RESTLESS LEADS TO

HEAT TREATING

INNOVATION AND IMPROVEMENTS

Materials thermal-processing research at TRDDC is aimed at providing solutions to all important issues in industrial thermal processing operations, such as rendering heat treatment operations energy-efficient, improving their productivity, enhancing product quality, and making them environmentally responsible.

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TRDDC is one of the India’s premier R&D centers, working in advanced software (such as algorithms, data security, formal methods, model-driven architecture, program analysis and requirements modeling) and process (model-based optimization solutions for minerals, casting, metal forming and thermal processing) engineering areas. TRDDC is a division of Tata Consultancy Services (TCS), a leading IT consulting organization and part of the Tata Group.

TRDDC was established in 1981 with a vision “to apply existing knowledge to the benefit of the industry and the people.” TRDDC initiated focused research on thermal processing of materials in 2000 to provide efficiency enhancement solutions to industrial thermal processing operations. The research was seen as addressing all important issues in thermal processing operations, such as rendering heat treatment operations energy-efficient, improving their productivity, enhancing product quality, and making them environmentally responsible. These objectives were also inspired from the comprehensive Vision 2020 and R&D plan laid out by the ASM Heat Treating Society, where the quantitative performance targets for the year 2020 are set, and the roadmap for the required technological advances are prioritized.

These broad objectives are being achieved through two interrelated activities: industrial projects focusing on model-based optimization solutions and industrial research aimed at quantum improvements in process efficiency and product quality. Innovation and research are the key components of this program, and are demonstrated during solution formulation for industrial problems. The aim of industrial projects in this program is to improve the process efficiency of existing operations, identify industrially relevant problems, and provide avenues for commercialization of innovative concepts.

During the past six years, the group has undertaken a number of challenging industrial and innovative research projects. Further, the group has built strong links with other important research groups (Fig. 1) in this area, as well as with the ASM Heat Treating Society’s R&D Committee, of which the author is a member. There is a strong emphasis on sharing the important results from research and industrial projects through patents, publication in peer-reviewed journals and technical magazines, and presentation at international conferences. This article summarizes these efforts and consolidates major results achieved during the past six years.

Industrial Projects: Model-based optimization solutions

Industrial process modeling brings several new complexities and challenges. As opposed to modeling of isolated laboratory or pilot-scale experiments, industrial operations need to be modeled within their complex environment. Interdependent upstream and downstream processes must be considered while developing the model. Moreover, validation of model prediction with plant data is a key step while developing a model for an industrial scale operation. Finally, to obtain a solution that can be implemented requires identifying controllable parameters and im-

Fig. 1 — Tata Research Development and Design Centre interaction with industry, research organizations, and academia to conduct thermal processing of materials.

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posing operational constraints during the optimization exercise. The core strengths of this group lie in the rigorous validations of these models using plant data collected amidst its complex interdependent environment, and in deriving solutions from the model simulations that can be readily implemented in the plant. The efficacy of this approach has been proven for several industrial operations through benefit quantification in terms of relevant process efficiency metrics; that is, productivity, energy consumption, and product quality for several industrial heat treatment operations.

The prevalent empiricism in process cycle design of heat treatment operations provides immense opportunity to optimize these operations through a formal approach of model-based process optimization. This has been demonstrated for several operations, such as:

- 14% energy reduction and 20% productivity improvement in carburizing bearing rings
- 66% reduction in salt-melting time and cycle design for salt-bath hardening of slip gauges
- 13% energy reduction during continuous annealing of tubes
- 15% energy reduction and 20% productivity improvement of roller hearth annealing operation
- 10% productivity enhancement potential for continuous carburizing automotive gears
- 9% productivity enhancement in a highly automated batch annealing operation

This methodology has not only benefited operations working on an empirical approach (see industrial case study on continuous annealing below), but also has produced benefits at modern operations already equipped with a model-based online control system (see industrial case study on batch annealing below). In the latter case, the approach was to move up the model hierarchy and develop an integrated model, which was superior to the prevalent thermal model. This group has developed integrated models for several industrially important operations extending the capability to predict underlying phase transformation, microstructure evolution, and final properties.

Before formally undertaking industrial problems as projects, they are carefully screened for research challenges. The solutions developed and proven by the research group are proliferated for repetitive implementations through the appropriate business group of the company. In addition to implementing these solutions in the plant, the project scope invariably includes quantifying the savings accrued through project execution. Some of these projects were undertaken with performance-linked consultancy charges with attractive return-on-investment (ROI) ranging from six months to one year.

The following case studies illustrate the work being addressed in the industrial projects.

**Model-based optimization of a continuous annealing operation.** Industrial heat treatment operations can be quite complex due to the large scale of operation, multiple grades and component types, and the absence of in-situ sensors, which precludes online monitoring and control of operations. As a result, many of these operations are empirically designed with several simplifying assumptions and plant trials. The perils of this industrial practice and resultant sub-optimal operations were demonstrated in a recent industrial project where bundles of tool-steel rods were annealed in a continuous furnace. The process was too complex to be heuristically analyzed considering the multiple variables such as rod diameter, number of rods, bundle diameter, and packing fraction of the bundle.

