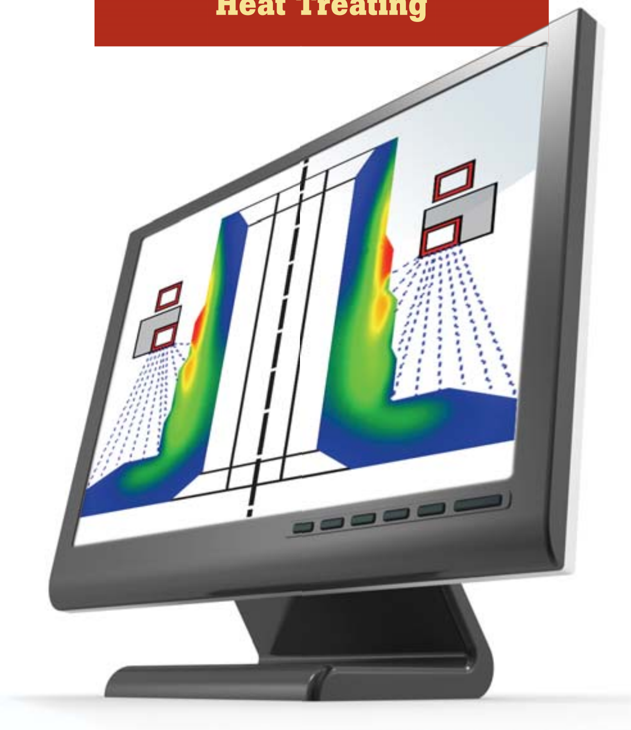

Computer Modeling of Induction Heating: Things to be Aware of, Things to Avoid

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In the last decade, when discussing subjects related to a computer simulation of induction heating, the word "usefulness" has been replaced by the word "necessity." Modern computer simulation is capable of effectively simulating electromagnetic and thermal phenomena for many processes, including those that involve electromagnetic induction.

By combining advanced software with a sophisticated engineering background, induction heating professionals possess the unique ability to analyze, in few hours, complex technological problems that could take days or even weeks to solve by running experiments or through physical modeling using the pilot models. Simulation provides the ability to predict how different, interrelated and nonlinear factors may impact the transitional and final thermal conditions. Simulation also helps to determine what must be accomplished to improve the effectiveness of the process, choose the most appropriate process recipes and serve as a comfort factor when designing new systems.

In 2007, ASM International began an ambitious undertaking to compile an all-new, comprehensive resource on modeling as it applies to a computer simulation of different metal-processing technologies. Carefully selected world-recognized experts from leading universities, national research laboratories and industrial corporations from 13 countries were chosen to submit materials. As a result, a brand-new two-volume set was published as a part of the ASM Handbook series (Fig. 1). The first part, "Volume 22A, Fundamentals of Modeling for Metals Processing," appeared in 2009. The second part, "Volume 22B, Metals Process Simulation," was published in 2010. This two-volume set covers a wide range of subjects including phase diagrams and transformations, heating and heat treating, casting and solidification, forming, joining, machining, powder metallurgy, integration modeling and equipment-design simulation.

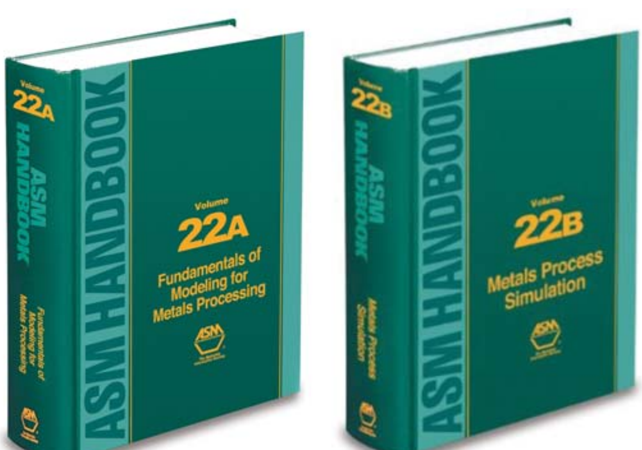


Fig. 1. ASM's new two-volume set on computer simulation of metal processing

Among other useful information, Volume 22B contains two articles (listed in the references) that are solely devoted to a computer simulation of induction thermal technologies.

How it was Done in the Past

An estimation of the process parameters based on single-formula "rules of thumb" as well as using the analytical methods and equivalent circuit coil design methods were popular in the 1960s through 1990s.[1,2] Though those techniques were easy to employ, they were very subjective with inherent major restrictions limiting their use for quick estimation of only ballpark parameters of induction systems. There was a danger of obtaining erroneous and inadequate results with such overly simplified estimations.

