manufacturing characteristics when welded. This essentially is the concept of microalloyed forging steels. These materials are designed to be cooled after the forging process at rates that induce properties suitable for use without further thermal processing. Design of new materials, and optimization of existing materials go hand in hand with the development of integrated process models. As models are developed, material characteristics of interest can be developed. Existing materials can be optimized for various steps of the process. Integrated process models allow materials to be selected/designed for optimal performance and processing throughout the entire process. The models drive material design, while advanced, real-time sensors enable the processes to be achieved. By contrast, in current materials selection, design engineers select materials based on prior history, or because a specific material is in stock. This research will provide a scientific basis for materials design and selection.

Gears suspended from the bore vertically to minimize distortion. Parts are masked with stop-off paint to prevent carburization of areas requiring subsequent machining after heat treat.

Photo courtesy of Cincinnati Steal Treating.

Steels for Carburization at High Temperatures - High temperature carburizing refers to the use of carburizing temperatures above 982° C (1800° F). The benefit of carburizing at higher temperatures is a reduction in cycle time. Vacuum furnaces can be used to perform high temperature carburizing, but there is a need for steels that can be carburized at high temperatures while maintaining the beneficial resultant properties.

A critical issue of carburization at high-temperatures is minimizing grain size coarsening. Published reports show that low alloy, nickel-containing steels carburized for short times (less than 2 hours) at temperatures up to 2000° F, have no significant grain coarsening. In contrast, the grain size of plain carbon steels coarsens quickly at temperatures greater than 982° C (1800° F). Tensile testing of AISI 8620 steel carburized at high temperatures shows there is no reduction in strength up to 2000° F. Charpy impact and reversed bending fatigue testing of carburized AISI 8620 steel indicate that toughness and fatigue properties are unaffected by carburizing temperatures up to 1038° C (1900° F). At 2000° F, however, a reduction in the ductile-to-brittle transition temperature, and a decrease in fatigue life occurs. Some aircraft gears are carburized at 1038° C (1900° F) and subsequently hardened and tempered. Performance of these gears is comparable to, or better than, conventionally processed gears.

There is much less work showing the effects of relatively long cycle times (greater than two hours) at high carburizing temperatures on microstructure and properties. Studies of noncarburized specimens exposed for relatively long times at high temperatures show that significant grain growth and a resultant decrease in ultimate tensile and yield stress occurs. Research shows that the coarse grain structure can be refined by repeated quenching with intermediate cooling to a temperature below the eutectoid temperature. However, this post-carburizing treatment tends to negate the time saving obtained from high temperature carburizing.

It appears from these investigations that components made of low-alloy steel can be carburized for short times at temperatures up to 1900° F with little change in grain size and properties. However, there appears to be a need for steels that will resist grain coarsening when carburized for relatively long periods above 1800° F.

Induction Hardening and Similar Processes - To meet the Vision 2020 goal of reducing energy consumption by 80%, heat-treating facilities must to take greater advantage of short-time, just-in-time heating techniques. Heating processes such as induction, laser, and electron beam are the most commonly used. However, there are a number of challenges that inhibit broader use of these processes. The goal of this research is to implement the advances in thermodynamics, kinetics, and structure-property relationships (embedded as elements of the integrated process models) to design materials that achieve the desired performance properties while consuming less energy. This approach is similar to advances in the understanding the hardenability of steels in the late 1970s that enabled the rational selection and deployment of materials.

Design of materials for specific applications requires a description of the material from a systems point of view (Keuhmann and Olson, *Advanced Materials and Processes,* May, 1998, p 40-43). The desired performance characteristics must be mapped to composition, processing, structure, and property characteristics. Development of an integrated process model that relates these variables is the key to designing materials to meet performance and processing goals. Computer-based modeling and simulation for design of materials and processing will speed the development of new products, and optimized materials and processes. Ultimately this technology will lead to the reduction of heat-treating process costs.

Some aspects of the needs and challenges as they relate to the development of new materials are listed below.

