

Computer Modeling Helps Identify Induction Heating Misassumptions and Unknowns

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Whenever someone is discussing induction heating, reference is often made to the skin-effect phenomenon, which is a fundamental property of induction heating. It can be clearly observed during billet heating (Fig. 1). Skin effect represents a nonuniform distribution of an alternating current within the workpiece cross section.

According to the skin-effect phenomenon in induction heating, eddy currents induced within the workpiece will primarily flow in the surface layer (the “skin”), where a majority of all induced power will be concentrated. This layer is called the reference depth or current penetration depth, δ . The value of penetration depth varies with the square root of electrical resistivity and inversely with the square root of frequency and relative magnetic permeability.^[1]

In a great majority of publications devoted to induction heating and induction heat treating, distributions of current density and power density (heat source) along the workpiece thickness/radius are

assumed to be exponentially decreasing from the surface into the workpiece.

Figure 2 illustrates the skin effect, showing the commonly accepted understanding regarding current-density distribution toward the core. At a distance equal to one penetration depth (δ) from the surface, the current magnitude will retain approximately 37% of its surface value. However, the power density retains only about 14% of its surface value because power relates to a current as I^2R . From this, one can conclude that about 63% of the current and 86% of the induced power in the workpiece will be concentrated within a surface layer of thickness δ . The fact that practically all induced power (heat source) is concentrated



Fig. 1. An appearance of skin effect when induction heating carbon-steel billets

with current penetration depth emphasizes the importance of having a clear understanding regarding skin-effect appearance during induction heating.

Many times, engineers calculate the distribution of the current density along the workpiece thickness (radius) using Bessel functions or numerous charts that are readily available to determine values of δ versus temperature when heating different materials using various frequencies.

Unfortunately, many people are not aware that the widely used assumption regarding current and power distribution due to a skin effect is not valid for a great majority of induction surface-hardening applications. Computer modeling helps to unveil this common misassumption.

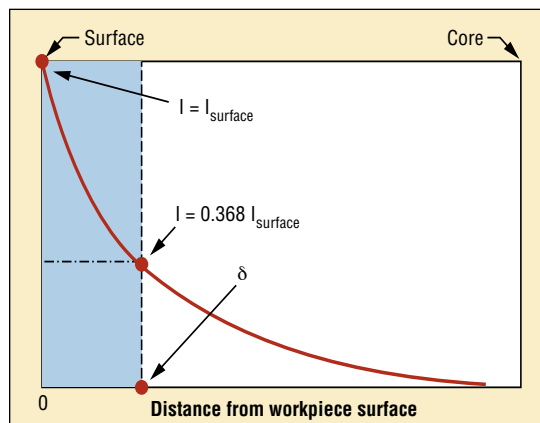


Fig. 2. Current density distribution versus distance from surface of the workpiece due to the skin effect.

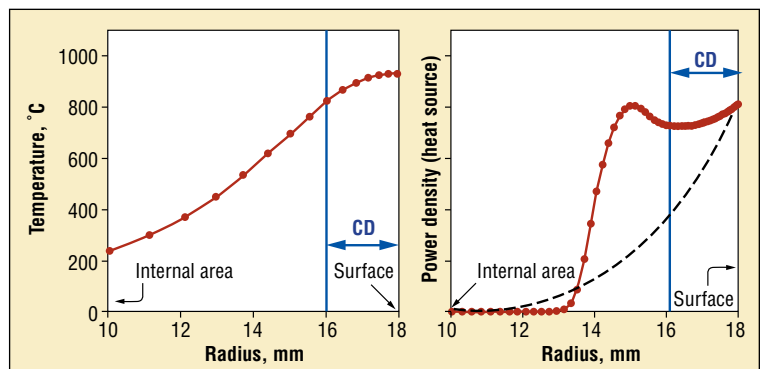


Fig. 3. Solid lines represent radial distribution of temperature (left) and power density (right) when induction surface hardening carbon-steel shafts using 10 kHz. Required case depth is 2 mm. The dashed black line in the graph at right is the commonly assumed exponential power-density distribution.^[1,2]

It is imperative to remember that the widely accepted assumption of exponential distribution of induced current and power is only appropriate for a solid body (workpiece) having electrical resistivity and magnetic permeability constant. Therefore, realistically speaking, this assumption can be made for only some unique cases of induction heating and heat treating, such as induction heating of non-magnetic materials to relatively low temperatures (i.e. preheating prior curing or bonding) or heating materials that exhibit insignificant changes in their electrical resistivity during the heat cycle.