Recent advancements in high-performance computers increased the complexity of induction heating applications. It further increased the demands to manufacture higher-quality parts in combination with improving cost-effectiveness of the development stage by shortening the learning curve and reducing development time, which significantly restricted the usefulness of simplified formulas.

Rather than using computational techniques with many restrictions and disputable accuracy, modern induction heating spe-

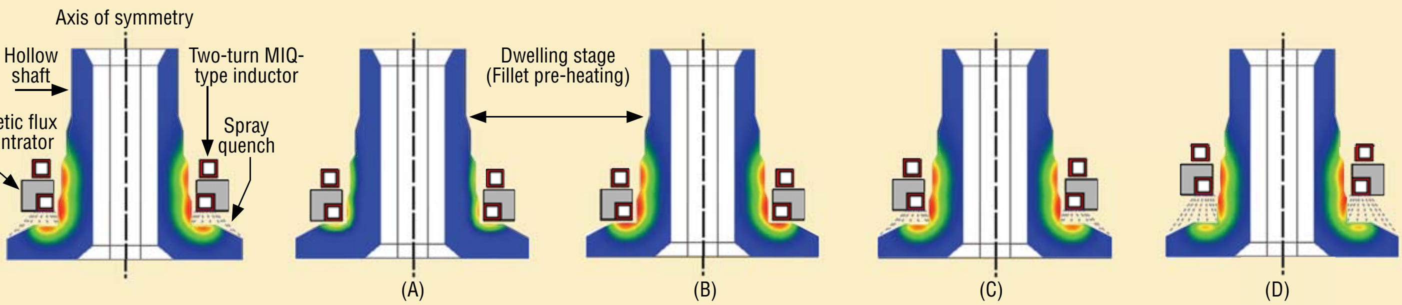


Fig. 2. Computer simulation of the sequential dynamics of induction scan hardening a hollow shaft using a two-turn machined integral quench (MIQ) inductor with an L-shaped magnetic flux concentrator ring (frequency = 9 kHz) *(Courtesy of Inductoheat, Inc.)*

cialists turned to highly effective numerical simulation methods such as finite differences, finite element analysis (FEA), edge elements, boundary elements and others. Each of those simulation techniques has certain pros and cons and has been used alone or in a combination with others.

In recent years, FEA became a dominant numerical simulation tool for a variety of engineering applications. Though FEA is a very effective modeling technique, it cannot be considered the ultimate computational tool for all induction heating applications. In some cases, a combination of different numerical methods is more effective, while FEA is a preferred choice for others.

Case Study: Scan Hardening

Numerical computer simulations allow manufacturers of induction equipment to determine comprehensive details of the process that would be difficult, if not impossible, to determine experimentally. As an example, Fig. 2 shows the results of computer modeling the sequential dynamics of induction scan hardening a hollow shaft using a two-turn MIQ (machined integral quench) inductor with an "L"-shaped flux concentrator ring (frequency = 9 kHz).

At the beginning (Fig. 2, A and B), a 2.6-second power dwell is applied to properly heat the shaft fillet area. During this stage, an inductor is energized but does not move, and quenching is not applied. Upon completing the dwell stage, the shaft fillet is sufficiently preheated and scanning begins. Scan rate and coil power are varied during scanning to allow proper accommodation of changes in shaft geometry. Computer modeling reveals several important process subtleties:

- During scanning, appreciable heating of the shaft begins at a distance a good deal above the top copper turn, creating a preheating effect. Factors responsible for preheating are heat flow in the axial direction due to thermal conduction and propagation of the external magnetic field, which generates heat sources outside of the induction coil.
- Presence of an external magnetic field outside the induction coil is also responsible for the post-heating of shaft areas located immediately below the bottom turn and, in some cases, even in regions where the subsequent quenchant impinges the shaft surface. With insufficient quenching, the latter can dramatically reduce quenching severity and potentially create conditions for crossing the nose of the CCT (continuous cooling transformation) curve. The result would be the formation of mixed structures with the presence of upper transformation products (e.g., bainitic/pearlitic structures or "ghost" networking). Such microstructures are notorious for scattering and lower hardness readings.
- Electromagnetic proximity effect and coil end effect both cause the hot spots appearing on a shoulder near a shaft diameter change. During scanning, the magnetic field preferably couples to the shoulders, leading to a power density surplus at those locations. The presence of hot spots produced by power surplus necessitates having prolonged cooling to remove excessive heat, which ensures sufficient hardness by martensite formation. At the same time, a heat deficit could occur in the undercut region and transition area near the shaft's smaller diameter.

