A fresh look at induction heating of tubular products: Part 1

PROFESSOR INDUCTION

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Professor Induction welcomes comments, questions, and suggestions for future columns. Since 1993, Dr. Valery Rudnev has been on the staff of Inductoheat Group, where he currently serves as group director – science and technology. In the past, he was an associate professor at several universities, where he taught graduate and postgraduate courses. His expertise is in materials science, heat treating, applied electromagnetics, computer modeling, and process development. He has 28 years of experience in induction heating. Credits include 15 patents and 118 scientific and engineering publications. Contact Dr. Rudnev at Inductoheat Group, 32251 North Avis Drive, Madison Heights, MI 48071; tel: 248/585-9393; fax: 248/589-1062; e-mail: rudnev@inductoheat.com; Web: www.inductoheat.com.

The extensive use of metal tubing in thousands of products demands a wide range of process concepts. For example, in automotive manufacturing alone, new applications for tubing are being advanced at an expanding rate. These typically small- and medium-size tubular parts include stabilizer bars, intrusion beams, structural rails, steering columns, axles, and shock absorbers. The air conditioning and refrigeration industries and oil- and gas-transmission lines have high-pressure requirements where larger tubular products are used. In all of these applications, induction heating has proven effective.

Although there are many similarities, there are several process features and physical phenomena that distinguish induction heating of tubular products from induction heating of solid cylinders. The conditions for maximizing the electrical efficiency of the induction coil is one of them.[1] The coil efficiency of an induction tube / pipe heater is a complex function of several design parameters, including "coil ID-to-tube OD" air gap, metal electromagnetic properties, coil length, tube wall thickness, and the very-critical frequency.

Solid cylinders and frequency

When induction heating a solid cylinder (Fig. 1), there will be high coil efficiency when the applied frequency $F > F_2$.[1] F_2 corresponds to a ratio of cylinder outside diameter, OD, to current penetration depth, δ, greater than three ($OD / \delta > 3$). The use of a frequency which results in a ratio of $OD / \delta > 6$ will only slightly increase the coil efficiency. At the same time, the use of very high frequencies ($>F_3$ in Fig. 1) tends to decrease the total efficiency due to higher transmission losses and high heat losses, since a long heating time will be needed to provide the required "surface-to-core" temperature uniformity. If the chosen frequency results in a ratio $OD / \delta < 3$ (frequency $<F_2$), the coil efficiency will dramatically decrease.[1] This is due to the cancellation of induced eddy currents circulating in the opposite sides of the solid cylinder.

Tubular parts and frequency

Figure 1 also shows that there is a different optimal frequency for induction heating of tubular products, compared with that for solid cylinders. In induction tube and pipe heating,

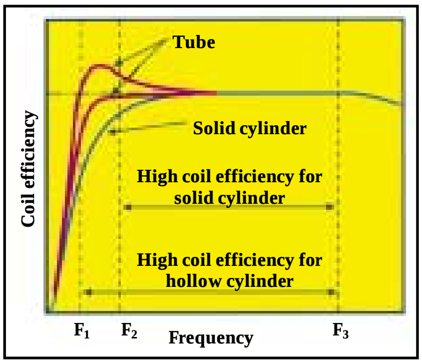

Fig. 1 — Conditions for maximizing the electrical efficiency of the induction coil are different for tubes and solid cylinders, as shown by these plots of coil efficiency vs. frequency. (Ref. 1)

the optimal frequency, which corresponds to maximum coil electrical efficiency, is shifted toward lower frequencies (frequencies between F_1 and F_2 for tubes instead of between F_2 and F_3 for solid cylinders).[1] The optimal frequency for heating tubes (hollow cylinders) typically provides a current penetration depth, δ, greater than the tube wall thickness (except for heating small-diameter tubes). This can result in a noticeable increase in coil efficiency. In some applications, it is possible to gain an improvement in electrical efficiency of 10 to 16%; in others, the increase in coil efficiency is less pronounced and may not be noticeable.