For the great majority of induction surface-hardening applications, the power density (heat source) distribution is not uniform, and there are always thermal gradients within the heated workpiece. These thermal gradients result in nonuniform distributions of electrical resistivity and, in particular, magnetic permeability within the heated workpiece. Presence of these nonlinearities leads to the fact that the common definition of current penetration depth does not “fit” its principle assumption.

Induction Hardening Specifics and Magnetic-Wave Phenomenon

The aim of surface hardening of steels and cast irons is to provide a martensitic layer on specific areas of the workpiece to increase the hardness, strength, and fatigue and wear resistance while allowing the remainder of the part to be unaffected by the process. If the frequency has been chosen correctly, the thickness of the nonmagnetic surface layer – the layer that is heated to above the Curie temperature for austenization – is somewhat less than the current penetration depth in hot steel. The desirable frequency is often chosen in such a way that it produces a current penetration depth that will be 1.2-2 times the required case depth.

In induction surface hardening, the power-density distribution along the radius/thickness has a unique “wave” shape^[1,2] that differs significantly from the commonly assumed exponential distribution.

Here, the power density has its maximum value at the surface and decreases toward the core. But then, at a certain distance from the surface, the power density suddenly starts increasing again, reaching a maximum value before it starts final decline (Fig. 3, right).

Originally, a hypothesis regarding a “magnetic-wave” phenomenon was independently introduced by Simpson^[3] and Losinskii.^[4] They intuitively felt that there should be situations where the power-density (heat-source) distribution would differ from that of the traditionally accepted exponential form. Both scientists provided a qualitative description of this phenomenon based on their intuition and understanding of the physics of the process. At the time, a quantitative evaluation of this phenomenon could not be developed due to a limitation in computer-modeling capabilities and the lack of software that could simulate the tightly coupled electro-thermal phenomena of induction hardening. Of course, it also was not possible to measure during heating the power/current density distribution inside the solid workpiece without disturbing an eddy-current flow. To the best of my knowledge, the first publication that provides a quantitative assessment of a magnetic-wave phenomenon was published in reference 2 with further research provided in references 1 and 5.

Modern tightly coupled electromagnet-

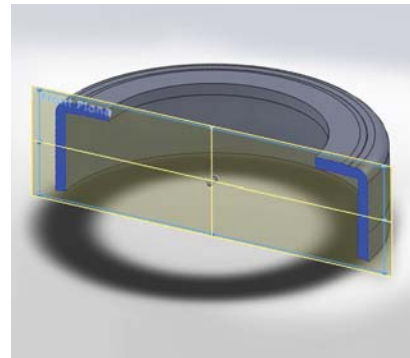


Fig. 4. Selective areas of cup-shaped components required induction hardening.

ic-thermal numerical software enables a quantitative estimation of the magnetic-wave phenomenon based on its ability to properly simulate interrelated electromagnetic and thermal phenomena. An example is given in Figure 3, which shows the temperature profile (left) and power-density distribution (right) along the radius of a 36-mm (1.42-inch) diameter medium-carbon steel shaft at the final stage of heating (just before quenching would be applied) using a frequency of 10 kHz. For comparison, the dotted curve represents the commonly assumed exponential curve for power-density distribution, and the solid curve shows an actual magnetic-wave distribution obtained as a result of numerical computer modeling.

