by Valery I. Rudnev • Inductoheat Group

A common misassumption in induction hardening

Whenever someone is talking about induction heating, reference is often made to the phenomenon of skin effect.[1] Skin effect is considered a fundamental property of induction heating, representing a nonuniform distribution of an alternating current within the conductor cross section. This effect will also be found in any electrically conductive body (workpiece) located inside an induction coil or in close proximity to the coil. According to this phenomenon, eddy currents induced within the workpiece will primarily flow in the surface layer (the "skin"), where 86% of all induced power will be concentrated. This layer is called the reference depth or current penetration depth, δ. The degree of skin effect depends on the frequency and material properties (electrical resistivity, ρ, and relative magnetic permeability, μ_r) of the conductor.[1]

Traditional view of the skin effect

It is often recommended to calculate the distribution of the current density along the workpiece thickness (radius) using Bessel functions.[2] However, for electromagnetically "thick" workpieces, the following simplified equation is frequently used:

$$I = I_0 \cdot e^{-y/\delta}, \qquad \text{(Eq. 1)}$$

where I is the current density (in A/m^2) at distance y (m) from the workpiece surface toward the core, I_0 is the current density at the surface (A/m^2), and δ is the current penetration depth (m). According to this equation, an eddy current density induced within an inductively heated workpiece has its maximum value at the surface and falls off exponentially.

Current penetration depth, δ, is described (in meters) as:

$$\delta = 503 \times (\rho / \mu_r F)^{½}, \qquad \text{(Eq. 2)}$$

where ρ is the electrical resistivity of the metal (Ω·m), μ_r is the relative magnetic permeability, and F is the frequency (Hz), or (in inches) as:

$$\delta = 3160 \times (\rho / \mu_r F)^{½}, \qquad \text{(Eq. 3)}$$

where electrical resistivity ρ is in units of Ω·in.

Thus, 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. Mathematically speaking, the penetration depth, δ, in Eq. 1 is the distance from the surface of the conductor toward its core, at which the current decreases exponentially to "1/exp" its value at the surface. The power density at this distance will decrease to "1/exp^2" its value at the surface.

Figure 1 illustrates the skin effect, showing distribution of current density from the workpiece surface toward the core. At one penetration depth from the surface (y = δ), the current will equal 37% of its surface value. However, the power density will equal 14% of its surface value. From this, we 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.

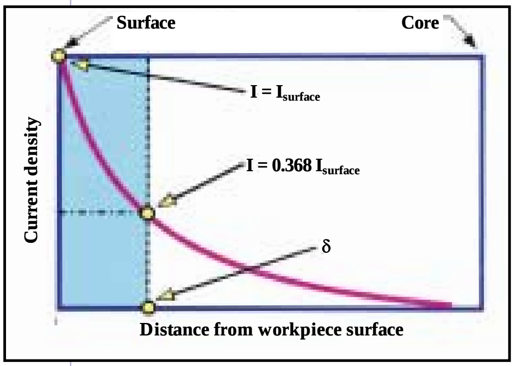

Fig. 1 — Current density distribution due to the skin effect. (Ref. 1)

Analysis of Equations 2 and 3 shows that the penetration depth has different values for different materials and is a function of frequency.

Selecting case depth, frequency

Surface hardening of steels and cast irons represents the most popular application of induction heat treatment. The goal in surface hardening 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 re-

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mainder of the part to be unaffected by the process.[1] The case depth, or hardness depth, is typically defined as the distance from the surface where the microstructure is at least 50% martensite. Below this depth the hardness begins to decrease drastically.

Power and frequency are two of the most important factors that affect case depth. In surface hardening applications, the frequency can range from as high as 4000 kHz (used for special applications such as hardening of thin wire) to as low as line frequency (used for hardening large rolls).

In many instances, it is possible to achieve the same desired case depth by using different combinations of power density and frequency. For example, when a shallow case is required it might be possible to achieve the same results with a lower-than-optimal frequency in combination with a higher power density applied for a shorter time. Conversely, if a deeper case is required with an existing system that utilizes a higher-than-optimal frequency, then a lower power density in combination with a longer heat time can be used. Figure 2 compares a required case or hardness depth with the current penetration depths obtained in hot steel using too high, too low, and optimal frequencies.

If the frequency has been chosen correctly, the thickness of the nonmagnetic surface layer — the layer that is heated to above the Curie temperature — is somewhat less than the current penetration depth in hot steel (Fig. 2, right).

If the frequency is too high for the specified case depth (Fig. 2, left), additional heating time is needed to allow heat to conduct to the desired depth. Not only does this add unnecessary time to the cycle, but there can also be significant overheating of the surface, which can lead to excessive grain growth. Overheating of the surface can also cause decarburization and excessive scaling.

