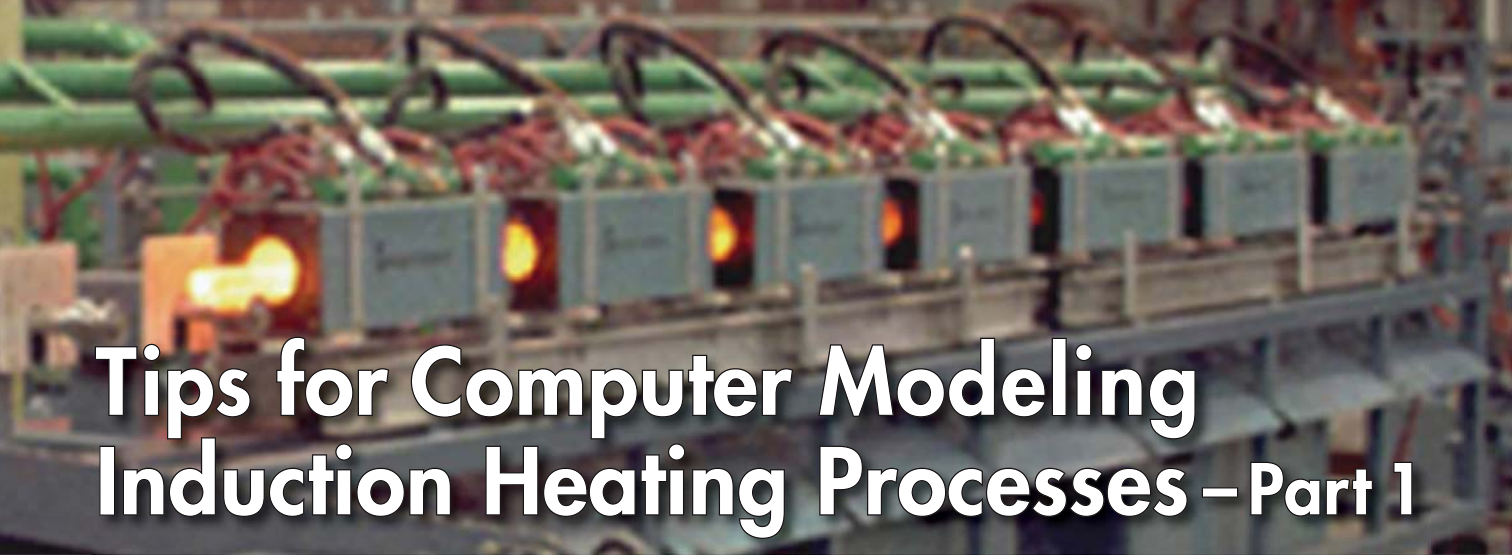

# Tips for Computer Modeling Induction Heating Processes – Part 1

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Figure 2. Seven-coil in-line induction bar heater

**Computer modeling is no longer just a useful tool, it has become a necessity. Computer simulation provides the ability to predict how different factors may affect the transitional and final thermal conditions of a heated workpiece and what must be done to determine the most appropriate process recipes.**

When designing new systems, computer modeling helps to minimize unpleasant surprises and shortens development time. Estimation of process parameters based on single-formula "rules of thumb" was popular between 1960 and 1990. Although those techniques were easy to employ, there was always a danger of obtaining erroneous and inadequate results from such overly simplified techniques.

## Numerical Computer Modeling

Rather than using single-formula rules-of-thumb modeling techniques, modern induction heating specialists have turned to numerical simulation methods such as finite differences, finite elements, edge elements, finite volumes, boundary elements and others. Each of these techniques has certain pros and cons and has been used alone or in combination with others.

Certain numerical methods or software are preferred for each type of induction heating application. There is not a single universal computational method that optimally fits all types of applications. In recent years, the finite element method (FEM) became the dominant numerical simulation tool for a variety of engineering applications. Though FEM is a very effective modeling technique, it is not the ultimate computational tool for all induction heating applications. In some cases a combination of different methods is more effective.