To make the problem tractable, process cycles were designed on the basis of rod diameter. The major implication of this approach was that bundle residence time increases with rod diameter. A mathematical model was developed by capturing the heat transfer within the bundle of rods and the annealing kinetics as the bundle traverses the furnace. The process model can predict spatial and temporal evolution of temperature and hardness in the bundle as it traverses through the furnace. Interestingly, the model-based process cycles are counterintuitive compared with normally used empirically designed cycles in the plant (Fig. 2). It was shown that due to the higher number of contact points in the bundles containing smaller diameter rods, bundle residence time should decrease with increasing rod diameter. Implementation of the results improved furnace productivity by 15% and reduced the energy consumption by 20%

**Enhancing productivity of a highly automated batch annealing operation using an integrated model.** Batch annealing is a critical operation for processing high quality cold rolled steel for automotive and white-goods applications. Long processing time (40-60 hours) and low productivity are major issues in the batch annealing operation. Modern batch annealing operations are highly automated, using process models to estimate cycle times for individual stacks. However, the models are essentially thermal models used to control the batch annealing operation, which ignore nonisothermal effects, such as the effect of heating rate on annealing kinetics, and result in designing conservative process cycles.

TRDDC developed an integrated process model with prediction capability extended to microstructure and mechanical properties during the batch annealing process. The model was extensively validated for several industrial batch annealing operations, and is capable of capturing nonisothermal kinetics, such as the effect of the heating rate on transformation kinetics. Figure 3 shows the thermal model, which ignores accelerated kinetics, provides cycles where reduction in the heating rate increases the cycle time. In contrast, the integrated batch annealing furnace simulator, which captures the nuances of phase transformations
(e.g., reduction in heating rate results in accelerated annealing kinetics for aluminum-killed, deep-drawing grade steel), designs a cycle having a reduced process time by reducing the heating rate. The difference is an opportunity area to enhance batch annealing productivity (see Fig. 3) by switching from the prevalent thermal model to the integrated model. This concept has already been implemented to achieve up to 9% productivity enhancement in a modern, highly automated industrial batch annealing operation [11-12]. (Such benefits were also envisaged by the authors of ASM Heat Treating Technology Roadmap, who identified integrated process models as an important technology enabler for significantly enhancing the process efficiency.)

Research Projects: Productivity and Efficiency Solutions

The group undertakes a number of research projects focused on developing innovative productivity and efficiency solutions for industrial thermal processing operations. As opposed to industrial projects where current operational constraints are imposed during solution formulation, a research project focuses on innovative concepts and solutions for industrial problems without being deterred by prevalent industrial constraints. Close interaction with industry helps to identify important research problems and issues facing this sector, and keeps the research focus relevant to the industry. In fact, the concepts for many research projects were initiated while executing industrial projects (Fig. 4).

For example, while developing integrated models for industrial operations, it was observed that conventional models are unable to capture nonisothermal effects present in the phase transformations. This resulted in a series of research projects that unraveled nonisothermal effects during thermal processing operations and led to the development of phase transformation models with improved prediction capability for such industrial operations. The results have widespread ramifications on improving process efficiency and product quality during thermal processing of materials (see the research case study on the nonisothermal effect). In another project on salt bath hardening, problems associated with oil quenching resulted in the development of eco-friendly quenchants (see the research case study on eco-friendly quenchants).

As mentioned above, strong emphasis is laid on quantifying the benefits accrued from the industrial projects. A formal framework of cost modeling with the capability of predicting process costs as a function of process parameters was developed to analyze, optimize, and quantify benefits from industrial heat treatment operations. In addition, the framework can also significantly enhance the value of process control applications through online monitoring of process costs. Case studies on industrial heating and reheating operations have been demonstrated.

Some important research projects carried out are:

- An integrated model for batch annealing operation [13-18]
- An efficient neural network model for the batch annealing operation [19]
- Heating rate effects during annealing of aluminum-killed steel [20]
- Development of an eco-friendly quenching medium for a hardening operation [2,4]
- Cost model for industrial reheating and carburizing operations [6,7,21]
- Development of oxidation-resistant coatings
- A novel image analysis-based technique for scale-loss quantification in reheating operation
- An online control system for reheating operations
- Model-based scheduling of continuous annealing operation [9,10]
- Modeling isochronal transformation kinetics [22,23]
- Accelerated kinetics during cyclic processing [24]
- Modeling the cyclic kinetics behavior [25]
- Cyclic thermal processing to obtain uniform microstructure [1]

As opposed to industrial projects, where the project performance is measured on the basis of quantifiable savings, the success of research proj-
ects is primarily evaluated on the basis of intellectual properties, such as patents and publications in peer-reviewed journals.