If the chosen frequency is too low (Fig. 2, center), the heating is deeper than necessary. The result is a large heat-affected zone, additional workpiece distortion, and unnecessary waste of energy. In some cases, the penetration depth can be so large, compared with the required case depth, that it will not be possible to meet the pattern specification.

In general, the optimum frequency will result in a current penetration depth that will be 1.2 to 2 times the required case depth. Maintaining this ratio compensates for the cooling / soaking effect of the workpiece's cold core.

Magnetic waves in hardening

In most publications devoted to induction heating and induction heat treating, distributions of current density and power density (heat source distributions) along the workpiece thickness / radius are simplified, and described as exponentially decreasing from the surface into the workpiece (see Eq. 1 and Fig. 1). It is important to remember that this assumption is correct only for a solid body (workpiece) having constant electrical resistivity and magnetic permeability.

Therefore, realistically speaking, this assumption can be made for only some unique cases. For the great majority of induction heating applications, the current density (heat source) distribution is not uniform and there always are thermal gradients within the heated workpiece. These thermal gradients result in nonuniform distributions of electrical resistivity and magnetic permeability within the workpiece. This nonlinearity means that the classical definition of current penetration depth often does not fully apply.

New explanation: An assumption of exponential current density distribution can be used for rough engineering estimates for induction heating nonmagnetic materials (aluminum and copper, for example) and through heating of carbon steels to forging temperature.

However, in some applications, surface hardening in particular, the power density distribution along the radius / thickness has a unique "wave" shape, which differs significantly from the commonly assumed, classical exponential distribution. Here, the power density is maximum at the surface, and decreases toward the core. But then, at a certain distance from the surface, the power density increases, reaching a maximum value before again decreasing.

This "magnetic-wave" phenomenon was introduced by Davies and Simpson,[2] and Losinskii.[3] They intuitively felt there should be situations where the power density (heat source) distribution would differ from that of the traditionally accepted exponential form. They provided a qualitative description based on their intuition and understanding of the physics of the process.

At the time, a quantitative description of the phenomenon could not be developed due to limited computer power and the lack of software that could simulate the tightly coupled electrothermal phenomena of induction heating processes. Of course, it also was not possible to measure the power / current density distribution inside the solid body (workpiece).

New software: Modern numerical computation software, such as Inductoheat's ADVANCE, enables a quan-

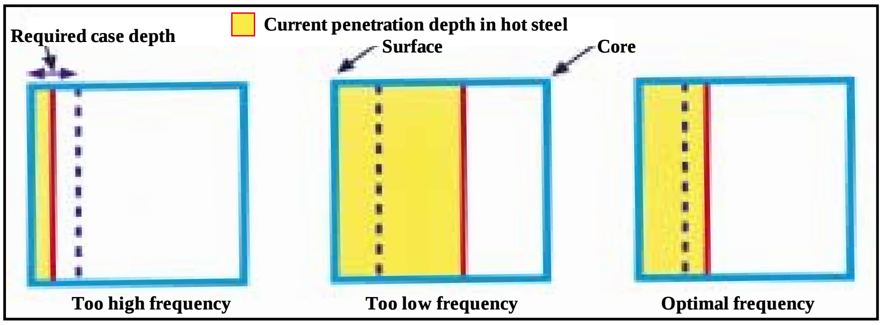

Fig. 2 — How frequency affects current penetration depth in hot steel. If the frequency is too high, left, surface overheating results, which can lead to excessive grain growth. If the frequency is too low, center, a higher power density and large heat-affected zone result, which can waste energy and cause excessive distortion. The optimum frequency, right, results in a current penetration depth 1.2 to 2 times the required case depth. (Ref. 1)

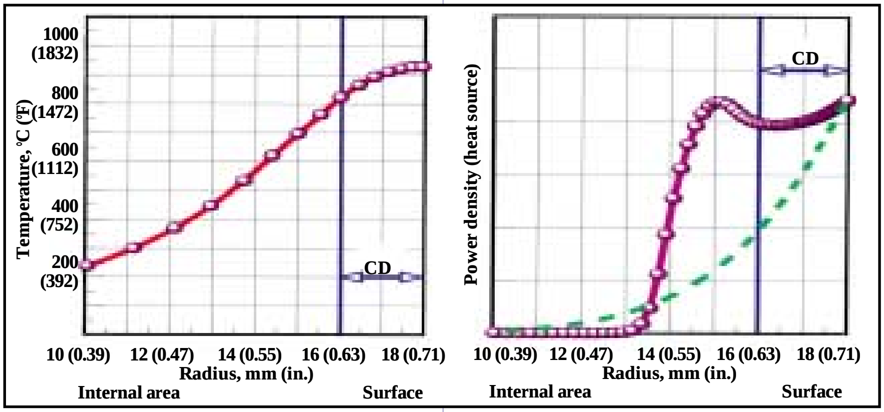

Fig. 3 — Actual temperature profile and power density distribution for induction surface hardening of carbon steel shafts using a frequency of 10 kHz. Case depth (CD) is 2 mm (0.08 in.). The dashed line in the graph at right is the commonly assumed power density distribution. (Ref. 1)

