Computer Simulation of Induction Heating and Quenching Processes

Dr. Valentin S. Nemkov, Chief Scientist
Mr. Robert C. Goldstein, Engineer
Centre for Induction Technology
1388 Atlantic Blvd., Auburn Hills, MI 48326
Phone 1 (248) 393-2200
Fax 1 (248) 393-0277
Dr. Vladimir A. Bukanin, Professor Associate
Mr. Alexei Zenkov, Engineer
Mr. Dmitri V. Koutchmassov, Engineer
St. Petersburg Electrotechnical University
Prof. Popov St. 5, St. Petersburg, Russia
Phone/Fax 7 (812) 234-3060

Abstract

Computer Simulation is an effective tool for the design of induction heat treating processes and coils. The experience, of the authors, in the development and practical use of different programs for 1-D and 2-D simulation of induction heating processes is presented in this paper. A comparison, of simulation versus experimental approach, is discussed. Special attention is paid to simulation of the quenching process. ELTA, a 1-D coupled electromagnetic and thermal program, is utilized for a study of a quenching process after induction heating. Temperature dependent heat transfer coefficients for spray quenching with different intensities of quenchant supply are used in the study. It's shown that the accuracy, of computer simulations of the quenching process, is mainly limited by the accuracy of the heat transfer coefficients and for better prediction of the results more experimental study must be done.

Introduction

Computer simulation is becoming more and more popular in the study, development, setup and maintenance of induction heating processes and equipment [1]. Many experts and groups in different countries are developing programs for induction heating simulation. Different methods used to solve the field problems include: Finite Difference Method (FDM), Finite Element Method (FEM), Volume Integral Method (VIM), Boundary Element Method (BEM) and their many variations and combinations [2,3,4].

However, computer simulation is not as widely used in induction heating as in electrical and mechanical engineering. This may be explained by the following reasons:

- Induction heating processes are usually complex. In general, it is necessary to simulate a set of mutually coupled non-linear and multi-dimensional problems (electromagnetic and thermal fields, quenching process, structural transformations, distortions, external supplying circuits etc., Figure 1);
- Induction processes, especially heat treating processes, have very diverse features which may require individual program structures and simulation methods;
- Personal computers with the high processing speeds and large available memory required for simulation of many of induction problems, only recently became widely available;
- The induction heating market is small compared to other industrial sectors and the development of specialized commercial codes for the induction heating sector is a low profit or possibly even unprofitable venture.

Strategy and Tools for Simulation

The programs for simulation of induction heating and quenching processes may be classified as 1-D coupled (electromagnetic + thermal), 2-D electromagnetic, thermal, or coupled, and 3-D electromagnetic or thermal. The majority of 2-D and 3-D programs used for induction heating simulation originate from the companies specialized in development of general purpose software for calculation of physical fields in electrical engineering. For induction heating simulation, we use only a part of whole package, usually an "eddy current block", a "thermal block", or a combination of these blocks with an electric circuit block (power supply circuitry). The programs usually do not have the proper data bases necessary for induction heating or the explicit means for simulation of the induction heating machine performance (scanning, pushing of billets etc.). Many of them must be adapted for simulation of real induction heating processes. Flux 2D is probably the exception from the rule, because it has been developed taking into account the special features of induction heating processes [2].

Induction heating coil designs and operating conditions are very diverse and different programs are necessary in order to meet the practical needs. Theoretically we can assume that a single, universally coupled 3-D program would be able to meet all the major needs of the simulation of induction heating systems. However, at the present time, no program like this exists despite tremendous progress in computer hardware and software tools. Any 3-D code requires powerful computers and the process of simulation is knowledge and time consuming. Workstations or the most powerful personal computers must be used. One week of work for a skilled operator may be used as an estimate for the average time for one case study electromagnetic simulation. This estimate takes into account the operator’s laborious preparation of input data, checking and correction of the almost inevitable errors or inaccuracies, geometry and mesh construction, physical property and boundary condition description, calculation itself and the analysis of the results. The complexity of 3-D analysis and the required skill of the user makes a direct 3-D optimization of induction heating processes and systems rather difficult. A strategy based on a hierarchical use of programs is the most effective [1].