The following case studies illustrate the work being addressed in the industrial projects.

Nonisothermal kinetics: Better model, productivity solution, and improved quality through an innovative method. Linear approximation to nonlinear engineering problems often becomes essential to simplify mathematical complexities resulting in solutions with acceptable accuracy. The negative side of this approach is the likelihood of overlooking special nonlinear effects (if any) in the system. This is also true for thermal processing of materials where most of the phase-transformation models formulated for isothermal conditions are used to describe industrial nonisothermal processes by using the additivity principle; i.e., by approximating them as infinitesimal isotherms.

The limitation of this approach, in terms of poor model predictions and necessity of a large number of model parameters, was shown for a number of materials systems [20, 22, 23]. It was also shown that it is possible to improve the model prediction by using a functional relationship between the apparent activation energy of transformation to the heating rate. Furthermore, it was shown that the same log-linear relationship between the heating rate and activation energy holds good for a wide variety of materials systems, including polymers, metallic glasses and metals [22, 23]. Because the apparent activation energy decreased with heating rate, it was hypothesized that phase transformation kinetics could be accelerated during nonisothermal cyclic processing (Fig. 5). This hypothesis was experimentally proven for a number of phase transformations, including recrystallization and grain growth in steel and titanium alloys [24]. Subsequently, accelerated kinetics was modeled from first principles, starting from Langevin equation of motion and logarithmic susceptibility (LS) for escape to derive an additional nonisothermal rate constant to the Arrhenius equation. Furthermore, it has been shown that in addition to energy reduction and productivity enhancement, cyclic processing can also result in uniform properties across the component cross section during conventional thermal processing [1].

Development of eco-friendly quenching media as an alternative to quenching oil. Quenching oil is one of the most common quenching media in the industry. Generally, quenching oil provides a moderate cooling rate, and, therefore, results in minimal distortion in the component. Thus, many precision components such as gears and bearing rings are hardened by means of oil quenching. Although quenching oil has this highly advantageous cooling response, the use of oil as a common quenching medium for hardening of steel currently is associated with several environmental liabilities such as oil fumes, smoke emissions, fire hazard, oil spills, leaking underground storage tanks, ground water contamination, and waste oil-disposal liabilities.

With increasing environmental awareness as well as strict regulations, the use of oil as a quenching medium is being discouraged in many environmentally conscious countries. For example, in the U.S., used quenching oil is considered a hazardous waste, and its disposal is regulated by strict EPA used oil-management standards. This issue has also been emphasized in the ASM Heat Treating Society’s Vision 2020 technology roadmap, where replacement of oil as a quenching medium has been given very high importance to achieve zero emissions impact from the heat treating industry. Significant efforts have been made to develop synthetic organic polymer quenching media as an alternative to oil. However, most synthetic quenchants are proprietary and expensive, which limit their use.

TRDDC examined a number of eco-friendly quenchants from natural products, such as starch, as potential replacements for quenchant oils. Test results showed that composition and concentration of such quenchant media could be tuned to achieve critical temperatures and desired cooling rates (Fig. 6) suitable for
different material grades and component dimensions [2,3]. Being natural products without toxic fumes and after use disposal liabilities, these quenching media are environmentally friendly compared with quenchant oils, and quite inexpensive compared with polymeric synthetic quenchants—a realizable dream for heat treaters.

Research Collaboration and Academic Interactions

During the past six years, the group has built strong links with several academic institutions including Illinois Institute of Technology (Chicago), University of Utah, Indian Institute of Technology at Kharagpur, Kanpur and Madras, and College of Engineering at Pune. Several undergraduate and graduate students are trained in industrial research under a paid internship program. Some of these interactions have matured into research projects as bachelors and masters theses. The group is also geared toward carrying out contract research and collaborative projects with other research organizations. The group recently initiated research collaboration with Bay Zoltán Institute for Materials Science and Technology in Budapest, Hungary. The group also has strong ties with the ASM Heat Treating Society R&D Committee (USA), whose Research and Development Plan has provided a guiding path to the group, whereas the immense industrial experience of this group was used to update the R&D plan, as well as contribute to the technology forecast [36-29].

Looking Ahead

The group intends to consolidate its research program and continue its focus on industrially challenging problems. The academic ties and collaboration with other research organizations will be strengthened. Several new activities have been initiated including industrial heat treatment of aluminum components, developing cellular automata-based microstructural models for industrial operations, and developing integrated models for galvanizing and galvannealing operations. In addition, significant efforts are being made to proliferate the intellectual properties developed by this research group and implement them at several commercial operations.

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References

1. Sahay, S.S. and Krishnan, K., A method of thermal processing for production of component with uniform microstructure and properties across the component cross-section, Patent filed in India in 2005
12. Sahay, S.S., et al., In pursuit of cycle time reduction of a highly automated industrial batch annealing operation, Tata Search, 2, 387, 2006