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A Balanced Approach to Induction Tube and Pipe Heating

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Unique electromagnetic and heat transfer factors of induction tube and pipe heating distinguish this process from other similar applications, including induction heating of solid cylinders, billets and bars. This article explains how these factors affect the main design parameters and presents avenues of improving these factors when induction heating tubular shape products. In addition, new approaches to the engineering of induction tube and pipe heating will be discussed.

The extensive use of tubing in millions of products being manufactured today demands a wide range of process concepts. Greater through-put and better control are demanded in order to survive the competitive thrust for higher quality, lower price, smaller space and timely delivery.

The physical nature of tubing makes it reasonable to use a continuous-feed type of material handling. Continuous convection furnaces require more expensive floor space and are being challenged by efficient electromagnetic induction systems. Induction processes are not only less demanding in floor space requirements,[1,2] but also have obvious ergonomic benefits, are environmentally friendly, and have the unique capacity to selectively heat only portions of a tubular product.

There are many heating requirements for tubular products that do not require continuous feeding: heating for annealing, pre-heating for inertia welding, heating for coating, hardening, parting, and bending, etc. (see Figs. 1 and 2)

In automotive manufacturing alone, new applications for tubing are being advanced at an expanding rate. From stabilizer bars to camshafts, intrusion beams and structural rails, driveshafts, steering columns, axles and shock absorbers, the list continues to grow.

Oil and gas lines with their high-pressure requirements represent another specific area where heating by induction prior to coating and the manufacturing of large diameter pipe bends has proven its high effectiveness.[3] Oil and gas pipe line ratings are based on the wall thickness. With conventional heating to make the bend, the outer side of the bend is in tension and has a reduced cross-section, while the inner side of the bend is in compression and normally shows an orange peel effect. Because the outer side of the bend area section is reduced by a minimum of 20%, the total pipe line pressure rating is correspondingly reduced. The pipe bend becomes the pressure limiting factor in the total pipe line. With induction heating, the cross-section typically is reduced only by 11% due to very even heating, use of a computerized bending machine and a narrow plastic zone of about 1 inch. These bends may be applied to pipe diameters up to 64 inches. So induction heating not only reduces the production costs and increases the quality of the bend, but can also reduce the total cost of pipe line which may run many hundreds of miles.

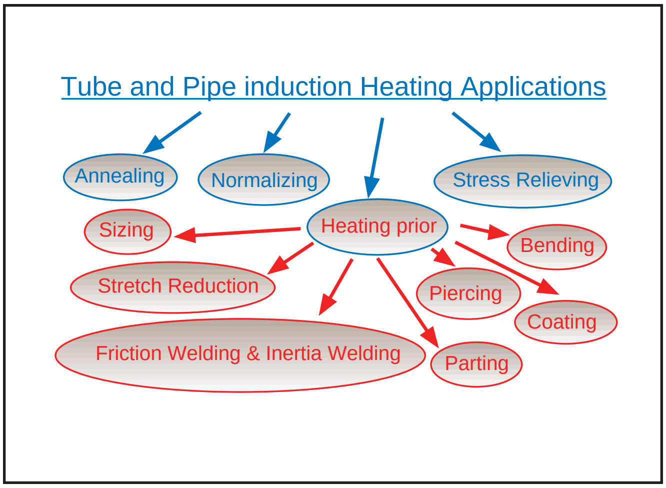

Fig. 1 Induction heating of tubular products.

Fig. 2 Friction welded (edge-to-edge induction welded) CV joint and its enlarged cross-section.

Focus on Electrical Efficiency and Cost

Energy savings result from improved process electrical efficiency which includes coil efficiency. Maximizing the coil efficiency is one of the most critical factors when designing an energy-efficient induction heating system. Coil efficiency is a complex function of several design parameters including the "coil I.D.-to-tube O.D." air gap, metal properties, coil length, tube wall thickness and frequency, with the latter being most prominent. Several process features and physical phenomena distinguish induction heating of tubular products from induction heating of solid cylinders. As one can see from Fig. 3, in the case of induction heating of a solid cylinder, there will be high coil efficiency when the applied frequency (F2) corresponds to a ratio of cylinder O.D. to current penetration depth, d, is greater than three (O.D./δ > 3). The use of a frequency which results in a ratio of O.D./δ > 6 will only slightly improve the coil efficiency. At the same time, the use of very high frequencies (Freq. > F3) tends to decrease the total electrical efficiency due to higher transmission losses. If the chosen frequency results in a ratio O.D./δ < 3 (frequency less than F2), the coils efficiency will dramatically decrease. This is due to the cancellation of induced eddy curents circulating in the opposite sides of the solid cylinder.

