Intricacies of Computer Simulation of Induction Heating Processes

Dr. Valery Rudnev, *FASM*

Director, Science and Technology

Inductoheat Inc.

INTRODUCTION

In the last decade, when discussing subjects related to a computer simulation of induction heating, the word "*usefulness*" has been replaced by a word "*necessity*". Combination of a sophisticated engineering background with advanced process simulation software that is capable to effectively model electromagnetic and thermal phenomena, induction heating professionals possess the unique ability to analyze, in few hours, complex technological problems. Computer modeling provides the ability to predict how different, interrelated and non-linear factors may impact the transitional and final thermal conditions and what must be accomplished to improve the effectiveness of the process, determine the most appropriate process recipes and serve as a comfort factor when designing new systems.

In 2007, ASM International has begun an ambitious undertaking to compile all-new, comprehensive resources 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 (Fig. 1) was published as a part of ASM Handbook series. 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 casting, solidification, forming, forging, rolling, heating, heat treating, coating, joining, machining, powder metallurgy, integration modeling and simulation in design of equipment and many others.

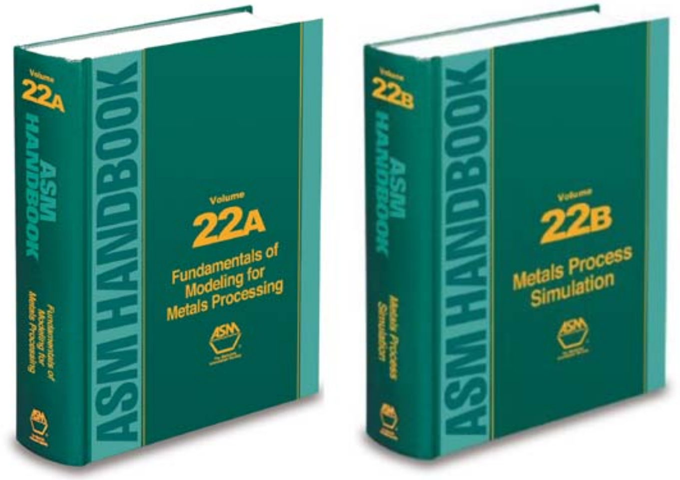

Figure 1. New two-volume set of ASM Handbooks on computer modeling and metal process simulation.

Among other useful information, Volume 22,B consists of two articles that are solely devoted to a computer simulation of induction thermal technologies: *Simulation of Induction Heating Prior to Hot Working and Coating* (pages 475 – 500) and *Simulation of Induction Heat Treating* (pages 501 – 546) [1,2].

HOW IT HAS BEEN DONE IN THE PAST

An estimation of the process parameters based on a single formula “rules of thumb”, as well as using the analytical methods and equivalent circuit coil design methods were popular in the 1960’s through 1990’s. 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 heating systems [1,2]. There was always a danger in obtaining erroneous and inadequate results with such overly simplified estimation techniques.

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

Rather than using computational techniques with many restrictions and disputable accuracy, modern induction heating specialists turned to highly effective numerical simulation methods such as finite-differences, finite-elements, 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 [2,5].

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

PHYSICAL PROPERTIES

Electro-magnetic properties of heated materials encompass a variety of characteristics. While recognizing the importance of all electro-magnetic properties, two of them is electrical conductivity (its reciprocal electrical resistivity) and relative magnetic permeability have the most pronounced effect on the process of induction heating. 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. Same kind of carbon steel at the same temperature and frequency can have a substantially different value of μ_r due to differences in coil power that is related to the intensity of the magnetic field.

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 non-linear functions of temperature.

Interrelated non-linear nature of the material properties dictates the necessity of developing special computational algorithms that properly couple electromagnetic and thermal phenomena. Critical review of applicability of different coupling techniques is provided in [5].

LIMITATIONS OF GENERALIZED COMMERCIAL CODES

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 software, many of generalized programs experience difficulties in taking into consideration certain features of a particular induction heating application. This includes but not limited to the presence of thermal refractory, heated workpiece can simultaneously move, rotate or oscillate in respect to induction coil, some operations combine heating and quenching, existence of non-uniform initial temperature distributions, presence of end plates, guides and liners, etc.

Therefore, be aware, that some critical feature(s) of a particular induction heating application could be limiting factor creating considerable challenges for generalized commercial software forcing making not well-defined assumptions and affecting an accuracy of simulations.