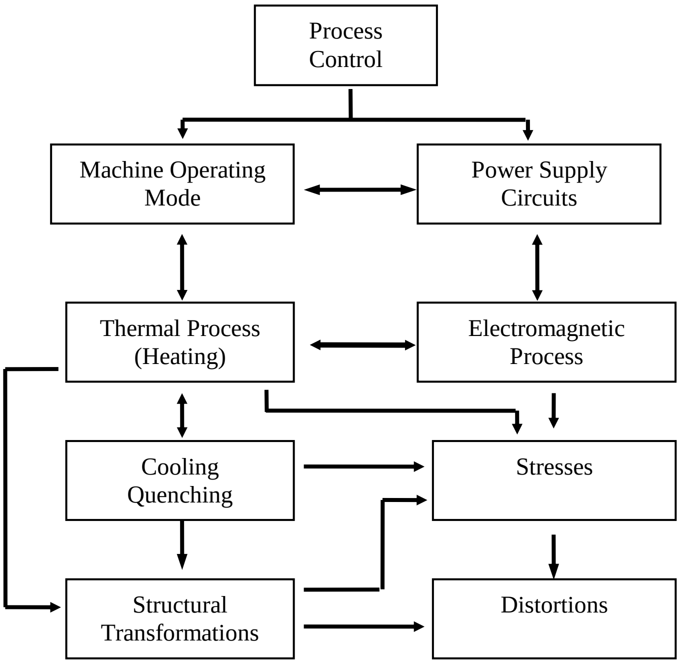


Figure 1 Main process in induction heat treating machine

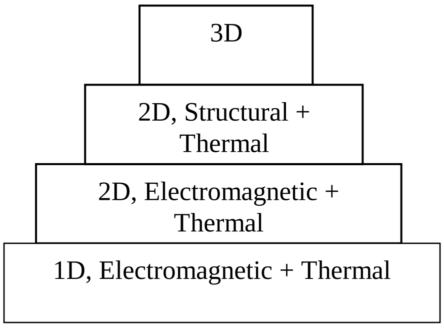


Figure 2 A rule of pyramid for computer simulation of induction heating

For most cases, the first stage in the simulation of the induction heating system should be a 1D coupled program. This allows you to study the influence of frequency, power density, quench type, and time variations on the process. The ranges of interest can be studied quickly and effectively. A good estimate for the heating time, coil power, coil voltage, and coil current can be made from the results of the 1-D simulation.

The second stage in the simulation may be done using 2-D electromagnetic or coupled code. The coil current, tube profile, coupling distance and magnetic flux concentrator dimensions that furnish the required field and power intensity may be determined. With this strategy, a 3-D simulation and/or experiments are only required for the coil design correction for the end zones where 3-D effects are significant.

The above analysis is based on the author’s current experience, but we believe that it reflects the existing situation in general. An inductor, in many cases, is made from a solid piece of copper by machining and it is difficult and expensive to modify it after it has already been built. Computer simulation plus the application of versatile magnetic flux controllers made of magnetodielectric materials provide an effective solution for the coil design [5,6]. This general approach may be called "a rule of pyramid". It states that more simple programs must be used as a basis for the further use of more complicated packages (Fig. 2).

Simulation Versus Experiments

For some processes, computer simulation provides very exact results and experimental tests may be quite unnecessary. Through heating of billets is an example of this type of process. The system geometry is simple, material properties are relatively well defined, and the magnetic permeability is equal to one during the major part of the process. In this case, only electromagnetic and thermal processes need to be simulated. For other processes, the accuracy of the results obtained from simulation may be lower. Surface hardening is a good example of this, because of the more complex nature of the process. More phenomena must be involved in the simulation to obtain the final results. The initial part of the coil design problem and process simulation may be rather far from the final metallurgical result. The case depth and hardness are separated from the coil design and power supply setup by electromagnetic and thermal process, quenching and structural transformations. Inaccuracies during each stage of computer simulation can accumulate resulting in more significant final discrepancies.

There are three sources of inaccuracy in computer simulation: errors of computation, mathematical description of the process and material properties or process parameters. The errors of computation depend strongly on the algorithm of the process simulation and the discretization of the problem in space and time. These errors may usually be controlled by the program user and can be reduced to a negligible value. Electromagnetic and thermal processes are quite accurately described by the Maxwell and diffusion (Fourier) equations respectively. With correct physical properties of materials, the solution of these equations may definitely be accurate. The processes of structural transformations and quenching have no accurate mathematical description. Existing descriptions of these processes are approximations of experimental data with parameters depending on the material composition and operating conditions [7]. These parameters and the inaccuracy in the physical properties of the material to be treated are the main sources of error in simulation.