The main cause of magnetic wave relates to the phenomenon in induction

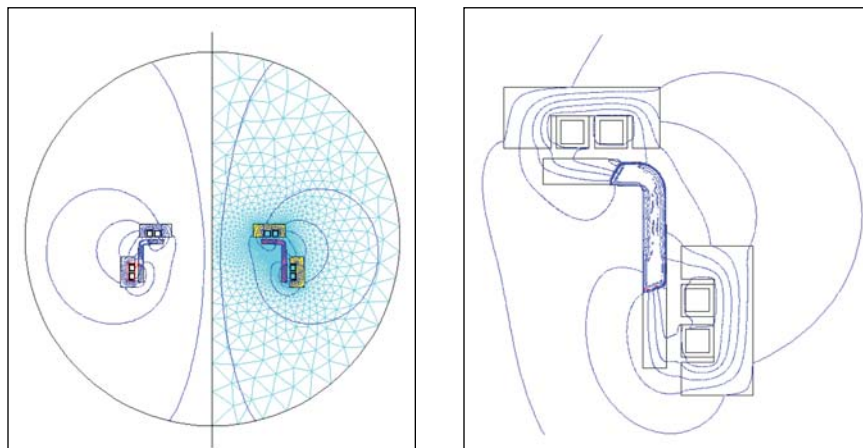


Fig. 5. FEA mesh (left) and computer-simulated magnetic-field distribution at the final stage of heating (right) using two two-turn inductors and “U”-shaped magnetic-flux concentrators when selective hardening of end regions of cup-shaped component. Due to the symmetry of the component, only the right half was modeled (courtesy of Inductoheat Inc.).

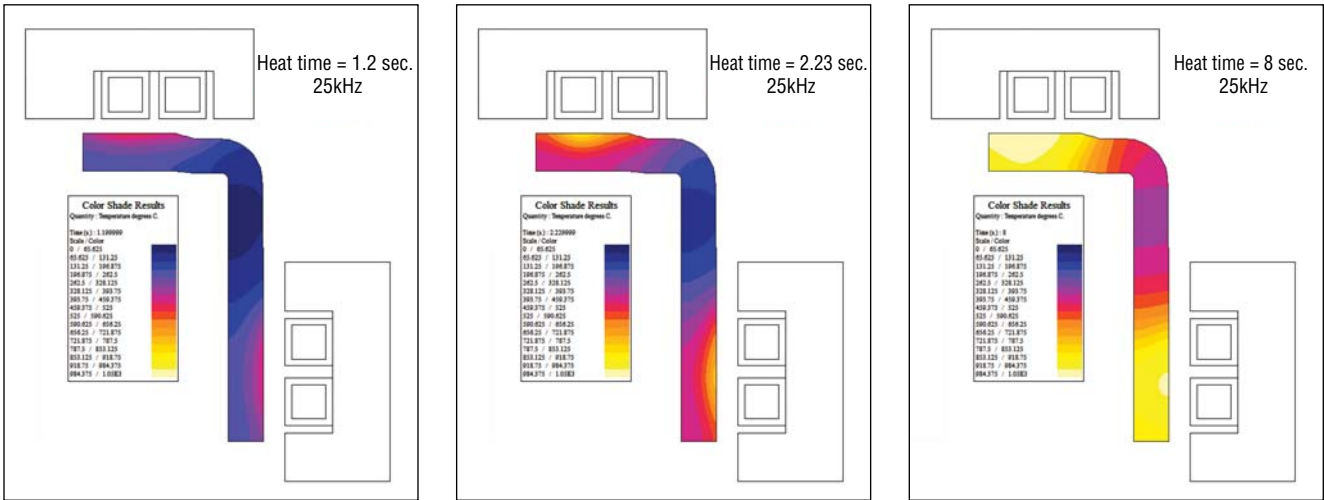


Fig. 6. Computer simulation of the sequential dynamics of the induction hardening of selected areas of cup-shaped components using two two-turn inductors and "U"-shaped magnetic-flux concentrators. Due to the symmetry of component, only the right half was modeled using FEA (courtesy of Inductoheat Inc.).

surface hardening that carbon steel retains its magnetic properties in the subsurface region, and the surface region is nonmagnetic being heated above A_{C2} critical temperature for austenitization. Note that this phenomenon can sometimes create the maximum heat source value below the surface of the workpiece and not at its surface. Further discussion regarding this phenomenon can be found in references 1, 2 and 5.