The total gain in electrical efficiency when applying a lower frequency is not only derived from improvements in coil efficiency, but is also the result of lower bus bar losses and a short heat time, as well as reductions in transformer and capacitor losses.

Another advantage of using lower frequencies is improved overall system cost-effectiveness, since, typically, the cost of lower frequency power supplies is less than that of higher frequency units.

Numerical computation using Inductoheat's ADVANCE software enables selection of the optimum frequency for a particular application.[1] To obtain a quick, but rough estimate of the appropriate frequency, several simplified formulas are used in the tube / pipe industry.[1] For example, in the case of "electromagnetically long" solenoid-type inductors, a suitable frequency, $F_{optimal}$, in hertz, can be calculated using the simplified formula recommended in Ref. 2:

$$F_{optimal} = 8.65\,(\rho \cdot 10^5 / A_m \cdot h), \text{ where}$$

ρ = electrical resistivity of the heated metal, in $\mu\Omega \cdot m$, and A_m = average tube diameter (OD – wall thickness, h), in meters.

In cases where induction heaters must be considered "electromagnetically short," rather than long, the value of the optimal frequency will be higher than that determined when using this formula.

Note, too, that audible noise can be a dominant factor in tube/pipe heating, and one that greatly affects frequency selection. (Certain tubes/pipes exposed to certain frequencies at high power density emit resonant sound waves that exceed the audible limit.[1])

In-line tube/pipe heat treating

Continuously-fed, multicoil induction heaters similar to the in-line systems used in bar/rod/wire heating applications are popular for through-heating of long tubular products. Hardening and tempering are among the suitable processes. An example is shown in Fig. 2: a time vs. temperature plot for carbon steel tubes hardened by an in-line system. The induction through-heating system consists of three in-line coils and a water-spray quench chamber.[3] Tubes having an OD of 127 mm (5 in.) and a wall thickness of 12.7 mm (0.5 in.) are hardened at a rate of 3 metric tons/h (3.3 tons/h). Frequency: 3 kHz.