Specific heat and thermal conductivity as functions of temperature are necessary for simulation of any heating process. For induction heating, we also need to know electrical resistivity versus temperature and magnetic permeability versus temperature and field strength. The errors in temperature field prediction resulting from material properties inaccuracy depend on the process type. For surface hardening they may be rather small because a surface layer of steel is nonmagnetic during the final stage of the cycle and the material properties are well defined. Correct temperature prediction in the simulation of the tempering process where the steel is magnetic and the high temperature properties are not as well defined may be more difficult. Errors in the prediction of the results of structural transformations, residual strengths and distortions may be more significant.

However, the results of computer simulation are very valuable even if they are not quite correct. With a series of calculations, the user can find the system’s response to the intended (process design) or unintended (input data tolerance) variation of parameters. He can then modify the process or design without experimental tests. Even more, an automatic optimization of the coil and process design may be effectively performed in some cases. For example, an optimal distribution of the coil ampere-turns may be found which provides a desired power or temperature pattern in the length of the workpiece.

A simulation’s accuracy may be improved by using the results of experiments or by a study of material properties for the different stages and parameters of the process. The existing data on structural transformation in steel during heating and cooling refers mainly to furnace heating conditions. The local heat concentration, high heating speeds and short processing cycles typical for the induction method influence material response to heat treatment. A special study of steels` properties for the purposes of induction heating computer simulation is strongly desired. It is especially important for the powder metal parts industry, where information on electromagnetic and thermal properties is almost non-existent.

The situation in computer simulation changes quickly and according to the opinion of experts in the USA, “computer simulation is one of the main trends in improvement of the induction heating processes”. Flux 2D and ELTA, programs used by the authors in practice, research, and design are described below.

Features and Capabilities of Flux 2D

Flux 2D is a 2-D coupled electromagnetic plus thermal program [2]. It is available on Unix, Windows 95, Windows 98 and Windows NT platforms. Flux 2D uses the Finite Element Method (FEM) to calculate the magnetic fields, currents and temperatures in the induction coil(s), surrounding area(s) and workpiece(s). Flux 2D contains a series of modules corresponding to the different steps in creating and running a computer simulation. These modules contain many preprogrammed functions to model common types of induction systems and material properties. For problems in which the system can not be described with a preprogrammed operation in Flux 2D, there is a User module that allows you to write your own subroutines in FORTRAN.

Flux 2D has a module designed for building and meshing a system of any shape in polar or cartesian coordinates. The user can model only part of the system by placing lines of symmetry to save on memory and computation time. Flux 2D also gives you good control of the mesh. For example, you can leave certain regions unmeshed (like the water cooling channel of a coil which doesn't influence the magnetic field distribution) to save memory. Flux 2D uses second order elements of triangular and rectangular shape to allow for linear changes of values across an element. Flux 2D also contains an automatic mesh generator which is very useful as a first draft, especially for users not familiar with mesh construction.

In Flux 2D, any type of material heating can be modeled. You can use anisotropic and nonlinear materials in addition to isotropic and linear ones. Flux 2D has a database that contains properties of some common materials (graphite, copper, etc.). You can also add your own materials to the database. To help you in doing this, Flux 2D contains many preprogrammed forms for physical properties. For example, to account for the peak in specific heat capacity near the phase transformation temperature, Flux 2D contains a function that combines Gaussian and exponential functions. If the behavior of some material's properties doesn't fit any of Flux 2D's forms, you can opt to describe the material's properties in the User module.

The User module can also be used to simulate quenching. The heat transfer coefficient (α) you use can be both time dependent (heating and quenching stages) and temperature dependent (for non-linear α). For example if you had a 3 second heating stage followed by an oil quench, you could make α zero for the interface with the part and the voltage in the coil constant for the first three seconds. Then you could make α temperature dependent with the properties of an oil quench and set the voltage in the coil to zero for the rest of the heating cycle. There is no limit to the number of heating and cooling stages you wish to use for a simulation.