Taking into consideration the wavelike distribution of power density is important when choosing the induction frequency necessary to provide the required hardness depth. In induction surface hardening, therefore, the selection of optimal frequency is not as obvious a task as it might appear using "rules of thumb" or as it was presented in a great majority of publications devoted to induction heating, based on the commonly accepted assumption of the heat-source distribution.

It is important to be aware that the magnetic-wave phenomenon of power-density distribution does not only appear along the radius/thickness of the workpiece. It also occurs when studying power-density distribution in axial direction as it occurs in through-hardening of selected areas of the component. Causes for its appearance remain the same. Numerical computer modeling using appropriate software helps to reveal this appearance.

Case Study

Induction hardening comprises three groups of applications: surface hardening,

through hardening and selective hardening. The goal of induction surface hardening is to provide a martensitic layer on sur-

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face areas (external and/or internal) of the workpiece that allows improving certain properties of the part without affecting the rest of the part. This is accomplished by raising only the required surface depth of steel above the transformation temperature to a point where it transforms to austenite and is then rapidly cooled.

In contrast to surface hardening, the goal of through hardening is to provide a martensitic structure throughout the entire workpiece. For this to occur, the entire cross section is raised above the transformation temperature and then rapidly cooled to produce a consistent martensitic structure through the entire cross section. The ability of the component to be through hardened depends upon the hardenability of the steel, the quenching conditions, grain size and the part's geometry.

Both induction through and surface

(case) hardening can be localized to a component's unique geometry, a process often referred to as selective hardening. Figure 4 shows an example of a selective induction-hardening application – top and bottom end regions of the cup-shaped component required being selectively hardened. The area between those two regions should retain ductility, and its hardening was prohibited.

Because of the symmetry of the component, only the right half was modeled using finite-element analysis (FEA). Figure 5 shows FEA mesh (left) and computer-simulated magnetic-field distribution (right) at the final stage of heating using two two-turn inductors and “U”-shaped magnetic-flux concentrators. The frequency is 25 kHz.

The plot of magnetic-field distribution (Fig. 5, right) clearly indicates demarcation of the cup's regions heated above the

Curie temperature and below it. Concentration of magnetic field lines can be clearly seen. Magnetic-wave phenomenon appears at a magnetic/nonmagnetic border. Sequential dynamics of temperature profiles during induction heating are shown on Figure 6.

Magnetic wave was not the only physical phenomena that needed to be taken into consideration in order to accurately simulate the process and determine an optimal coil design that results in a desirable temperature distribution. Some of those challenges were related to the following phenomena:

From an Electromagnetic Perspective

It was necessary to assure the balance of the following three electromagnetic effects: proximity effect, “ring” effect and end effect. Each affects the distribution of the heat generation and temperature

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profile. By determining an optimal coil design and process recipe, it was possible to balance the electromagnetic effects and obtain desirable final temperature distribution.

From a Heat-Transfer Perspective

During the heating cycle, the presence of colder neighboring areas creates a greater cooling effect (cold-sink effect) experienced by particular regions. This means that during the heating cycle, uneven amount of heat will be removed from different areas of the required heat zones due to thermal conductivity. This demands designing inductors that can intentionally distribute the power density nonuniformly, compensating for an intensive heat-sink effect and producing the required temperature pattern at the end of heating.

From a Design Perspective

It is important to come up with a relatively simple, cost-effective and robust coil design that will induction harden selective areas of the component with high, repeatable quality and with minimum shape distortion.

Computer modeling precisely addressed the presence of the reviewed process features and determined an optimal inductor design and process recipe, dramatically reducing development time. **IH**

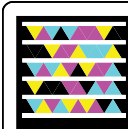
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