Needs

- **Uniform Processability** - Starting materials are needed that have fast response to rapid thermal processing, and that form austenite quickly and uniformly. Better understanding of the "on-heating" transformation kinetics of carbon and alloy steels will allow the design of the composition and processing of steels to minimize energy use during hardening by induction, laser, and electron beam, and variability resulting from the nonuniformity of initial structures (volume fraction ferrite, volume fraction pearlite, ferrite morphology, segregation and banding, degree of decarburization, etc.). Steels can be designed to minimize ferrite in the structure at the mill by varying carbon and alloy content and controlling pearlite formation temperature.
- **Structure-Property Relationships** - Starting materials that have sufficient carbon and alloy content to achieve the desired properties (strength, hardness, toughness, etc.) through high-speed, short time thermal processing are needed. Better understanding is needed of the structure-property relationships for rapidly austenitized materials with inhomogenous microstructures. Properties as a function of carbide size and distribution, matrix carbon content and gradient, as well as properties of the various phases that form during quenching and tempering are critical to understanding how to optimize properties for a given application. Understanding the relationship of structure and residual stress is crucial.
- **Machinability and Formability** - Starting materials received from the mill that have good machinability and forming characteristics without additional processing are needed. This requires quantitative data relating the effects of initial structure on machinability and formability.

A model-based approach allows design of the materials processing sequence to produce machinable, formable materials, which heat treat rapidly, and develop optimum properties. Upon agreement on how to achieve the Vision 2020, we can start with the knowledge available to realize near-term benefits and continue through the mid- and long-term research to continue optimizing materials for thermal processing and become world leaders in minimizing heat-treating cycle times and energy use.

Challenges, Research Areas Required

- Material variability from the mill
  - Chemistry variations
  - Segregation and banding
  - Substructure variations due to deoxidation practice, hot-working schedule, finishing temperature
- Lack of understanding of variability of "on-heating" transformation kinetics
  - Heat-to-heat variations due to mill variability (above)
  - Initial microstructure
    - Ferrite-pearlite, effects of pearlite volume fraction and ferrite morphology
    - Tempered martensite, effects of tempering temperature and alloy content of carbides
    - Speroidized structures, carbide size and spatial distribution, alloy content
    - Decarburization
  - Stress state (macro and microscale)
    - Need to understand the effects of tensile and compressive stresses that form as local areas and layers are austenitized and their impact on phase transformation kinetics
- Lack of understanding of variability of "on-cooling" transformation kinetics from conditions characterized by nonuniform phase fields
  - Quenching from austenite plus ferrite phase field
  - Quenching from austenite heated for short times at high temp with significant carbon gradients
  - Quenching from variable macro and microscale stress fields, both compressive and tensile
- Lack of understanding of mechanical property and residual stress development
  - Austenitizing and quenching using short time processing
  - Subsequent tempering, using furnace or other short-time processes (induction, laser, E-beam)
  - Back-tempering effects due to processing of adjacent material (especially in laser and E-beam processing). Need a validated tempering model that incorporates a broad range of time-temperature-chemistry variables.

Photo courtesy of Euclid Heat Treating.

III. Energy and Environment

Energy consumption, operating costs, and environmental impact must be reduced by the year 2020. The goal is a reduction of 80% in energy consumption, and zero environmental impact. The high priority areas selected by the committee are:

Goal A: Energy Reduction
Goal B: Zero Environmental Impact

Energy and Environment		
Goal A: Energy Reduction	**Short/Mid-Term**	**Long Term**
Depends on development of:		
• Energy map of commercial and captive heat treating facilities	•	
• High heat-transfer rate heating and cooling systems to reduce process time and energy losses	•	•
• Low-cost heat recovery and low temperature heat utilization	•	•
• Process changes to reduce heat-treating energy requirements	•	
• Hybrid natural gas/electric heating systems to minimize process energy cost	•	•

