Common Mispostulation in Induction Surface Hardening

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Introduction

Hardening of steels, cast irons, and P/M materials represents one of the most popular applications of induction heat treatment. One of the main goals of surface (case) hardening is to form a martensitic layer on specific areas of the workpiece to increase the hardness and wear resistance while allowing the remainder of the part to be unaffected by the process. Formation of desirable compressive residual stresses is another important aspect of surface hardening. As an example, Fig.1 illustrates a small array of a vast variety of geometries of components that are routinely surface hardened using electromagnetic induction.

Fig. 1

Induction hardening is a multi-disciplinary phenomenon comprising a complex interaction of electromagnetic, heat transfer, metallurgical phenomena, and circuit analysis that are tightly interrelated and highly nonlinear because the physical properties of materials depend on magnetic field intensity, temperature, chemical composition and microstructure.

A typical induction hardening procedure involves heating the region that needs to be hardened, to the austenite phase temperature, holding it (if required) for a period long enough for a completion of the formation of sufficiently homogeneous austenite, and then rapidly cooling it below the temperature where martensitic transformation begins (Ms temperature). Rapid cooling allows replacement of the diffusion-dependent transformation of austenite by diffusion-less shear-type transformation.

There are much less frequent cases of induction hardening when instead of forming martensitic structures; it might be desirable to form mixed structures, predominately bainitic or even fine pearlitic structures. Nevertheless, it is more the exception than the rule, and for the great majority of induction hardening applications, the goal is developing fully or predominately martensitic structures.

Because of the physics of the electromagnetic induction, the heating can be localized to areas where metallurgical changes are desired. Ability to provide selective generation of the heat sources within the desirable areas of the workpiece is associated with several electromagnetic phenomena, including but not limited to (1) skin effect; (2) proximity effect; (3) ring effect; (4) slot effect; (5) end effect; (6) edge effect, etc.

Skin Effect

Recognizing the importance of all electromagnetic phenomena, the skin effect represents a fundamental property of induction heating (IH). It is convenient to illustrate the skin effect by positioning the electrically conductive body inside an induction coil. Eddy currents induced within the heated workpiece primarily flow in the surface layer, where 86% of all generated heat sources will be concentrated. The thickness of this layer is called the current penetration depth or reference depth, δ, and it is proportional to the square root of electrical resistivity ρ and inversely proportional to the square root of the electrical frequency F and the relative magnetic permeability μ_r of the workpiece.

Unfortunately, in many publications devoted to IH, distributions of electrical current and power density (heat source) along the workpiece thickness/radius are simplified and introduced as being exponentially decreasing from the surface into the workpiece (Fig.2). However, this common postulation is correct only for a homogeneous nonmagnetic solid body with constant ρ. Therefore, realistically speaking, this assumption can be made for only some unique cases because for the great majority of IH applications including surface hardening, there are always thermal gradients within the heated workpiece. These thermal gradients result in non-constant distribution of ρ and μ_r within the workpiece.

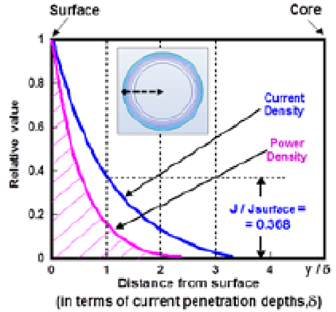


Fig. 2

Thus, the main postulation of exponential heat source distribution does not "fit" its principle assumption due to the presence of the non-linearities of physical properties of heated workpiece. In reality, at different stages of IH, the power density (heat source) distribution along the radius/thickness of the workpiece may have a unique wave shape, which differs significantly from the commonly assumed exponential distribution. There might be a maximum of power density at the surface. Then power density starts to decrease from the surface towards the core. However, at a certain distance it might suddenly begin to rise again, reaching its second maximum before its final falloff. It would be beneficial to review a case study.

Case Study: Surface hardening of solid shaft

The hardness distribution along the workpiece radius (or thickness) depends on the following factors: final temperature distribution, thermal history, chemical composition, prior microstructure, quenching conditions, grain size, and the hardenability of the steel.

Fig.3 shows the results of numerical modeling illustrating the dynamics of surface hardening (heating and quenching stages) of the SAE 4340 carbon steel solid shaft (24 mm diameter) using a frequency of 10kHz. Minimum required effective hardness case depth is 3 mm and maximum total case depth is 6 mm.