Flux 2D's postprocessor allows the user to view the results in many ways. For any time step in the process, Flux 2D can display many physical, electromagnetic field, and thermal field quantities in color shades, vectors, or isovalue lines for all or part of the geometry. Flux 2D can also graph these values along an arbitrary straight line or arc. Within regions, Flux 2D has preprogrammed functions to calculate integral quantities (total power, total current, etc). If the integral quantity you wish to know isn't listed in the Flux 2D menu, you can enter in the formula to be integrated and Flux 2D will calculate it. For a number of time steps in the process, Flux 2D can graph any of the non-integral quantities versus time for any point in the geometry. The integral quantities can be graphed versus time for a given region of the system.

Features and Capabilities of ELTA

The ELTA program (ELectro Thermal Analysis) has been developed specifically for use in the induction heating industry as a practical tool for induction through and surface heating and many other applications [5]. It may be run on PC 486 or higher and is very user friendly. No special knowledge in computers or in induction heating simulation is necessary. The user must only choose the options in standard Windows style menu. The workpieces may be cylindrical (solid or hollow) or flat in the form of single or multi-layer plate with an induction coil on one side or on the both. Multi-layer thermal insulation may be inserted between the workpiece and the coil. Databases of the workpiece and refractory materials offer default or customer installed properties. For dependence of permeability versus temperature and field intensity $\mu(H,T)$, an analytical formula $\mu(T)$ has been used with a default or customer defined dependence $\mu(H)$ at room temperature.

Operating conditions may contain a set of time intervals with user defined coil current, voltage, power and frequency setup on each time interval (stage). Heat exchange conditions may be set separately on external and internal surfaces during heating, pause or cooling stages.

The heat exchange conditions available are: heat exchange between refractory and the workpiece, free heat radiation, heat transfer coefficient. A heat transfer coefficient may be constant on each interval or temperature dependent, specified for each cooling media and cooling method (immersion in oil, polymer quenchant or water, water or oil showers of different intensities etc.). Corresponding curves of heat transfer coefficient $\alpha(T)$ may be chosen automatically from the database or added thereto by the operator (Figure 3).

Calculation time for a process of heating and water shower quenching using PC 486, 100 MHz is from some seconds to 1-2 minutes depending on process complexity, input data and desired level of accuracy (normal or high precision). The greatest time is required for simulation of intensive quenching when the temperature gradients and cooling speeds are very high while the heat transfer coefficient depends strongly on the surface temperature. A special method of solution of a system of algebraic equations has been used in order to provide fast and stable calculation process.

The results of calculations may be shown in the form of tables or curves. Coil current, voltage, power, electrical efficiency, power factor variation in time, and other data as well as energy consumed by the workpiece are available with documentation in a report form. 3-D presentation of temperature in coordinates “time - radius” may be very useful for evaluation of the process dynamics. Cooling diagrams with natural and logarithmic time scales can be used for predicting hardness depth and structural transformations.

The program is especially effective for the design of multi-stage processes. For example, the process can consist of heating, soaking, quenching, second heating at another frequency for tempering with a partial use of residual heat, and final cooling. The user can interrupt the calculation process at any time, modify the operating conditions and continue the design of the process stage by stage. Temperature dynamics curves at any point of the workpiece allow the user to choose optimal operating conditions, to define time intervals and power levels and to predict the hardness depth, energy consumption and production rate.

Development of the Induction Heat Treating Process for Heavy-Walled Tubes

Presented below is an example of induction heat treating process development using computer simulation. The "rule of pyramid" is followed in this example. The 1-D coupled electromagnetic plus thermal program ELTA and the 2-D coupled electromagnetic plus thermal program PERI have been used for simulation.

The process is induction heat treating of heavy-walled drill tubes. The tubes are 7 cm thick with an inner radius of 4.5 cm. The length, of the end that must be heat treated, is 150 cm. The steel contains 0.4% C, 1% Cr, 2% Ni, 0.5-0.8% Mn, and 0.2% Mo. The tubes are heated using line frequency (50 Hz). There are five steps in the heat treating process: austenitizing; quenching; two-stage tempering; and the final cooling.

Heavy-walled drill tubes have very tight specifications for surface hardness and structural distribution. The tubes surface hardness must be 35 ± 2 HRC. The achievement, of uniform surface hardness and structural characteristics on the length of the workpiece, requires a uniform temperature distribution during the hardening and tempering stages. To meet the surface hardness specification, the temperature variation during austenitizing and tempering must be no more than ± 15 C. The austenitizing temperature is 900 C and the tempering temperature is 600 C.