A. Energy Reduction

- *Energy map of heat treating facilities:* Overall heat treating energy consumption patterns and interrelationships must be defined to help identify and measure energy-saving opportunities. Modeling representative facilities that integrate a mix of commercially available technologies will provide some direction. Immediate development of these models will support later R&D and capital investment decision-making, and energy-reduction strategies. Models need to capture changes in heat-treating practice such as integration of heat treating with manufacturing production cells. There is a need for independent testing facilities, and field-data acquisition to provide technology performance input data for models. Best practices including process heating-equipment operation and maintenance need identified.
- *High heat-transfer heating and cooling systems to reduce process time:* The heat-treating cycle can be divided into heating, holding, and cooling stages. The reduction of process time in each of these stages will reduce unit system energy losses while increasing system productivity. Rapid heating devices combined with process models and advanced controls, proposed in other sections of this plan, will significantly reduce energy consumption. Development and application of long-lived, high heat flux, direct and indirect gas heating systems is needed. More cost-effective, and versatile, high-intensity electrical heating systems need to be developed. Control of part temperature will be essential at high energy deposition rates and will require advancements in air/gas flow controls and temperature measurement.
- *Low-cost heat recovery and low-temperature heat utilization:* Materials, design, and fabrication improvements are needed to reduce the cost of heat recovery devices to achieve advancements beyond current obtainable energy efficiencies. Heating value of waste process gases must be captured more cost effectively, directly in the heat-treating process, for part preheating, combustion-air preheating, and operation of a lower temperature process.
- *Process changes to reduce heat-treating energy requirements:* There is a need to develop and prove the effectiveness of lower temperature surface treatments, which can replace whole-part heating and still meet required wear service specifications. Advancements in energy and chemical deposition rates and process control are required. Alternately, higher temperature carburizing processes would significantly reduce diffusion cycles, furnace time, and energy consumption.
- *Hybrid natural gas/electric heating systems to minimize process energy cost:* Deregulation of natural gas and electricity is leading to real-time energy pricing and myriad purchase options. Development of integrated natural gas and electric heaters will provide the energy purchaser and operator with flexibility to minimize energy costs based on changes in energy supply/demand conditions. This can be accomplished either through complete or partial replacement of either energy source for a selected time period. Combined electric/natural gas vacuum furnace heating systems, natural gas/electric infrared heating systems, natural gas/induction hybrid heating processes, hybrid natural gas/electric radiant tubes, and natural gas engine/electric motor combinations must be developed. Integrated heating control systems also must be developed, as well as small, low-cost point of use energy measurement devices and energy management software. Continued microturbine, small gas engine, and fuel-cell technology development is needed.

Energy and Environment		
Goal B: Zero Environmental Impact	**Short/Mid-Term**	**Long Term**
Depends on development of:		
• Pollution prevention and/or pollution-control technologies	•	•
• Alternate quenchants to oil	•	•
• Alternates to NO_3/NO_2, CN and Ba salts and solvent cleaners	•	•
• Reducing CO and NO_x emissions	•	