TEMPERATURE REQUIREMENTS

In billet heating, it is required not only to raise the billet’s temperature to a specified level at required production rate but also provide a certain degree of heat uniformity. The uniformity requirements include maximum tolerable thermal gradients: “surface-to-core,” “end-to-end,” and “side-to-side.” A billet that is heated with appreciable non-uniformity can cause problems with premature die wear on hammers and presses and may cause other problems by requiring excessive force to form the metal and quality of products.

It is important that the maximum temperature anywhere within the billet does not exceed certain level ensuring that none of the billet’s areas are overheated and “hot shortness” as well as steel “burning” does not appear. Taking into consideration that pyrometers can only reliably measure billet’s surface temperature at certain spots, there is always a danger to “miss” an overheating of the local or/and sub-surface areas. Therefore, precise temperature control based on a reliable prediction of temperature distribution within the billet using advance computer modeling capability is imperative in designing modern induction heating systems.

EFFECT OF FREQUENCY

One of challenges in induction heating arises from the necessity to assure the required “surface-to-core” temperature uniformity. Due to the physics of the induction process (including “skin” effect), the billet’s core tends to be heated slower than its surface.

The choice of frequency is always a reasonable compromise in induction heating. Too low frequency might result in undesirably large penetration depth that, in turn, might lead to poor coil efficiency due to an eddy current cancellation and have greater impact on presence of sub-surface overheating. When the frequency is too high, an induced current concentrates within a fine surface layer compared to the diameter of the billet requiring long heat times that in progressive induction heating call for longer heating line. Optimal frequency is a complex function of several process features [5].

A COMMON INCORRECT ASSUMPTION

Some practitioners incorrectly assume that with induction billet heating the coldest temperature is always located at the core of the billet and the maximum temperature is always located at its surface. It is also often assumed that overheating does not occur if surface temperature measured by a pyrometer or thermocouple does not exceed the maximum permissible level. Besides that, process control systems that predict rise of an average (mean) temperature and temperatures of surface and core of the billet often assumed to be sufficient to guarantee proper heating providing a comfortable factor for some practitioners. Example of such typically predicted “surface-to-core” temperature profile is shown on Figure 2. However, it is imperative to recognize that under certain but very realistic conditions, the presence of heat losses from billet’s surface may shift the temperature maximum further away from the surface marking its location somewhere beneath the billet’s surface.

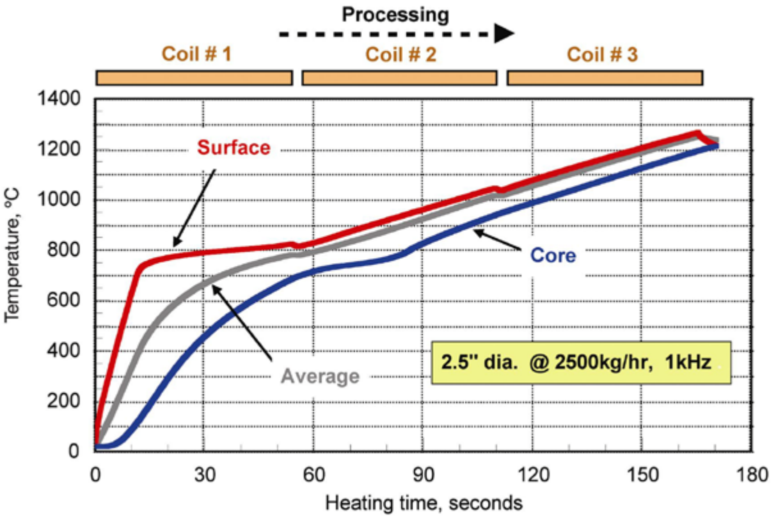

Figure 2. Conventional “surface-to-core” time-temperature profiles

Study shows [3,4] that positioning and magnitude of the subsurface temperature surplus and potential steel overheating is a complex function of four major factors: *frequency*, *refractory*, *final temperature*, and *power distribution along the heating line*.

Lower *frequencies* increase the current penetration depth resulting in more “in-depth” heating and leading to a faster temperature raise at billet’s core. This shortens the induction line, but on another hand, under some conditions, it can also increase the subsurface overheating by making it more pronounced and shifting the location of the maximum temperature further away from the surface.

The use of an appreciably thick *refractory* with improved thermal insulation properties does just the opposite, reducing subsurface over-heating and shifting billet’s maximum temperature towards its surface.