Let's review a simple example. Any computer-modeling technique requires a network mesh of the modeling area, which includes induction coil(s), the heated workpiece, fixtures and other electrically conductive bodies in close proximity to the induction coil(s). Specifics of mesh generation affect the accuracy of simulation, the required time for pre- and post-processing and the actual time to run simulations. Figure 1, for example, shows network meshes for the three most popular modeling techniques.

Even a cursory look at network meshes reveals that the selection of one technique over another depends on the specifics of the particular induction application. It is easy, for example, to apply the finite-difference method (FDM) when the modeling area has simple geometries, such as cylindrical or rectangular. The orthogonal mesh divides the area of simulation into a finite number of nodes (Figure 1, left). Because of the orthogonal grid, the modeling algorithm is simple. This method is quite universal because of its relative simplicity to apply.

The FEM is another group of numerical techniques devoted to obtaining an approximate solution for different technical problems, including those encountered in induction heating. Whereas the FDM provides a point-wise approximation, the FEM provides an element-wise approximation of the governing

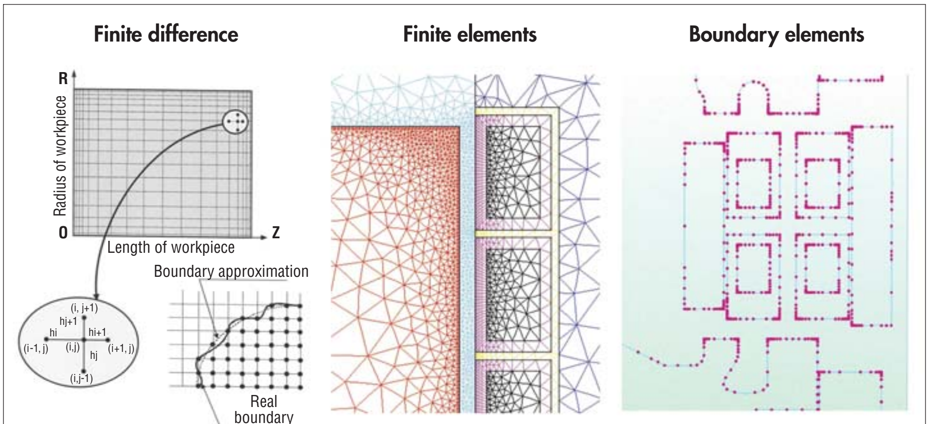


**Figure 1. A comparison of network meshes for the three most popular computer modeling techniques used in induction heating: finite difference (FDM), finite element (FEM) and boundary element (BEM).**

equations. According to FEM, the area of study is divided into the finite element mesh as shown in Figure 1, center.

FDM is usually not as well-suited as FEM for the simulation of induction heating systems with complex boundary configurations or in the case of a mixture of materials and forms. In this instance, FEM has a distinct advantage over FDM. The need to always carry out a computation of the electromagnetic field in the air, however, is a disadvantage of both the FDM and FEM analyses.

With the boundary element method (BEM), only the boundaries of the electrically conductive components of the induction system are considered (Fig.1, right). This substantially simplifies one of the most time-consuming parts of numerical model preparation compared to FDM and FEM and dramatically reduces computational time.

Continuous and progressive multi-stage horizontal heating are two popular technologies used to heat small- and medium-size bars and billets. Two or more heated workpieces (i.e. billets, blanks, bars) are moved (via pusher, indexing mechanism, walking beam, rolls, etc.) through a single coil or multi-coil induction heater. Components are sequentially heated at certain predetermined heating stages. Figure 2, for example, shows an induction system consisting of seven inline induction coils.

Quite often, the length of multi-stage systems exceeds 15 feet and, in some cases, can be as long as 70 feet. In long systems, because FDM and FEM require mesh generation not only within the heated workpiece and induction coil(s) but also in the air around them due to electromagnetic field propagation outside of induction coils, computational time can be exceedingly lengthy. Another challenge in modeling such a system arises from the fact that the surface-to-core temperature profile of the workpiece continues to change as the bar passes through the line of induction coils. In such cases, Inductoheat's proprietary modeling software, called ADVANCE, allows for the effective and accurate modeling of the system.