B. Zero Environmental Impact

- *Pollution-prevention strategies and/or pollution-control technologies:* To attain zero environmental impact, pollution prevention strategies that focus on eliminating the sources of pollutants generated by heat-treating processes must be developed. This includes material substitutions and process changes. After "at-source" reduction strategies have been exhausted, pollution-control technologies that treat, recover, recycle and/or reuse waste products must be developed. Opportunities available for both of these approaches are described in the paragraphs below.
- *Alternative Quenchants to Oil:* Oil is a commonly used quenchant in the heat treating industry; it introduces numerous environmental liabilities. New oil is regulated by EPA's Spill Prevention Control and Countermeasure (SPCC) regulation, waste oil by EPA's Used Oil Management Standard, and in some states, waste oil is regulated as a hazardous waste. Oil spills and leaking underground storage tanks have also resulted in surface water, soil, and groundwater contamination problems at some heat treat facilities. Using an alternate quenchant would eliminate smoke emissions and oil-spill potential, enhance in-plant air quality, reduce wastewater-treatment requirements, greatly minimize fire hazards, and eliminate the need for waste oil treatment/disposal. An alternate quenchant to oil also would significantly contribute to reaching the goal of zero environmental impact. Alternates could include inert gas, water, and synthetic quenchants. R&D is needed to identify materials that provide good quenchant properties but are environmentally benign.
- *Alternatives to NO_3/NO_2, CN and Barium Salts, and Solvent Cleaners:* Hazardous wastes commonly generated in the heat treating industry include waste salts used for heat treating and quenching and spent halogenated solvents used for parts cleaning. NO_3/NO_2 salts are considered oxidizers and CN, barium, and halogenated solvents are designated as toxic materials; they are regulated as hazardous wastes by EPA. Achieving zero environmental impact requires identifying alternative materials for salt baths and parts cleaning and/or technologies that treat (i.e., completely break down) or recover and recycle these contaminants. Although R&D has been conducted in the area of parts cleaning, a material/process that is an effective cleaner, dries quickly without leaving a residue, does not generate waste oil or wastewater requiring disposal, is nonhazardous and cost effective, has not been discovered. The reduction in the use of oil as a quenchant in the heat treating industry would significantly impact associated parts-cleaning requirements and reduce or eliminate the need to use solvents to clean parts after quenching. Substitute rust preventatives other than oil also need to be identified.
- *Heat Treating Changes or Pollution Treatment Technologies that Eliminate Air Pollution Emissions:* To achieve zero environmental impact, the combustion products generated by heat-treating processes must be addressed. This includes investigating not only burner technology, but also the various atmospheres used in heat treating processes. Gases such as ammonia and methanol are considered highly hazardous chemicals and are regulated by EPA's SARA Title III regulation, Clean Air Act, Risk Management Program; and OSHA's Process Safety Management Standard. These gases and others, such as endothermic and exothermic gases, contribute to NOX and CO emissions from heat-treating process atmospheres. R&D is needed in the areas of process changes and/or material substitutions to eliminate the generation of these air pollutants. Exhaust gas treatment technologies that would remove air pollutants such as CO and NOX, or allow recycle and reuse of off gases and recovery of heat and waste gases, also must be investigated.

Benefits of achieving the goal of zero environmental impact include: reduced operating costs and liabilities, better working environment and increased productivity, a safer workplace, reduced regulatory burden, and a cleaner environment. Research and development projects can best be achieved through the collaboration of industry, government agencies, and universities. Government agencies, such as EPA and DOE, and trade associations, such as MTI and HTN, are sources of sponsorship for R&D projects. Other sources that potentially could be interested in collaborative projects include the powder metallurgy, galvanizing, and die casting industries.

Implementation Plan

Strategies

This R&D plan lays the groundwork for the immediate needs of the heat treating industry and the areas that must be addressed to achieve the "Heat Treating Industry Vision 2020." As summarized in the Vision:

"By the year 2020, many of the technical challenges currently facing the heat treating industry will have been met. Materials and processes will be much better understood, and the sequence of operations will be more tightly controlled. All processes will be environmentally benign. Computer controls and robots will enable both salaried and hourly employees to work in a clean, comfortable environment. In order to efficiently operate and maintain this advanced equipment, workers will be among the most technologically capable in manufacturing."

Powder Metal automotive sprockets being induction hardened on a lift/rotate work station.

Photo courtesy of Cincinnati Steel Treating.

This is a tall order and will require a tremendous amount of cooperation from not only the heat-treating community, but also from other thermally dependent manufacturing industries (e.g. bar steel, aluminum, and forging communities). In addition, government and academia will have similar interests/needs. Ongoing support from technical societies and trade associations will be necessary. Although such collaboration adds an element of complexity, there appears to be no clear or easier alternative to improve the efficiency and competitivenessof the heat treating industry in the USA.

The Heat Treating Society Research & Development Committee's role is to develop mechanisms to plan, fund, and implement R&D programs to meet the technology needs identified in the Technology Roadmap. The high priority needs identified as part of the 1999 R&D Plan will be the focus for the next 12 months. ASM-HTS will encourage industry, trade associations, academia, research centers and government to work together to initiate the specific research where each is a stakeholder. ASM-HTS also will strive to transfer these technology developments into the industry base where appropriate. Another important role of ASM-HTS is to find on-going research that parallels the technology needs identified in the Roadmap and to communicate this so that the research can be leveraged and not duplicated.