The first stage in the simulation is to design the quenching process. The 1-D program ELTA is an effective tool for this purpose. A low intensity, water spray (.28 m^3/m^2 sec) was selected for quenching the tube from its initial temperature of 900 C. The cooling curves are tracked for different radii from the instant the temperature drops below 800 C when the phase transformation starts (see Figure 3). Figure 3 also contains the continuous cooling transformation diagram for this steel. We can conclude that this quench gives us a 1 cm thick martensite layer on the surface, while the rest of the tube is bainite. Simulation showed that increasing the intensity of the quench would not provide a deeper hardness depth, because of the large thickness of the piece. The above simulations gave us the duration of the quenching stage and confirmed the process feasibility.

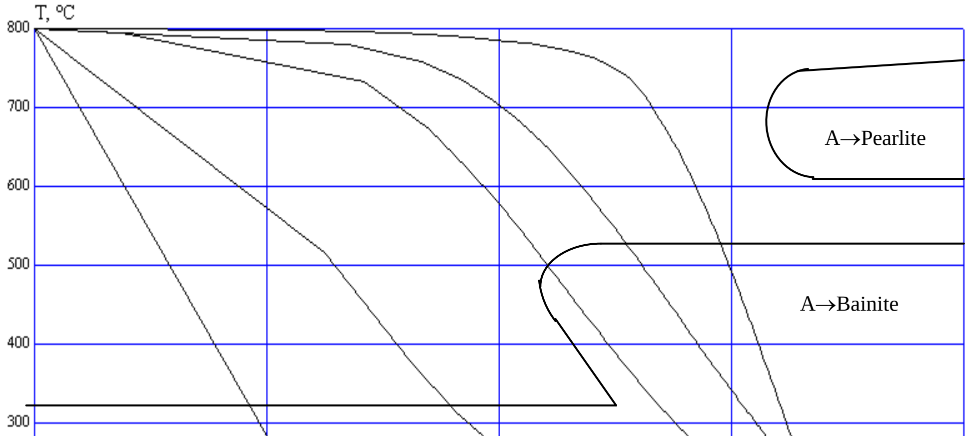


Figure 3 Cooling curves for radii 4.5, 9, 10, 11 and 11.4 cm for the quenching stage after austenitizing

ELTA was then used to simulate the entire heat treating cycle (see Figure 4). With ELTA, we were able to obtain good estimates for the power, coil currents, voltages, cooling and heating times with an account of the specific conditions at the manufacturing site. Figure 4 shows that an almost uniform temperature has been achieved during the austenitizing stage. The surface temperature at the end of the austenitizing phase is even less than the temperature inside because of losses on the surface.

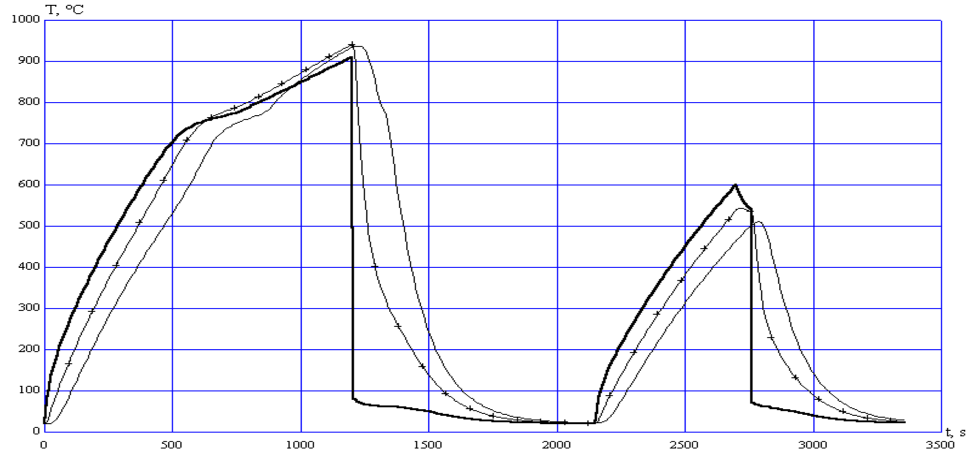
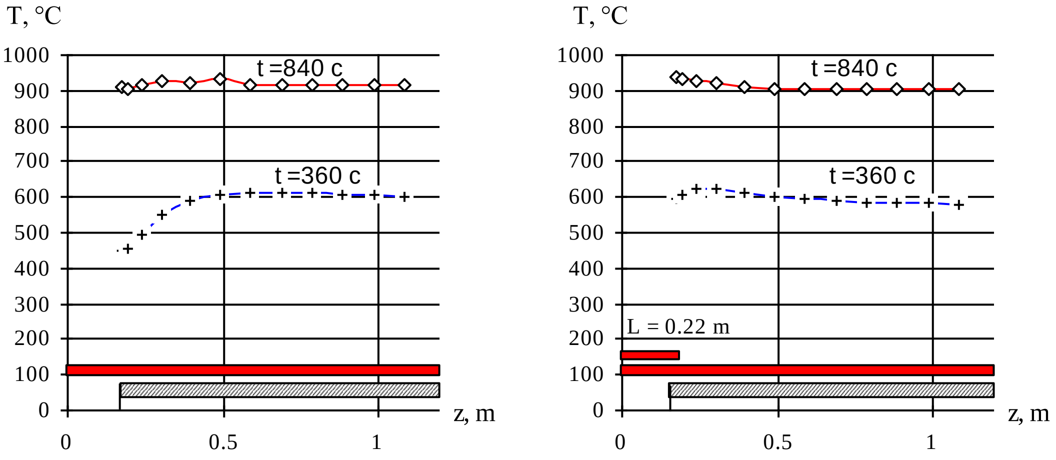