### Limitations of Generalized Modeling Software

Many of the commercial codes used for computer modeling of induction heating processes are all-purpose programs developed primarily for modeling electro-thermal processes taking place in electrical machines, motors and other devices that were later adapted to induction heating applications. The need to sell their products to as many customers as possible forced early software developers to produce universal simulation tools that could be used within a broad industrial base.

## Case Study: FluxManager Technology for Stress Relieving Pipe Ends

The stress relieving of steel tube/pipe ends is typically done prior to the machining of the thread. To accomplish this, the tube/pipe end is placed in a multi-turn induction coil and heated for the specified time and specified process parameters, which include final part temperature, required heated pipe-end length and other parameters.

Some applications call for a sharp longitudinal heat transition zone while others require certain transient temperature profiles. Pipe diameters typically range from 0.375-20 inches with wall thicknesses from 0.150-1.25 inches. The length of heated tube/pipe end ranges from 2-18 inches, depending upon application specifics. In many instances, achieving axial and radial temperature

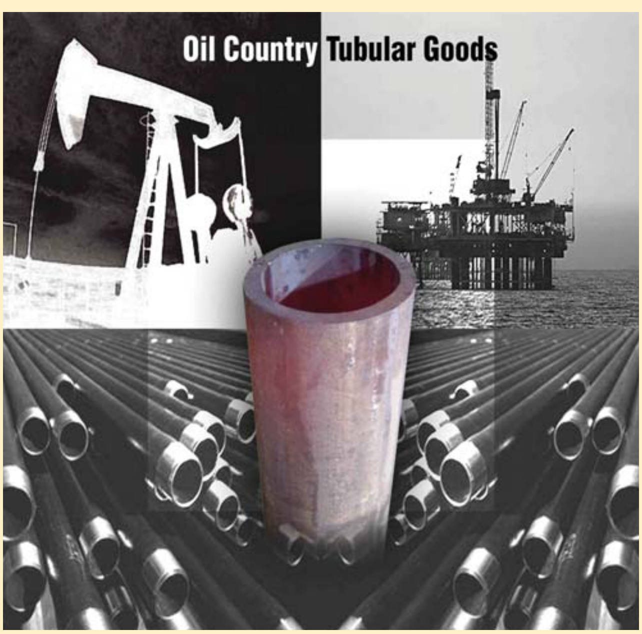


Figure 3. Oil-country tubular goods require stress relieving of their ends.

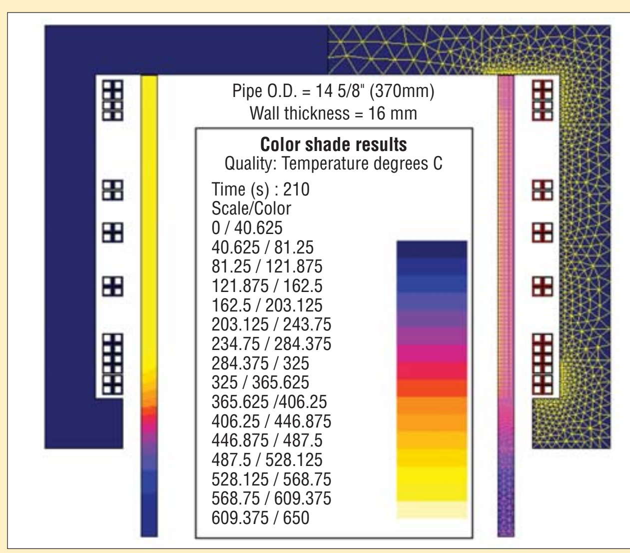


Figure 4. FEM analysis of induction heating a 12-inch-long end portion of a 14.625-inch-diameter carbon-steel pipe with a wall thickness of 0.625 inch from ambient temperature to 1110°F. FEM mesh is indicated on the right side.

Consequently, certain process subtleties related to induction heating were either overlooked or substantially simplified by software developers. The result is that many generalized programs cannot address certain features of specific induction heating applications. Some of the difficulties include:

- The presence of a thermal refractory and the necessity to take thermal radiation view factors into consideration
- A heated workpiece that simultaneously moves, rotates or oscillates relative to the induction coil(s)
- Operations that combine heating and quenching process stages
- The existence of nonuniform initial temperature distributions
- The presence of end plates, guides, fixtures, liners, etc.