Increase of the *forging temperatures* leads to an effect similar to an effect of lowering frequency in regards to a location of maximum temperature and severity of the subsurface heat surplus.

An effect of *power distribution along the heating line* on billet's temperature distribution is more complex and it is seldom discussed in the literature. In most publications devoted to progressive induction heating of billets, it is strongly suggested to have a graded (profiled) power distribution along induction line by putting more power into the coils at the beginning of the line. Putting more power up-front might sound as a universal "rule of thumb" since it forces more energy into the billet at the front of the heating line, allowing more time to soak into the core and shortening the length of the line. This approach typically utilizes a single inverter that powers several coils with graded number of copper turns or/and series/parallel coil circuit connections.

The problem with this approach, however is that the power distribution along the heating line in some installations cannot be easily modified if the production rate, kind of metal or billet size changes. For example, if the production rate is reduced, a subsurface overheating typically worsens with a conventional induction design potentially negatively affecting the billet's subsurface microstructure. It is also very common to find an appearance of billet-sticking problems to be more pronounced with graded power distribution along induction line when the system runs at a rate slower than the nominal for which it was designed. Since the system puts more energy into the billet in the beginning of the heating line, too much energy soaks down into billet's subsurface area in cases when the line runs slow. The presence of surface heat losses can reverse a traditionally expected radial temperature profile leading to the subsurface temperature being greater than at its surface.

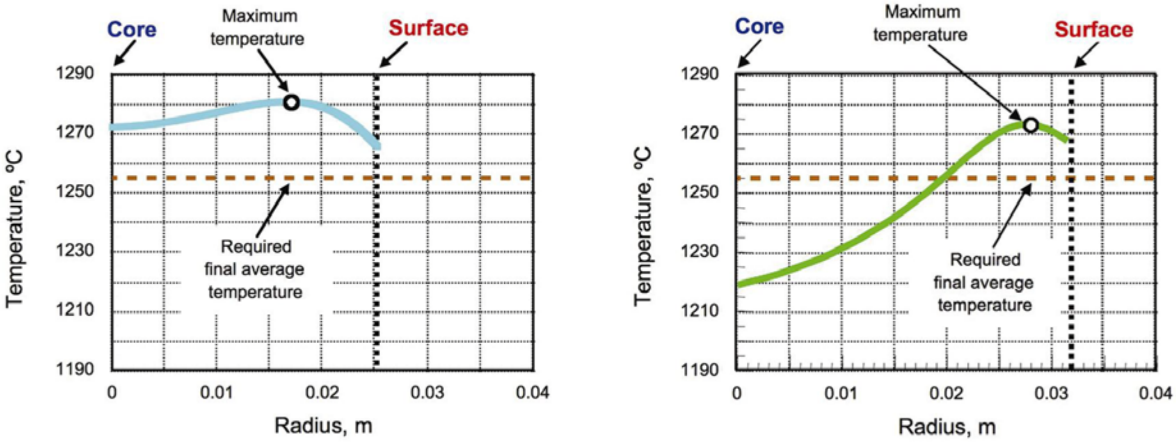

Figure 3. Final "surface-to-core" temperature profiles when heating 2"(50.8mm) dia. billets at a slower rate (left) utilizing a conventional induction line designed for processing 2.5"(63.5mm) billets at a nominal rate (right) [2-4].

In many cases, subsurface temperature might be hot enough to cause the billets to fuse together. The effect of subsurface overheating is particularly pronounced when heating smaller size billets at a lower rate using an induction line designed for heating larger billets at a nominal rate. As an example, Figures 3 shows "surface-to-core" profiles when heating 2"(50.8mm) diameter billets (Fig.3,left) at a slower rate utilizing a conventional induction heating line designed for processing 2.5"(63.5mm) billets (Fig.3,right) at a nominal rate (see Fig.2). Note that in both cases the billet's surface temperature that would be recorded by pyrometer is the same. Further reduction in billet's diameters could worsen a severity of subsurface overheating [3,4].

Besides a potential danger of a premature die wear on hammers and presses, as well as other issues related to altering a quality of forged parts improperly heated billets can raised some safety concerns.

Practice shows that when heating large billets at nominal rates, more power should be shifted towards the beginning of induction line. At slower rates however, when heating smaller than nominal size billets it is desirable to re-distribute power by its shifting towards the end of the induction line.