Figure 4 Temperature curves at radii 4.5 (thin line), 9, and 11.4 (thick line) cm for the entire heat treating cycle

For this case, 1-D simulation can not provide the correct data for the heating of the end of the tube. Following the "rule of pyramid", simulation was conducted using the 2-D program PERI. The original coil design was an outer diameter coil with an extension to compensate for end effects (see Figure 5a). The temperature distribution for this configuration was good for the austenitizing stage, because the steel is non magnetic at this temperature (900 C). For the tempering stage where the steel is magnetic, the temperature in the end of the workpiece is too low. This phenomena is typical for induction heating of magnetic bodies at low frequencies.

The first simulation revealed that the extension of the coil was not sufficient to compensate for the end effects in the piece. To provide addition heating of the end during tempering, a secondary coil was added around the original coil extension (see Figure 5 b). The temperature distribution during tempering was good for this coil design. The coil and process design have been proven effective both experimentally and in industry with close agreement between predicted and actual results.

.



a b

Figure 5 Temperature distribution on the length of pipe having outer diameter 0.229 m without using (a) and with using the additional coil (b).

Simulation of Quenching Methods

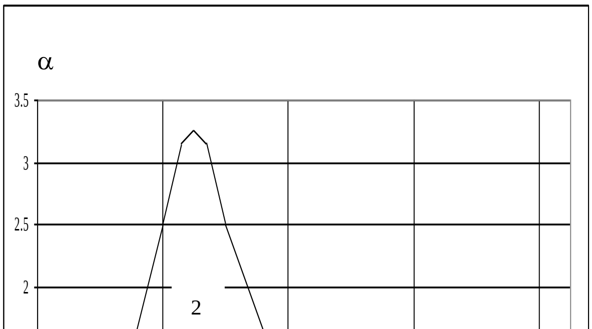
ELTA may be effectively used for computer simulation of different quenchants and quenching conditions (intensity of spray, temperature and quenching time). The ELTA database contains heat transfer coefficients for several quench types. Included in the database are several non-linear, temperature dependent heat transfer coefficients for oil and water immersion and spray cooling. This data is derived from original experiments performed in St. Petersburg, Russia, mainly for the specific conditions of induction heat treating.

This research was conducted to compare the results of simulation using the non-linear heat transfer coefficients included in ELTA to the traditional values of mean heat transfer coefficients. Figure 6 demonstrates the variation of the heat transfer coefficient (α) with temperature for unagitated oil and immersion in water. Figure 6 also shows a mean heat transfer coefficient for immersion in water. The maximum heat transfer coefficient value is an order of magnitude higher than the initial and final values for both the water and oil quenches. Heat transfer is greater for all temperatures for immersion in water than in oil. The maximum values differ more than five times and correspond to different temperatures (200-250 C for water and 400-500 C for oil).