Analysis of Fig. 3 shows that there is a difference in optimal frequency for induction heating of tubular workpieces compared to solid cylinders. In induction tube heating, the optimal frequency which corresponds to a maximum coil efficiency is shifted towards the use of lower frequencies (frequencies between F1 and F2 for tubes instead of an interval of frequencies from F2 to F3 for solid cylinders). The appropriate frequency typically provides a current penetration depth larger than a tube wall thickness and can result in a significant increase in coil efficiency in an induction tube heater. In some applications, it is possible to gain an improvement in electrical efficiency of 10%-16%. In others, the increase in coil efficiency is less pronounced and may not even be noticeable.

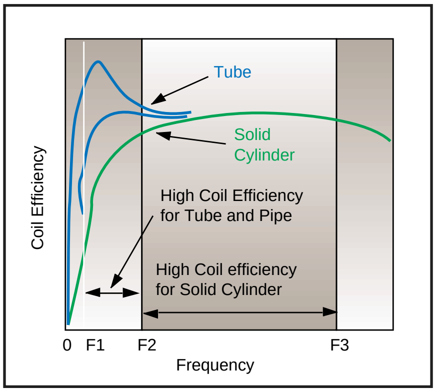

Fig. 3 Coil efficiency versus frequency.

Computational Aspects of Modern Induction Tube and Pipe Heating

Thermal conductivity, specific heat, and electrical conductivity of metals are non-linear functions of the workpiece temperature (Fig. 4). At the same time, magnetic permeability is a function of two parameters: magnetic field intensity and temperature.[1] Analysis shows that during induction heating the values for magnetic permeability of carbon steel can vary more than a couple hundred times.[1,2] At the same time, its electrical resistivity can change six times. As result of those variations, the change in current penetration can exceed 15 times (e.g., for 1040 steel). Due to this variation, the power density space distribution within the tube drastically changes during the heating cycle. In addition, a variation of thermal conductivity and specific heat exceed two times and four times, respectively.

Even a cursory look at the behavior of the material properties reveals the danger in using methods that cannot take into account variation of properties during the heating cycle. Inappropriate handling of a non-linear behavior of material properties and oversimplification of this behavior by using average values can lead to design errors and possible financial loss to the supplier and to the customer.

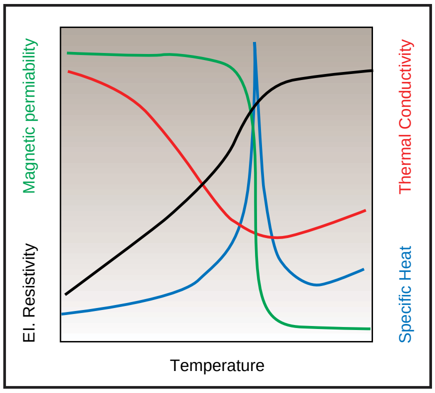

Fig. 4 Typical variation of physical properties of carbon steel.

In order to obtain acceptable computational accuracy in induction tube and pipe heating, the use of an advanced software program is necessary. For induction heating processes, contemporary software for analyzing induction heating should take into consideration such major features as the interaction of electromagnetic and heat transfer phenomena. Heat transfer and electromagnetics are tightly interrelated because the physical properties of heated metals depend strongly on both magnetic field intensity and temperature. Because of this interrelation, uncoupled finite element or boundary element software can only be useful in obtaining ballpark figures in simple cases. In order to provide a precise analysis of the process parameters, including the required coil power, optimal frequency and temperature profiles, numerical software which is based on either finite element or boundary element methods should have a coupling between electromagnetic and heat transfer phenomena.

There are several ways to couple electromagnetic and heat transfer problems. One of the most common coupled approaches calls for an iteration process.[1] This is a time-step procedure and consists of a combination of several electromagnetic-temperature computations. The temperature distribution within the workpiece obtained from the time-stepped heating computation is used to update the values of specific heat and thermal conductivity of a metal at each time step. As soon as the heat source variations become significant (due to the variation of electrical conductivity and magnetic permeability), the recalculation of the electromagnetic field and heat sources takes place. Following this approach, it is possible to obtain the required accuracy and required reliability in determining optimal design parameters of induction heating process.[1]

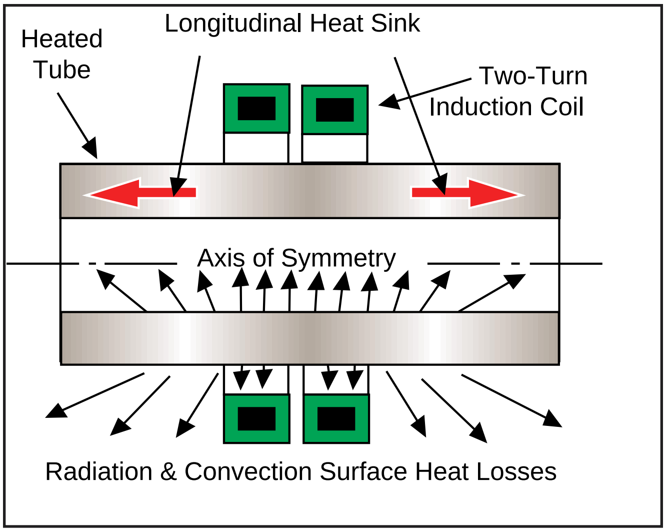

Fig. 5 Heat transfer during selective induction tube heating.