Taking into consideration that pyrometers can only reliably measure billet's surface temperature, there is always a danger to "miss" an appearance of the sub-surface overheating. Therefore, precise temperature prediction is imperative in order to avoid localized over-heating that is related to "hot shortness" problems due to residuals and possible variations in the chemistry of given steel.

"NOSE-TO-TAIL" TEMPERATURE DISTRIBUTION

One of critical issue related to quality of heating is associated to providing required "nose-to-tail" temperature uniformity. This issue is increasingly critical when heating longer billets. Due to its complexity this subject is seldom discussed in publications. "Nose-to-tail" temperature distribution is associated with several interrelated phenomena including electromagnetic end effect, transient end effect and thermal end effect [5]. Depending upon system's specifics, an impact of each factor can be different calling for a specific design features. As an example, Figure 4 shows the results of computer modeling revealing an appearance of transient electromagnetic end effect while billet exits induction coil. Experience of previous jobs and computer modeling capability of manufacturer of induction heating machinery is essential in providing required heat uniformity and developing appropriate process recipe and coil design features that will assure required "nose-to-tail" heat uniformity.

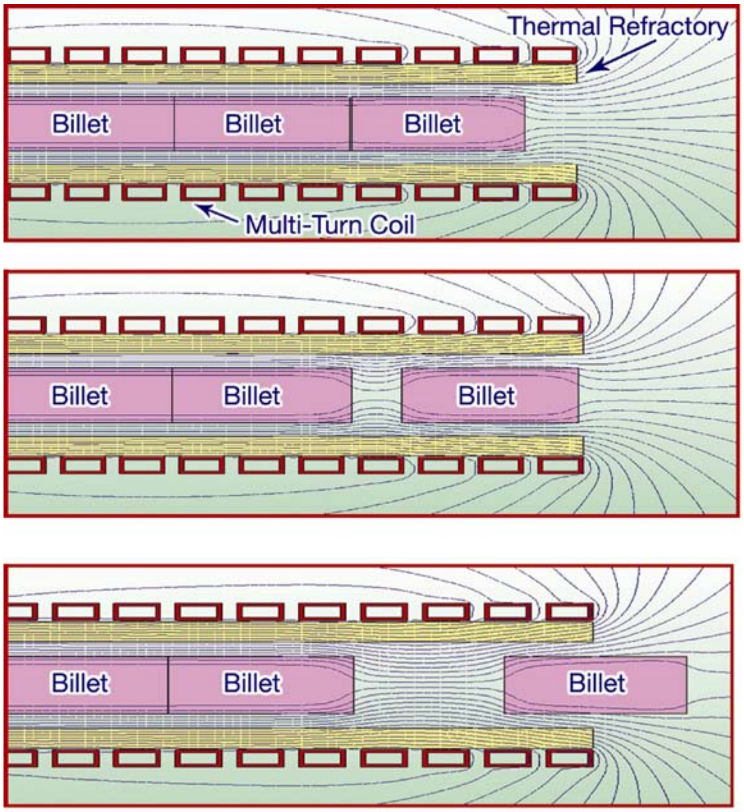

Figure 4. Computer modeled electromagnetic field distribution at exiting end of induction coil.

Clear understanding of factors involved in an appearance of electromagnetic and thermal end effects and ability to properly computer model induction heating processes taking into consideration all important inter-related and non-linear process factors, allows Inductoheat to select the most appropriate design strategy and determine optimal process recipes to handle end effects (Fig. 5).

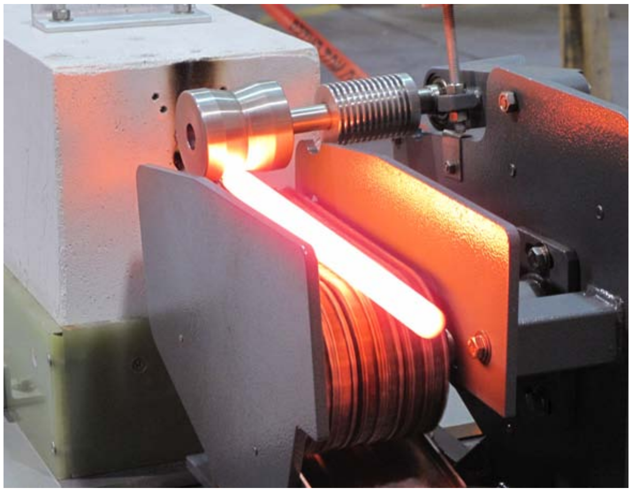

Figure 5. Properly controlled electromagnetic and thermal end effect result in ability to guarantee desired billet's thermal conditions along its radius as well as along its length.