Communication

The first step in achieving the Technology Roadmap will be to communicate the immediate, high-priority research areas identified as part of this document. The R&D Committee members and others, will seek ways to identify the stakeholders for the enabling technologies for these high-priority research areas and gather the support necessary for collaboration. The R&D Plan should be prominently showcased at the appropriate technical society and trade association conferences and publications with an emphasis on building partnerships. It will be necessary to share the R&D Plan with other manufacturing industries that play a role in the implementation, either through the appropriate Vision committees or at conferences.

Building alliances and initiatives

Each of the high-priority areas identified as part of the 1999 R&D Plan have critical technologies that need to be developed to enable them. It is important to remember that the critical or enabling technologies identified most often apply to all thermally oriented industries. As part of the implementation plans, it will be necessary to interact and coordinate with the relevant industries. For each of the high-priority research areas identified in the roadmap section of this R&D Plan, stakeholders must be identified and encouraged to participate collaboratively to accomplish the technical achievements identified. A preliminary summary of the high-priority research areas, their enabling technologies, and the potential stakeholders who would play a role in accomplishing the research follows:

Equipment and Hardware Materials

High-Priority Research Area	Enabling Technologies	Stakeholders
Attain Higher Operating Temperatures	• Improved heating source materials • Improved heating source configuration • Improved convection sources • Improved insulation materials	• Furnace manufacturers • GRI, EPRI • Commercial and captive heat treaters • AGA • AISI, AFS, FIA
Alternative Hardware Development	• Overall cost reduction in bath, fluidized, and vacuum systems • Development and application of accelerated heating technologies	• Commercial and captive heat treaters • Equipment manufacturers • NIST/ATP

Processes and Heat Treated Materials

Integrated process models

High-Priority Research Area	Enabling Technologies	Stakeholders
Quenching Models	• Robust methods to compute heat-transfer coefficients from time-temperature data • Heat-transfer coefficient database • Scaling rules to estimate heat-transfer coefficients • A more sophisticated probe that addresses surface finish and geometry issues for quenching • CFD modeling capability of quench baths to predict the flow patterns in loaded baths	• Quenchant suppliers • EMTEC • NCMS • Commercial and captive heat treaters • ORNL, LANL, SNL • Software model suppliers • DOE, NSF, NIST/ATP
Electro-magnetic (EM) Models	• Methods to analyze 3-D problems in time frames that can be useful for individual runs • Temperature dependent electro-magnetic material properties database	• Induction equipment suppliers • Commercial and captive heat treaters • EPRI • NCMS • FIA • SNL • Software model suppliers • DOE, NIST/ATP
Mechanical Models	• Stress-strain database as a function of phase, temperature and strain rate • A general theory for partitioning strain among all the phases • Transformation plasticity database	• Alloy suppliers • Commercial and captive heat treaters • NCMS • AFS • ORNL, LANL, SNL • Software model suppliers • DOE, NIST
Transformation Databases	• Quantitative transformation diagrams	• ASM • Alloy producers • NCMS • ORNL, SNL, LANL • Software model suppliers • AISI, AA • DOE, DOD, NIST

Implementation Plan *(continued)*

Smart and reliable sensors

High-Priority Research Area	Enabling Technologies	Stakeholders
Real-time Process Sensors/ Predictive Sensors	• Sensors with ability to control a system with multiple chemical and physical inputs • Controlling algorithms to quantitatively integrate sensor inputs • Real-time case-carbon sensors • Real-time quenching sensors to quantify heat transfer	• Equipment suppliers • Commercial and captive heat treaters • SNL, ORNL, LANL, INEEL • FIA, AFS, AISI, AA • NCMS • DOE, NIST

New materials

High-Priority Research Area	Enabling Technologies	Stakeholders
Materials for High Temperature Processing	• Steels for carburization at high temperatures	• Alloy suppliers • AISI, AA • End users/manufacturers
Materials for Rapid Heat Treating Technology	• Materials that achieve the desired performance properties while consuming less energy in the heat treatment	• Alloy suppliers • AISI, AA • End users/manufacturers