Comet-Tail Effect

It is imperative to take into consideration a "comet-tail" effect when developing a scan-hardening process recipe. Figure 3 shows a magnified temperature pattern of an intermediate process stage (Fig.2, F). The comet-tail effect manifests itself as a heat accumulation in shaft subsurface regions below the scan inductor. This effect is pronounced in the areas of a diameter change. Upon quenching, the temperature of the shaft surface can be cooled sufficiently below the M_s temperature. At the same time,

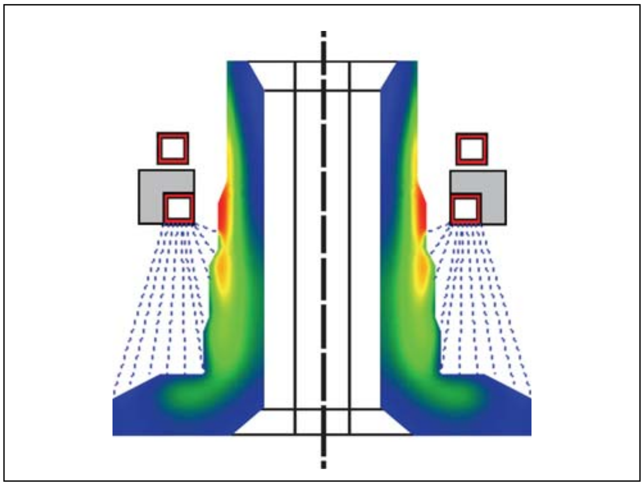
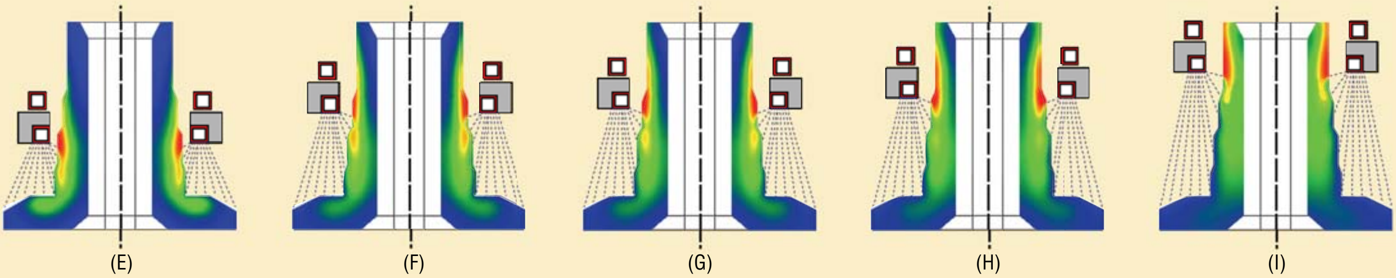


Fig. 3. The comet-tail effect manifests itself as a heat accumulation in shaft subsurface regions below the scan inductor. *(Courtesy of Inductoheat, Inc.)*



the heat accumulated in the shaft subsurface might be sufficient for the tempering of as-quenched surface regions and could potentially result in the appearance of soft spots within the case depth. Sufficient quench-out is essential to prevent this undesirable phenomenon.

Critical Issues with Computer Modeling of Scan Hardening

A limitation of the great majority of commercially available software is that they are not capable of taking into consideration a comet-tail effect when trying to model induction scan hardening. In addition, some software cannot properly handle pre- and post-heating effects as a result of external magnetic-field propagation and axial heat flow due to thermal conduction. Make sure that applied software is free of these restrictions and properly models all-important physical phenomena.

When designing inductors and developing optimal process recipes, it is imperative to properly model not only heating but the spray-quenching stage as well. Otherwise, crucial aspects of the process might be missed, having a negative impact on modeling accuracy and its usefulness.

Before You Hire Somebody to do a Computer Simulation

First Step

It is important to remember that any computational analysis can, at best, produce only results that are derived from the correctly defined theoretical model, governing equations and boundary conditions. Therefore, before you hire somebody to do computer simulations, make sure that the analyst(s) has a clear understanding of the process specifics and has an appropriate education in the area where you are seeking help. For example, when you are flying an airplane, you expect a pilot to have appropriate training. When you need medical assistance, you expect a doctor to have a proper education and appropriate medical degree. The same principle should be applied when you are choosing a company or analyst to do computer simulations for you.