A standard silver probe (16 mm diameter) [8] with an initial temperature of 850 C was used for this study. The temperature of the oil and water quenchants was 40 C. The cooling curves (see Figure 7) are tracked from 800 C, because this is the temperature below which phase transformations occur in steel. Figure 7 shows the cooling curves generated using mean heat transfer coefficients and non-linear heat transfer coefficients. The cooling time during the early stages of quenching for mean value heat transfer coefficients is less than half of the actual cooling time. This section of the curve is where the pearlite node is on a continuous cooling diagram. This difference could have a significant effect on the prediction of the final metallurgy of the part.

Accounting for the strong non-linearity of heat transfer coefficients will provide more accurate results than the widely used mean values. However, heat transfer coefficient data is not available for most media and operating conditions (temperature, method of quenching, intensity of agitation or spray). The existing data comes from different sources and is not always in good agreement. This data was not in great demand before, when there was no simulation tools to correctly account for the non-linearity. Now, this information is essential for the accurate modeling of the quenching process.

.



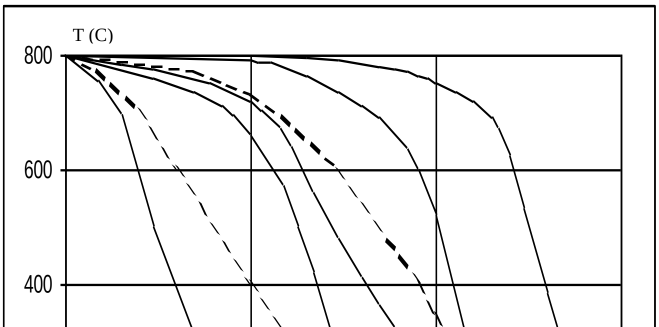


Figure 6 Heat transfer coefficients (α (W/cm^2 K)) for immersion in water and unagitated oil

Figure 7 A comparison of the cooling curves for a silver probe (8 mm radius) under different quenching conditions

1- Fast oil unagitated
2-Water unagitated
3-Oil shower (0.7 m^3/(s•m^2))
4-Water shower (0.28 m^3/(s•m^2))
5-Water shower (2 m^3/(s•m^2))

** Dashed lines represent simulation with mean value heat transfer coefficients for cases 2 and 4

Conclusions

Computer simulation is an effective tool for induction heat treating process and coil design. There is no universal program that can accurately simulate every feature of the induction heat treating process. There are a number of different programs available for simulating the induction heating, but only a few of them, such as Flux 2D and ELTA (1-D), take into account the special features of induction processes. The authors suggest a heirarchic approach, whereby the simpler software packages are used as a basis for the more complicated simulations if they are required. This approach has been used in practice and has been found to greatly reduce design time and process development costs. The main source of error in simulation of the induction heat treating processes lies in the accuracy of the material property and heat transfer coefficient data. More experimental study must be done in this area to create a database for accurate simulation of induction heat treating processes.

References

[1] Nemkov, V.S., Role of Computer Simulation in Induction Heating Technique. *International Induction Heating Seminar, May 13-15, 1998 Padua, Italy*.

[2] Fontanet, A., Flux 2D, Flux 3D - Tools for Induction Heating Modeling. *Cedrat-Recherche, France, 1996.*

[3] Lupi, S. et al. Induction Heating. Industrial Application. *Publ. UIE, France, 1992.*

[4] Bukanin, V.A, Lupi, S. et al., 3D - FEM Simulation of Transverse Flux Induction Heaters. *Proc. of Conference on EM Fields Computation. Grenoble, France, 1994.*

[5] Ruffini R.S., Ruffini R.T. and Nemkov V.S., Advanced Design of Induction Heat Treating Coils, Part I: Design Principles, *Industrial Heating, June 1998*.

[6] Ruffini R.S., Ruffini R.T. and Nemkov V.S., Advanced Design of Induction Heat Treating Coils, Part II: Magnetic Flux Concentration and Control, *Industrial Heating, November 1998*.

[7] D.S. MacKenzie, G.E. Totten, Quenching Fundamentals: Heat Transfer, *Proceedings of the Second International Conference on Quenching and the Control of Distortion, 4-7 November, 1996. Cleveland, Ohio.*

[8] Soren Segerberg, Jan Bodin, Quenching and Testing And Evaluation of Quenchants for Hardening Steel Components, *Institutet for Verkstadsteknisk Forskning (IVF), 1997*