HEATING OF NON-CYLINDRICAL WORKPIECES

Induction heating is popular approach to the heating non-cylindrical workpieces, such as rectangular shape parts including RCS (round-cornered-square) billets, bars, blooms, plates, slabs, etc. There are three basic induction approaches to heat RCS billets: static, progressive and oscillating heating [1,5]. With progressive multi-stage horizontal heating being the most popular approach, billets or bars are moved through a single coil or multi-coil horizontal induction heater. As a result, the billet or bar is sequentially (progressively) heated at predetermined locations inside of the induction heater. Depending upon application, different coils positioned in-line can have various power levels and frequencies.

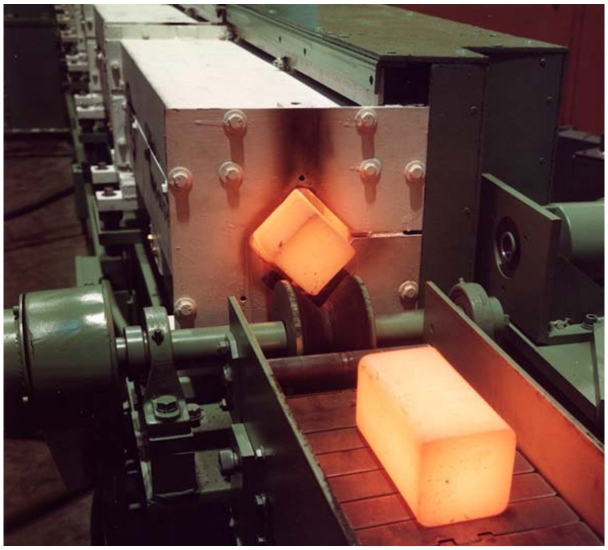

Figure 6. Induction heating of RCS billets

Due to a non-cylindrical geometry of the RCS billets (Fig.6), besides the "surface-to-core" temperature uniformity, customers often specify temperature uniformity in its transversal cross-section, including maximum allowable "central part – to - corner" temperature gradient. Depending upon specifics of process parameters, edge areas of RCS billets can be under-heated, over-heated or heated uniformly. Transversal electromagnetic edge effect and thermal edge effect (Lambert's law) are primarily responsible for temperature distribution within the transverse cross-section of the RCS billets including edge regions [5].

Electromagnetic edge effect represents a distortion of electromagnetic field and induced heat sources in corner areas of RCS billets. The maximum value of the eddy current density is located on the surface of the central part of RCS billet. It does not, however, mean that the maximum temperature is always located there. Higher frequencies and smaller penetration depths make the skin effect to be more pronounced. In this case, the path of the induced current matches closely the contour of the heated RCS billets [5]. If the skin effect is pronounced, then the eddy current and power density are approximately the same along the billet perimeter, except its edge areas, where the distortion of induced power takes place. Even though heat losses at the edge (corner) area are higher than heat losses at the central part, the edge areas can be overheated compared to the central part. An appearance of heat surplus in edge is more likely to be occurred in the induction heating of magnetic steels, and low resistive metals such as aluminum, silver, brass or copper where skin effect is typically pronounced.

If the skin effect is not pronounced, then under-heating of the edge areas may occur. In this case, the path of eddy currents in transverse cross section does not match the contour of the billet's geometry and most of the induced eddy currents close their loops earlier, without reaching the corners and the edge areas. As a result, there will be a deficit of the power densities and heat sources in edge areas compared to corresponding values in its central part resulting in colder corners and requiring using dual or multiple frequency designs [5,6].