Imagine, for instance, that you have purchased software to simulate two polar process stages (cold-start and hot-start) of induction billet heating prior to forging. Cold-start represents a process condition in which the induction heater was switched off for a sufficiently long time and its thermal refractory was cooled down to ambient temperature (such as after a long weekend). In contrast, hot-start designates a condition in which there was a relatively short interruption in the process cycle. Suppose you know the physical properties of the refractory's material, thickness, geometry, etc. and, therefore, expect to be able to predict the effect of a cold-start versus a hot-start on billet thermal conditions. Suddenly, you might realize that your software package does not allow inputting specifics of a refractory design. The manual suggests that the user somehow quantify the effect of refractory temperature on a billet's thermal boundary condition. Unexpectedly, such a common design feature of any induction forge heater becomes an obstacle when using generalized modeling software.

Our experience shows that there is not a single universal computational method that optimally fits all induction applications. As a result, our software designers utilize and integrate both commercial and proprietary computer-modeling techniques. This allows them to select the technique that is most appropriate to a particular application and a particular induction heating system.

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uniformity is imperative for a quality product.

Historically, induction tube/pipe-end heating has been very successful. Recent trends to increase pipe wall thicknesses for oil-country pipes (Figure 3), combined with tighter requirements for heat uniformity, have illustrated several drawbacks of using higher frequencies versus line frequency when heating thick-wall magnetic steel pipes to stress-relief temperatures. These include:

- When heating thick-wall pipes, the "skin" effect (even at line frequency) is very pronounced and the ratio of "wall thickness to eddy-current penetration depth" is quite large. Higher frequencies tend to increase this ratio. Therefore, there is a danger of localized overheating to the outside surface of thick-wall magnetic pipes, which could result in an undesirable heterogeneous stress-relieving structure.
- Higher frequencies are noticeably more sensitive to pipe positioning inside the induction coil. This means that even slight variations in coil-to-pipe proximity due to non-symmetrical positioning could lead to an appreciable temperature variation at the pipe end. This lowers process repeatability and negatively affects process controllability, typically resulting in the appearance of "hot" and "cold" spots.
- High frequencies require using solid-state inverters that, in some cases, could appreciably increase the capital cost of the machinery.

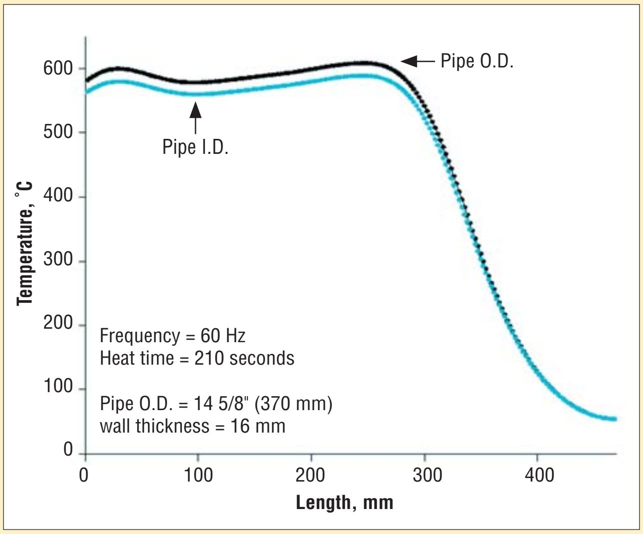


Figure 5. Axial (longitudinal) temperature distribution

Computer simulation is an ideal tool to determine the appropriate coil design and heat recipe for this application. Figure 4 shows an example of FEM applied to the induction heating of a 12-inch-long end portion of a 14.625-inch-diameter carbon-steel pipe with a wall thickness of 0.625 inch from ambient temperature to 1110°F. The required temperature uniformity of ±36°F at any point within the required end region of the pipe is achieved using FluxManager technology (frequency = 60 Hz).

The induction coil comprises five groups of turns (8 + 4 + 4 + 4 + 12 turns). Lamination shunts placed outside the induction coil enhance heat efficiency and repeatability. Figure 6 shows axial (longitudinal) distribution of outside diameter and inside diameter.