titative estimation of the magnetic-wave phenomenon (also known as the "dual-properties" phenomenon[1]) based on a coupled approach of solving electromagnetic and thermal problems.

An example is given in Fig. 3, which shows the temperature profile, left, and power density distribution, right, along the radius of a 36 mm (1.42 in.) in diameter carbon steel shaft at the final stage of heating using a frequency of 10 kHz. For comparison, the dotted curve in the power density distribution represents the classical exponential distribution.

As can be seen, a power density maximum is always located at the surface of the cylinder, and in the subsurface area, the density decreases toward the core. However, at a certain distance from the surface, the density starts to increase again, creating a "magnetic wave." The cause of this phenomenon is the remaining magnetic properties of the heated steel at this distance.

Note that in some applications, due to this phenomenon, the maximum value of heat sources can be located in an internal layer of the workpiece and not at its surface. A discussion of how this can occur at higher frequencies (25 and 100 kHz) can be found in Ref. 1.

Consideration of the wavelike distribution of power density (heat source) will make a significant difference in the frequency chosen for induction surface hardening. Conclusion: frequency selection is not as easy a task as it appears to be at first glance. A detailed evaluation of the entire heating process using modern computer modeling software is required.

Magnetic waves in bars and billets

The electromagnetic wave phenomenon just described is always present when the final temperature of a magnetic workpiece exceeds the Curie point. Figure 4 shows power density profiles at different stages during in-line induction heating of 75 mm (3 in.) in diameter carbon steel bars. The magnetic-wave effect takes place during the transition from the cold to the hot heating stage, when the workpiece temperature rises from below the Curie temperature to above it.

In other applications, the importance of this complex phenomenon may differ. In applications such as surface hardening, the magnetic-wave phenomenon plays a very important role in the prediction of final temperature profile and case depth. On the other hand, in applications such as through hardening or induction heating of steel products prior to hot forming, the duration of the transition stage is much shorter compared with both the cold stage and, in particular, the hot stage. For example, the hot heating stage in a heating-for-forging application is usually 65 to 70% of the total heating time (which also includes the cold and transition stages). Here, and in other applications like it, the magnetic-wave phenomenon has an insignificant effect on the final temperature distribution and often can be ignored.

Note that the magnetic-wave phenomenon can also play an important role in some low-temperature induction heating applications, such as coating and plating. For example, if a nonmagnetic, electrically conductive coating is applied to a carbon steel part, the phenomenon will occur and can be quite pronounced, depending on the frequency and thickness of the nonmagnetic surface deposit.

References

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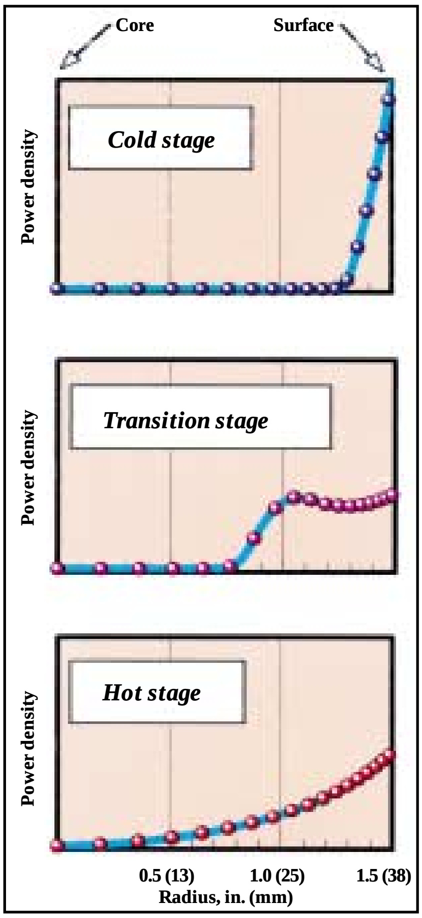

Fig. 4 — Power density profiles at different stages of in-line induction heating of 75 mm (3 in.) in diameter carbon steel bars. (Ref. 1)