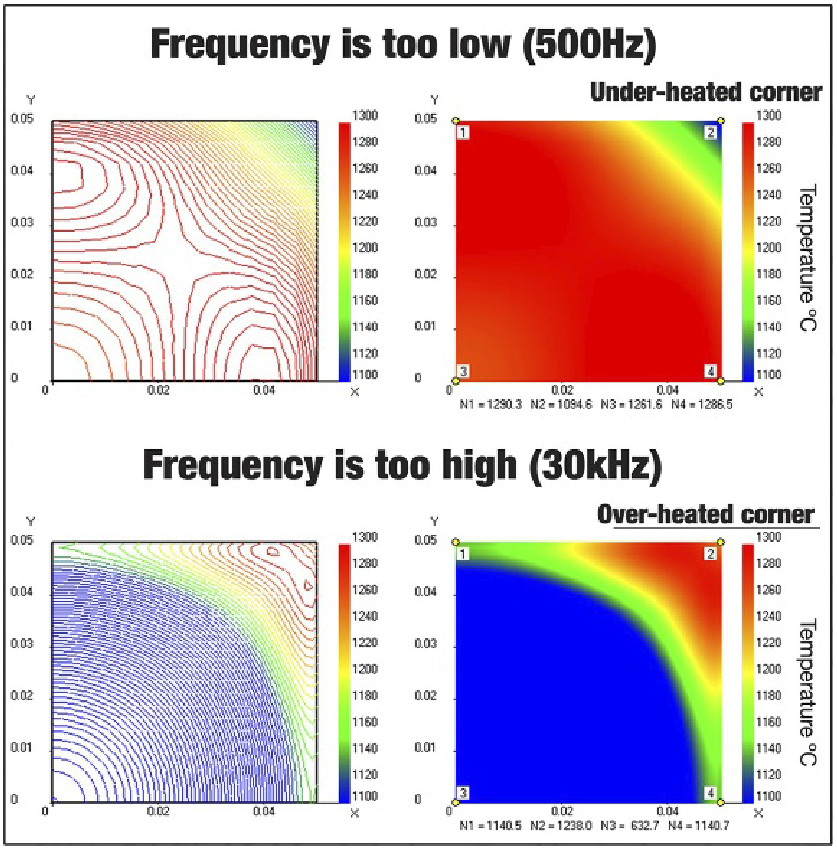

Figure 7. Examples for two polar cases of the temperature distribution within ¼ of transverse cross-section of the RCS billet

As an example, Fig.7 shows results of computer simulation for two polar cases of the temperature distribution within ¼ of transverse cross section of the RCS billet. Node #3 indicates the core (center) and Node # 2 indicates the corner of the RCS billet. For that particular billet size, frequency of 30kHz resulted in a pronounced skin effect acting as example when chosen frequency is too high. This may lead to dramatically overheated corner of RCS billet. In contrast, 500Hz resulted in too large penetration depth leading to a clearly under-heated corner. It is important to note that though frequency of 30kHz has appeared to be too high frequency in this case, in other applications when sizes of RCS billets or slabs would be much smaller, it could "act" as too low frequency. Terms "too high" frequency or "too low" frequency are relative to a particular geometry of the workpiece and its material properties.

Figure 8 shows a computer simulated two-dimension temperature profiles of top-right ¼ of RCS bar transverse cross section showing a dynamics of induction heating of a RCS carbon steel bar 0.1m (4") cross-section using frequency of 500Hz. It is important to have a clear understanding of the magnitude of thermal gradients not only at the end of heating, but during intermediate and particular during initial heating stage. Presence of excessive thermal gradients may result in appearance of longitudinal and transverse cracks there. As can be seen at Fig.8, due to properly chosen process parameters temperature distribution within the ¼ cross section of RCS bar is quite uniform at the end of heating.