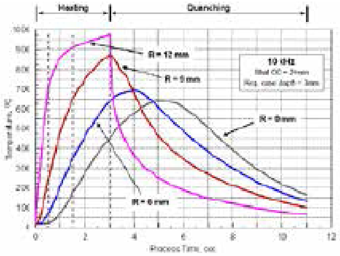


Fig. 3

After 3 s of heating, the surface layer of the shaft reaches the needed thermal condition for austenization, taking into consideration the non-equilibrium nature of the phase transformation associated with rapid IH. Because of the short heat time, the core temperature (R = 0 mm) is approximately 450°C at the end of the heating cycle (where R is radius of the heated shafts: R = 12 mm represents the shaft's surface and R = 0 represents its core).

Spray quenching begins practically immediately after the completion of the heating stage (though in other applications, a short dwell or soak time might be applied). A dramatic decrease of surface and subsurface temperatures (R = 12 mm through

R =9 mm) occurs practically instantly during spray quenching. At the same time, there is a measurable time delay in the cooling of the internal regions (e.g., R = 6 mm) and particularly the shaft's core (R = 0 mm). The core temperature continues to rise during the 2 s of quenching.

The internal regions located at a distance greater than 6 mm below the surface will not be heated above Ac$_1$ critical temperature; thus, austenite will not be formed and those regions will not be hardened. This also means that the total heat-affected zone will be slightly less than a distance of 6 mm below the surface, which satisfies the hardening requirement for a maximum total case depth.

A comparison of temperature profiles and heat source distributions at different heating stages is shown in Fig.4 through Fig.6. At the initial stage of heating, the entire cylinder is magnetic; thus, the δ is quite small and the skin effect is highly pronounced. As can be seen in Fig.4, left, after 0.5s of heating, the surface approaches Ac$_1$, but there is no rise of the core temperature. The maximum of power density is located at the surface and then it rapidly decreases (Fig.4, right). This stage is characterized by highly efficient and intense surface heating. The temperature profile does not match the power density distribution because the thermal conduction spreads the heat from the surface toward the internal areas.

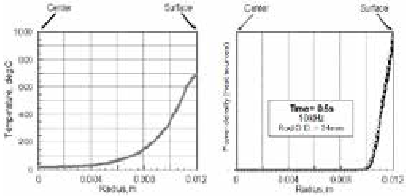


Fig. 4

After 1.5s of heating, the temperature of the surface layer (approx. 2 mm thick) exceeds the Curie point (Fig.5, left). Since the surface layer became nonmagnetic, there is a noticeable reduction of the heat intensity. A decrease of μ_r and an increase of ρ cause a corresponding increase in δ compared to its values during the initial heating stage. Though the surface layer is nonmagnetic, its subsurface retains its magnetic properties. Note that the arrows indicate the radial positioning of the Curie temperature (A$_2$).

At this point, the power density distribution along the radius has a unique non-exponential ("wave-shaped" profile), which is very different from the commonly postulated exponential distribution. Fig.5, right shows that the maximum of power density (heat sources) is located in the subsurface area (about 2.2 mm below the surface). This maximum occurs where there is a "below Curie–to–above Curie" border. With time, the surface layer heated above the Curie point is expanded, resulting in further reduction of the heat intensity.

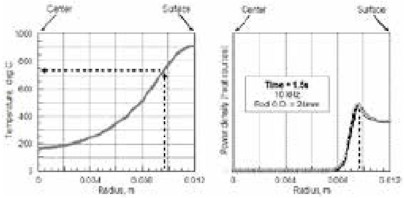


Fig. 5

Fig.6, left shows that at the end of heating (after 3s of heat), the entire region located at 3 mm below the surface is austenitized, assuring that, upon sufficient quenching, the minimum hardness case depth of 3 mm will be achieved.