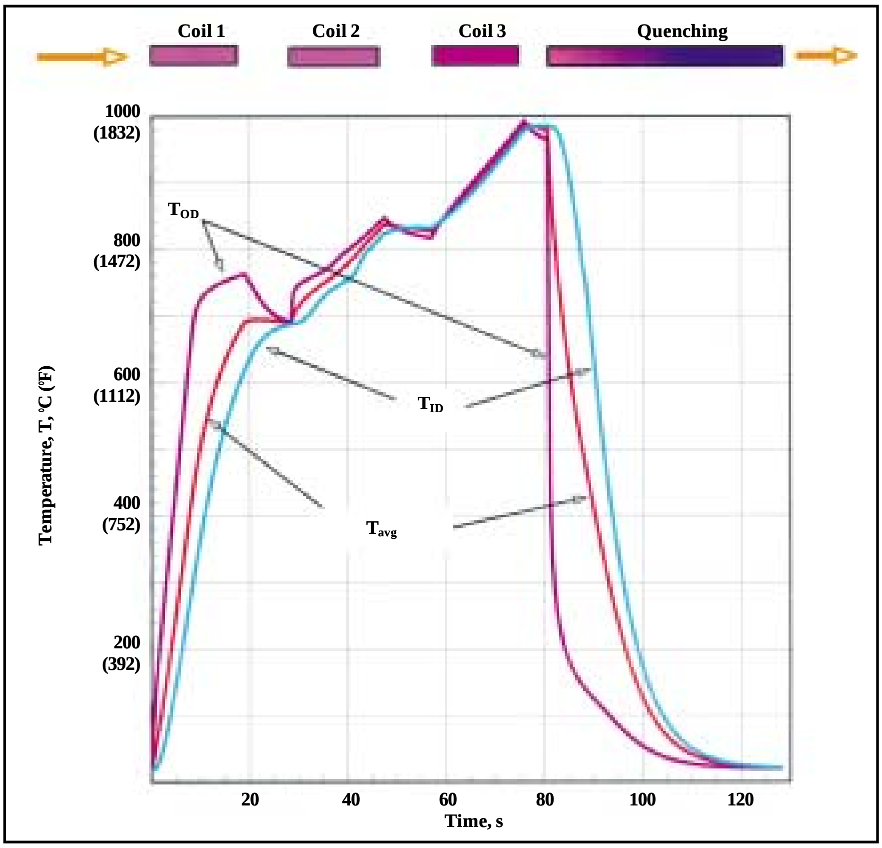

Fig 2 — Temperature vs. time plot for the in-line induction hardening of carbon steel tubing, 127 mm (5 in.) OD, 12.7 mm (0.5 in.) wall, at a frequency of 3 kHz. Each of the three induction coils is 40 cm (1.31 ft) long. Distance between coils: 20 cm (7.9 in.). (Ref. 1)

Annealing stainless: In-line "whole-body" induction annealing is suitable for carbon and stainless steels, as well as nonferrous metals such as titanium and copper.

Gas-quench bright annealing of stainless steel tubes is a good example of the in-line system design approach.[3] In this application, tubing is induction heated to about 1150°C (2100°F) and than fed into a hydrogen-nitrogen gas-quench tunnel.

During the quench, nitrogen is used to purge the system of oxygen, while, simultaneously, hydrogen is fed into the system. This eliminates the possibility of an explosion that might occur should an excessive hydrogen and oxygen leak develop.

Also, an annealing system's quench tunnel should be sufficiently long to ensure that the temperature of the stainless steel tube as it exits the chamber is below the oxidation point. This will prevent tarnishing of the tube surface when it reacts with the oxygen in the air.

Success of induction bright annealing of stainless steel tubes with a gas quench also is greatly affected by the quality of the gas. As the dew point rises, the gas contains more moisture and the corresponding volume of hydrogen has to be increased; otherwise, the process will not provide the required quality and surface appearance. The culprit is oxidation: the chromium in the stainless steel reacts with moisture to form Cr_2O_3.

Nonferrous metals: Induction heating also can be used to anneal nonferrous metals; for example, the copper tubes used in plumbing and in air conditioning and refrigeration (ACR) applications. Requirements for thin-wall ACR copper tubing include:[1,4]

- Small wall-thickness eccentricity
- Accurate dimensional tolerances
- Maximum heat transfer area
- Proper grain size and properties of the annealed tube to facilitate forming
- Clean inside wall

After the tube is heated to the annealing temperature, it enters a holding zone to await full grain recrystallization. The tube then enters the quench station where it is cooled rapidly to normal handling temperature. A typical induction "basket-to-basket" system for annealing thin-wall copper tubing is shown in Fig. 3. It was manufactured by Inductoheat Australia, Seaford, Victoria, in collaboration with Mitsui Engineering & Shipbuilding Co. Ltd., Tokyo. Its standard line-speed is 200 to 500 m/min (660 to 1640 ft/min).

Tube-coating applications

Deposition of metallic and nonmetallic coatings on steel tubular products also may demand in-line induction heating.[1] An example of the former is galvanizing, in which a fine zinc or Zn-Al alloy layer is deposited on the OD surface of a steel tube. A metallurgical bond is formed.[1]

Examples of nonmetallic coatings that benefit from in-line induction heating are solvent-based paints (primers and top coats), epoxies and other polymers, and heat-cured powders. Clean, oxide-free tube surfaces are required to meet demands for uni-