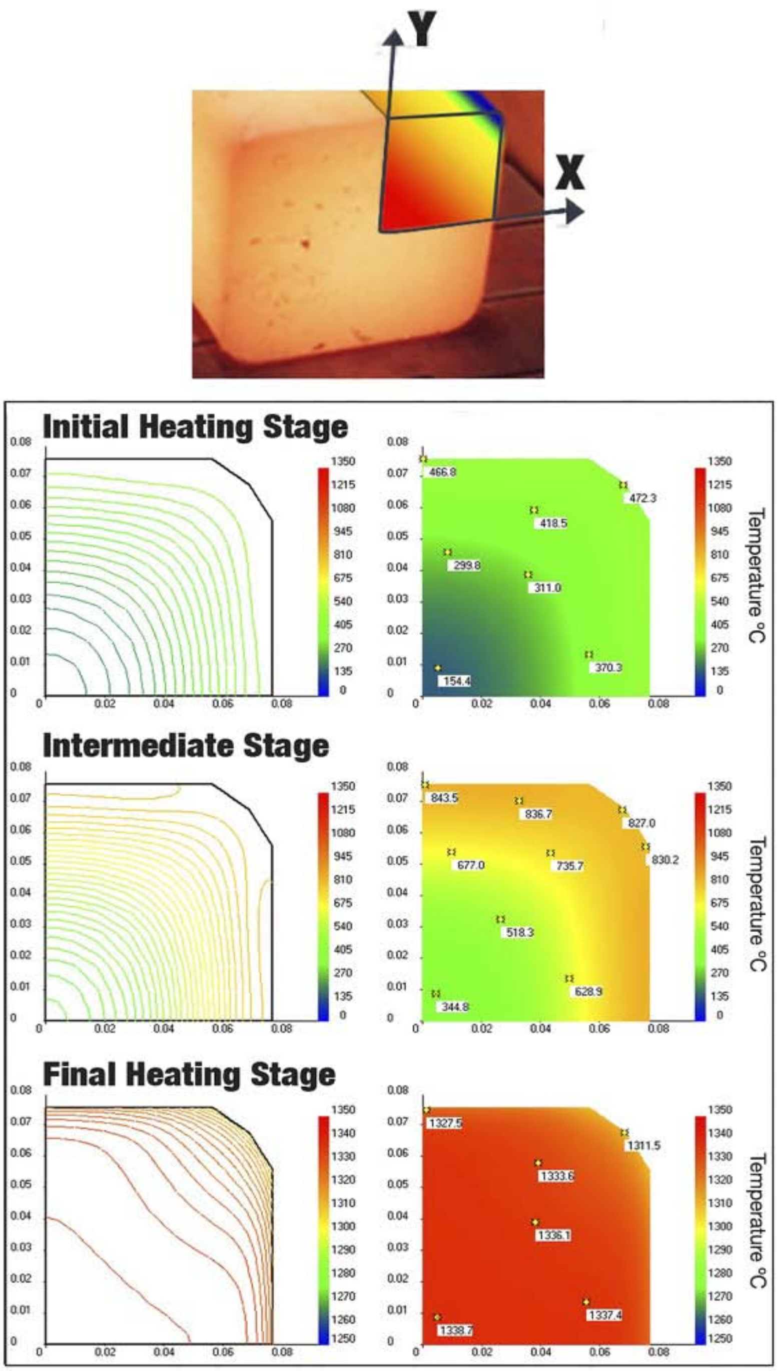

Figure 8. A computer simulated two-dimension temperature profiles of top-right ¼ of RCS bar transverse cross section showing a dynamics of induction heating of a RCS carbon steel bar 0.1m (4") cross-section using frequency of 500Hz

Steps to consider <u>before</u> you hire somebody to do a computer simulation.

<u>First step</u>. 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 analyst(s) has clear understanding of the process specifics, as well as an appropriate education in the area where you are seeking help. For example, when you are flying an airplane, you expect from a pilot to have an appropriate training. When you need medical assistance, you expect from a doctor to have a proper education and appropriate medical degree. Same principle should be applied when you are choosing a company or analyst to do computer simulation for you.

<u>Second step</u>. Make sure that physical properties of heated materials are properly defined. Well-know but rude saying "garbage in - garbage out" clearly indicates a necessity of having accurate physical properties of heated material. Experience shows that poorly defined material properties are responsible for appriciable amount of simulation errors. Only reliable sources should be used when adapting physical properties.

<u>Third step</u>. It is important to recognize that the use of modern numerical software (including finite elements, boundary elements, finite difference, edge elements, etc.) does not guarantee obtaining correct simulation results. It must be used in conjunction with experience in numerical computations, proper education of analyst and his/her engineering background. This is especially so because even in modern commercial software,

regardless of the amount of testing and verification, a computer modeling program may never have all of its possible errors detected. The analyst must consequently be on guard against various kinds of possible errors. The more powerful the software, it is more complex with potentially having the greater probability of errors. Be aware that computer generated attractive pictures might be misleading if were obtained by amateur. Common sense, engineering "gut feeling" and advance education in area of modeling are always the analyst's helpful assistants.

CONCLUSION

In fast-pace world economy an 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 opposite to academia, a rapidity of industry does not often have a luxury to wait several days in order to obtain the results of modeling but demand having reliable results of computer simulation within a few of hours. Measures should be taken in making sure that properly educated analysts use proper simulation software to perform a computer modeling. This is the reason why some induction heating manufacturers besides using commercially available generalized software also developed various subject-oriented highly effective proprietary codes that allow to effectively simulating particular group of induction heating applications taking into consideration all critical process features.

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