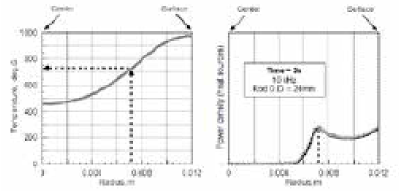
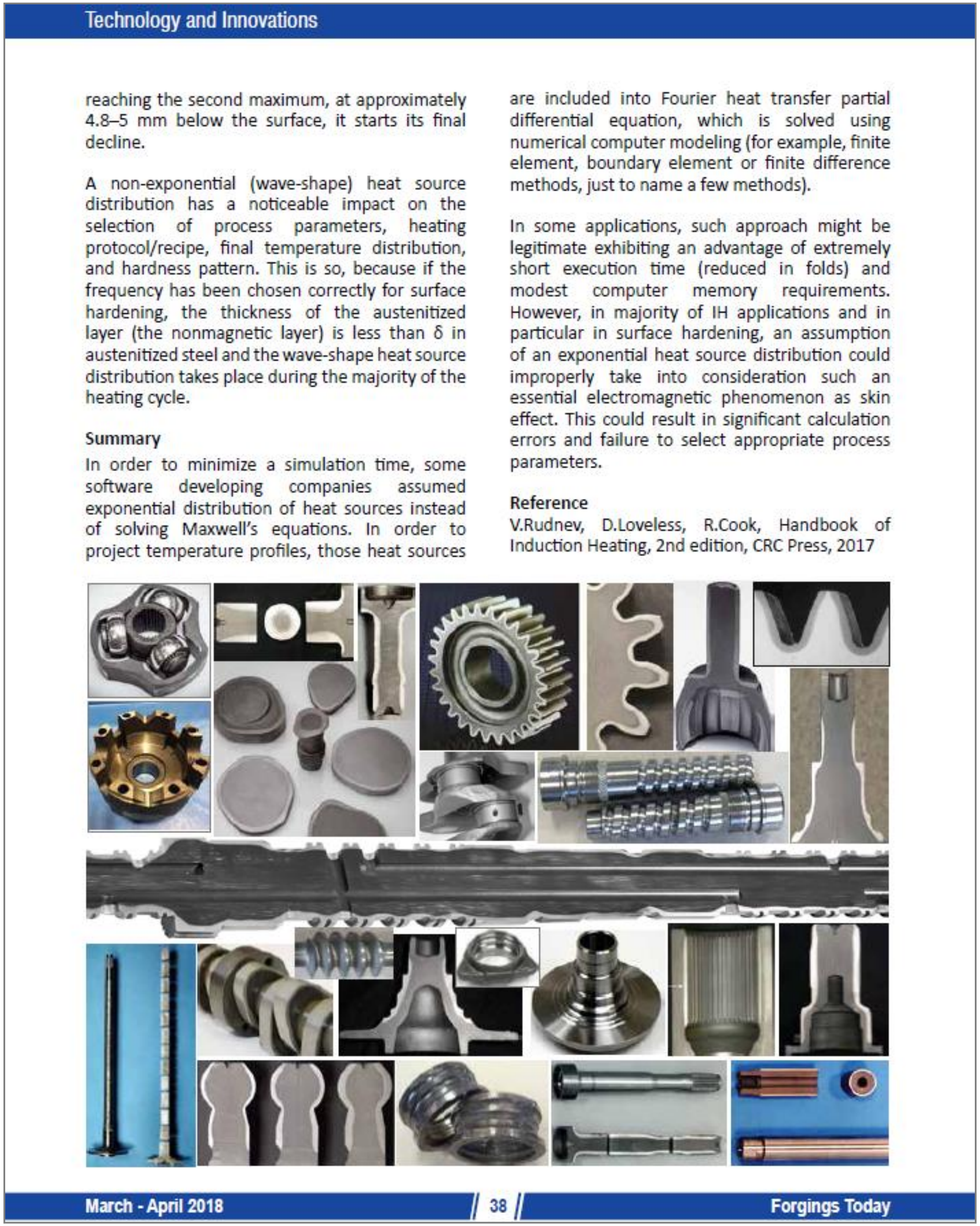


Fig. 6

There are two maximums of an induced power density at this point. Fig.6, right shows that the first maximum of power density is located at the surface and then the power density decreases toward the core. However, once it reaches approximately 2.5–3 mm below the surface, the power density starts to increase again, and after



reaching the second maximum, at approximately 4.8–5 mm below the surface, it starts its final decline.

A non-exponential (wave-shape) heat source distribution has a noticeable impact on the selection of process parameters, heating protocol/recipe, final temperature distribution, and hardness pattern. This is so, because if the frequency has been chosen correctly for surface hardening, the thickness of the austenitized layer (the nonmagnetic layer) is less than δ in austenitized steel and the wave-shape heat source distribution takes place during the majority of the heating cycle.

Summary

In order to minimize a simulation time, some software developing companies assumed exponential distribution of heat sources instead of solving Maxwell's equations. In order to project temperature profiles, those heat sources are included into Fourier heat transfer partial differential equation, which is solved using numerical computer modeling (for example, finite element, boundary element or finite difference methods, just to name a few methods).

In some applications, such approach might be legitimate exhibiting an advantage of extremely short execution time (reduced in folds) and modest computer memory requirements. However, in majority of IH applications and in particular in surface hardening, an assumption of an exponential heat source distribution could improperly take into consideration such an essential electromagnetic phenomenon as skin effect. This could result in significant calculation errors and failure to select appropriate process parameters.

Reference

V.Rudnev, D.Loveless, R.Cook, Handbook of Induction Heating, 2nd edition, CRC Press, 2017

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