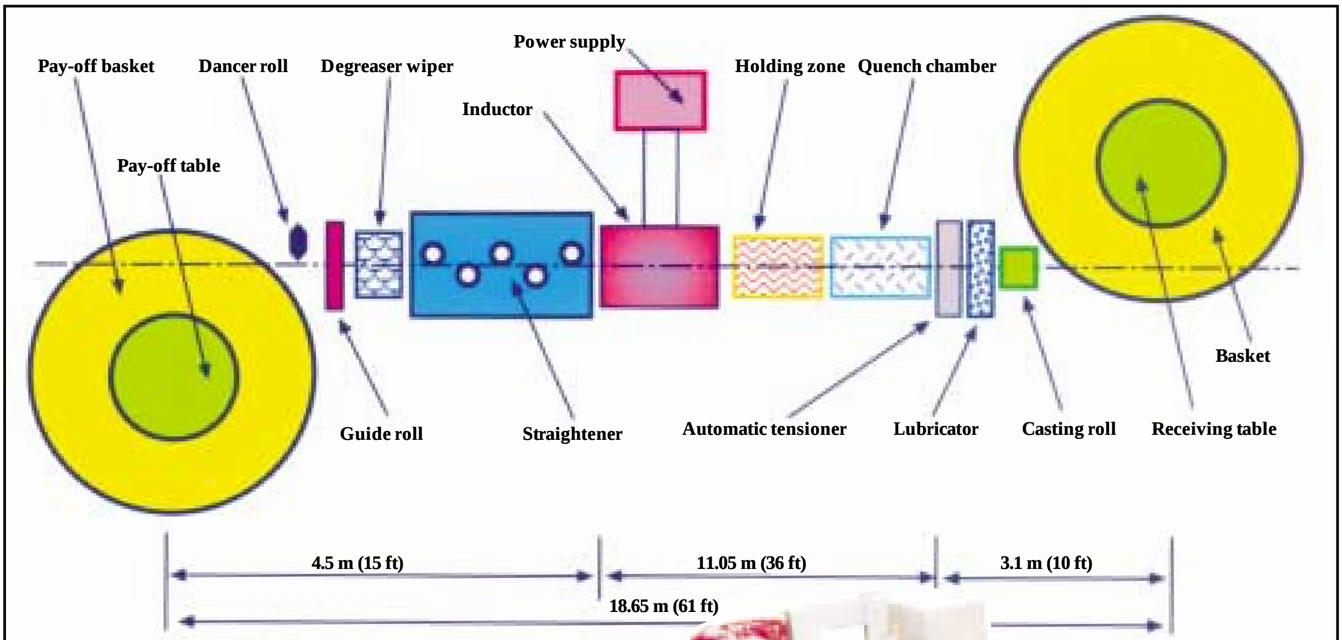

Fig. 3 — Photo and typical layout of a "basket-to-basket" induction system for annealing ACR (air conditioning and refrigeration) copper tubing. Courtesy Inductoheat Australia.

form heating and a constant application temperature.

In a typical pipe coating system, the outside of the pipe is first induction heated to about 210°C (410°F). Note that surface radiation and the cold "sink" effect of a thick-wall pipe are important considerations in determining the total mass of metal to be heated.[1]

As the pipe emerges from the induction heater, heat is lost by radiation and convection over a large surface area. These losses may be relatively insignificant, compared with the heat loss from the surface due to the sink effect of the inside wall. If the system is designed to through-heat the pipe, then thermal conduction from OD to ID is eliminated. This is a sound engineering design that minimizes the possibility of rejects. The downside of through-wall heating is increased energy consumption, which adds to total operating costs. In general, however, through-wall heating should be specified unless the wall is very thick, and / or the coating station can be located very close to the exit end of the induction coil.

Furnace heating: There is a fundamental difference between induction heating and heating in furnaces that rely on thermal convection and / or radiation. Induction can heat the metal substrate beneath the coating — from the inside out — leaving the surface soft, which allows solvents to evaporate from the coating much more rapidly than if cured in a furnace by convection or radiation, which heats from the outside in. In furnace heating, the surface of the coating cures and hardens first, trapping solvents between the substrate and this "skin." Much more time is needed for solvents to evaporate, and pinholes in the coating also may be produced. Pinholing is not a problem with induction curing. **HTP**

References

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2. *Induction Heating Equipment*, by A. Slukhotskii, *et al.*: St. Petersburg, Russia, 1981 (in Russian).
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4. "Induction Heating of Pipes Before Coating," by J. Powell: *Tube & Pipe Equipment,* September 1996.

Correction noted: In Dr. Rudnev's *HTP* March / April 2004 Professor Induction column, the label "Heating time, 1.5 s" in Figure 5 on page 19 is incorrect. It should be "Quenching time, 1.5 s." We apologize for the error.
— The Editors