Energy and Environment

Energy

High-Priority Research Area	Enabling Technologies	Stakeholders
Energy Reduction	• Energy map of heat treating facilities • High heat transfer rate heating and cooling systems to reduce process time and energy losses • Low-cost heat recovery or low-temperature heat utilization • Process changes to reduce heat treating energy requirements • Hybrid natural gas/electric heating systems to minimize process energy costs	• Commercial and captive heat treaters • Equipment suppliers • GRI, EPRI • DOE • State governments

Environment

High-Priority Research Area	Enabling Technologies	Stakeholders
Zero Environmental Impact	• Pollution prevention strategies and/ or pollution control technologies • Alternative quenchants to oil • Alternatives to NO_2/NO_3, CN and barium salts, and solvent cleaners • Reduction of CO and NOx emissions	• Equipment suppliers • Commercial and captive heat treaters • Salt bath suppliers • Cleaner suppliers • EPA

When identifying the potential stakeholders, the entire community associated with the technology must be recognized (i.e., the technology providers, the technology users, the regulating agencies, the technical associations, federal and local governments, consortiums, etc.). Since heat treating is a cross-cutting industry, attempts must be made to leverage the research that is occurring to meet the requirements of other industry roadmaps such as the forging, steel, and aluminum industries. For example, to address the development of furnaces that can attain higher temperatures, a coordinated effort could be fostered by GRI or EPRI where equipment manufacturers work in conjunction with the commercial and captive heat treaters to develop advanced insulation materials. This effort could be supported by several organizations such as HTS, AGA, AISI, AFS, and FIA. Another example of an implementation plan could be for the commercial and captive heat treating industry to encourage NSF to fund basic research in understanding the heat-transfer phenomenon occurring in the quench bath to develop scaling rules for simulation of the heat transfer during quenching. Each enabling technology will require a unique plan for implementation according to the stakeholders identified and the current state of the art.

For the next 12 months, it is the mission of the HTS R&D Committee to identify collaborative efforts for the immediate high-priority needs identified in the 1999 R&D Plan. However, there is much more to be accomplished, as noted in the results of the HTS Roadmap Workshop (February 1997). HTS intends to regularly assess the progress of the Roadmap implementation and encourage development in all of its activities. For the next several years, the R&D Plan will focus on achieving the Roadmap's technology needs, focusing on the high-priority needs that are not being met.

Glossary

AA	Aluminum Association
AFS	American Foundrymen's Society
AGA	American Gas Association
AISI	American Iron and Steel Institute
ASM	ASM International (formerly the American Society for Metals)
CCT	Continuous Cooling Transformation
CFD	Computational Fluid Dynamics
CHT	Continuous Heating Transformation
DOD	Department of Defense
DOE	Department of Energy
EMTEC	Edison Materials Technology Center
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FIA	Forging Industry Association
GRI	Gas Research Institute
HTN	Heat Treating Network
HTS	ASM Heat Treating Society
IHT	Isothermal Heating Transformation
INEEL	Idaho National Engineering and Environmental Laboratory
LANL	Los Alamos National Laboratory
MTI	Metal Treating Institute
NCMS	National Center for Manufacturing Sciences
NIST/ATP	National Institute of Standards and Technology/ Advanced Technology Program
NSF	National Science Foundation
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
PLC	Programmable Logic Controllers
SARA	Superfund Amendments and Reauthorization Act
SNL	Sandia National Laboratories
TTT	Time-Temperature-Transformation

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ASM International Heat Treating Society
An Affiliate Society of ASM International

ASM Heat Treating Society's 1999 Research & Development Plan

About the ASM Heat Treating Society

HTS is the world's largest society dedicated to serving the technical and networking needs of heat treaters. We're dedicated to:

- Bringing heat treaters together to discuss the challenges that face all of us
- Providing the technical information, knowledge, and education needed by all heat treaters
- Serving as a central clearinghouse for information of value to heat treaters
- Interfacing with all organizations that serve heat treaters

When you join HTS, you gain access to the world's largest network of heat treaters. We represent the entire heat treating community, including captive heat treaters, commercial heat treaters, suppliers to the heat treating community, researchers, manufacturers, and customers of heat treating.

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