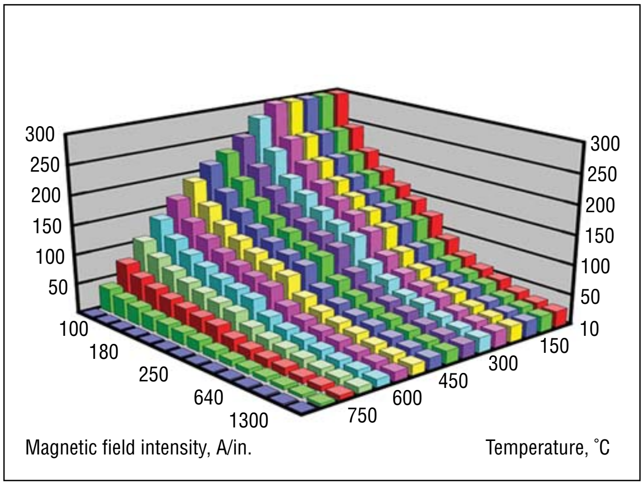


Fig. 4. Relative magnetic permeability as a function of magnetic-field intensity (range 100-1500 A/in., or 39-590 A/cm) and temperature (range 10-750°C)

Second Step

Make sure that physical properties of heated materials are properly defined. The well-known but rude saying "garbage in – garbage out" clearly indicates a necessity of having accurate physical properties. Experience shows that poorly determined material properties are responsible for an appreciable amount of simulation errors. Only reliable sources should be used when adapting physical properties.

Third Step

It is important to recognize that the use of modern numerical software (including finite elements, boundary elements, etc.) does not guarantee obtaining correct computational results. It must be used in conjunction with experience in numerical computations, proper education and engineering knowledge to achieve the required accuracy of mathematical simulation. This is especially so because even in modern commercial software, regardless of the amount of testing and verification, a computation program may never have all of its possible errors detected. The engineer must, consequently, be on guard against various kinds of possible errors. The more powerful the software, the more complex it is with a greater probability of errors. Be aware that computer-generated attractive pictures might be misleading if obtained by amateur. Common sense, engineering "gut feeling" and advanced education are always the analyst's helpful assistants.

Physical Properties Issue

Electromagnetic properties of heated materials encompass a variety of characteristics. While recognizing the importance of all electromagnetic properties, two of them – electrical conductivity (its reciprocal electrical resistivity) and relative magnetic permeability – have the most pronounced effect on the induction heating process. Keep in mind that both properties nonlinearly vary with temperature, chemical composition, microstructure, grain size, etc.

Relative magnetic permeability, μ_r, is not only a complex function of grain structure, chemical composition, microstructure and temperature but also frequency and magnetic-field intensity. The same kind of carbon steel at the same temperature and frequency can have a substantially different value of μ_r due to differences in the intensity of the magnetic field. Figure 4 illustrates the complex relationship among μ_r, temperature and magnetic-field intensity for carbon steel.

Three of the most critical thermal properties of heated material comprise thermal conductivity, specific heat and surface heat losses due to thermal radiation and convection. All these thermal properties are also nonlinear functions of temperature.

The interrelated nonlinear nature of the material properties dictates the necessity of developing special computational algorithms that combine electromagnetic and thermal phenomena. There are several ways to couple the electromagnetics and heat transfer when modeling induction heating, including a two-step approach, indirect coupling and direct coupling. Even a cursory look at the behavior of the material properties reveals the danger in using some of these approaches in certain induction heating applications. Critical review of applicability of these coupling techniques is provided in reference 2.

Limitation of Some Commercial Codes

A great majority of commercial codes used for computer modeling of induction heating processes are all-purpose programs. Regardless of well-recognized, impressive capabilities of modern commercial simulation tools, some generalized programs experience difficulties taking into consideration certain features of a particular induction heating application. This includes, but is not limited to the following: the presence of thermal refractory; heated workpiece can simultaneously move, rotate or oscillate with respect to induction coil; scanning operation that combines heating and quenching; simultaneous use of two frequencies for contour gear hardening; nonuniform initial temperature distribution; etc.

Therefore, be aware that some critical feature(s) of a particular induction heating application could be a limiting factor in creating considerable challenges for a majority of presently available generalized commercial software, affecting an accuracy of simulations. This subject has been discussed in detail in reference 2.

Conclusion

In a fast-paced world economy, the ability of induction heating manufacturers to minimize time between a customer request for quotation and quotation through efficient computer modeling is critical for company's success. In addition, in opposition to academia, the fast pace of industry does not often allow the luxury of waiting several days in order to obtain the results of modeling. Industry demands the reliable results of computer simulation within a few of hours. Measures should be taken to ensure that a properly educated analyst using proper simulation software conducts a computer modeling. **IH**

References:

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