Physics and Design Considerations for Selective Induction Heating

One of the unique features of the induction process is the ability to selectively heat only certain portions of tubular products. Such applications as brazing, parting, annealing of welds, bending and friction welding are typical candidates for selective induction tube heating. Fig. 5 illustrates some of electromagnetic and heat transfer features of selective induction tube heating. A two-turn induction coil has been used as an example. Maximum temperature will be observed under the inductor in the middle of the heat zone. As a result of radiation and convection heat losses, there will be cooling from the O.D. and I.D. surfaces. Of course, cooling from the I.D. surface will be much less pronounced compared to cooling from the O.D. surface.

Convection and radiation losses greatly affect coil thermal efficiency. An analysis shows,[1] that convection losses are a major part of the heat losses in low-temperature (< 350˚C or 662˚F) applications. At higher temperatures, radiation losses are much greater than convection losses. A high value of heat loss reduces the total efficiency of the induction heater.

Heat insulation or refractory materials can significantly decrease the heat losses. At the same time, the use of refractory results in larger "coil-to-tube" air gap. This results in deterioration of magnetic coupling between the induction coil and tube, and as a result leads to a decrease in coil electrical efficiency (Fig. 6). Total efficiency of the induction coil is a combination of both coil thermal efficiency and coil electrical efficiency. Therefore, on one hand, refractory allows one to improve a coil thermal efficiency. On the other hand, it results in a reduction in coil electrical efficiency. A decision to use or not to use the refractory is always a reasonable compromise. In some cases it will be more energy and cost efficient not to use a refractory at all and, therefore, have the smallest possible "coil I.D.-to-tube O.D." air gap. In other cases, it is wise to use a refractory to significantly decrease surface heat losses and more than compensate the loss of energy due to a greater "coil-to-tube" air gap. Numerical computation helps to make an appropriate decision whether to use or not to use a refractory.

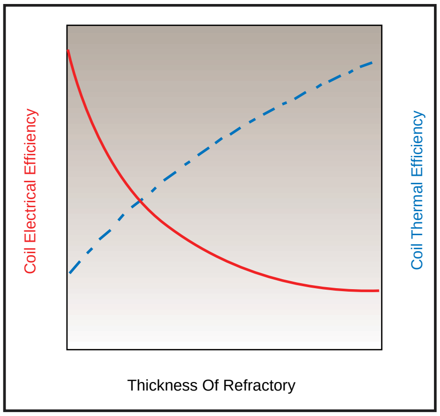

Fig. 6 Electrical efficiency and thermal efficiency versus thickness of refractory.

Another important feature that strongly effects the required power, coil design and frequency choice is the existence of so called "transition zones" and a cooling effect due to longitudinal heat sink from the cold ends of the tube (Fig. 5). It is important to understand that longitudinal transition zones and "heat sink" phenomenon are primarily responsible for mistakes in determining the required coil power and temperature profiles when calculations are based on simple formulas, one-dimensional computation approaches, or uncoupled numerical software. Without knowing the length of the transition zone and temperature profiles within these zones, it is very difficult to make a reasonably accurate guess on the total amount of the heated metal and, therefore, to determine the required power to heat a tube to the final temperature in the desired time.

As an example of what numerical computation can do for the designer or practitioner, Fig. 7 illustrates the dynamics of selective induction heating of a 1045 carbon steel tube prior tube parting. The charts provide valuable process information such as temperature profiles at different stages of the induction heating process and allows a user to have full understanding of the intricacies of the process and obtain important information regarding the most valuable process parameters. These results cannot be obtained by applying traditional one-dimensional software or electromagnetic simulation only. The optimal algorithm of power variation applied to the induction coil was also obtained during computation.

Typically, a design procedure includes several computations. As a result of computer modeling, the influence of different factors on process parameters can be evaluated. For example, in some cases it is wise to use a single-turn coil instead of a multi-turn coil.

The choice of the coil length is another critical issue, which can be quite contradictory. It is quite clear that a shorter coil results in a smaller mass of metal to be heated and, therefore, results in a smaller coil power requirement. From another perspective, coil electrical efficiency is a function not only of the frequency, the material properties of a metal and "coil-to-copper" air gap, but it is also a function of the coil length. Shortening of a coil length (L) results in the decrease of coil electrical efficiency.

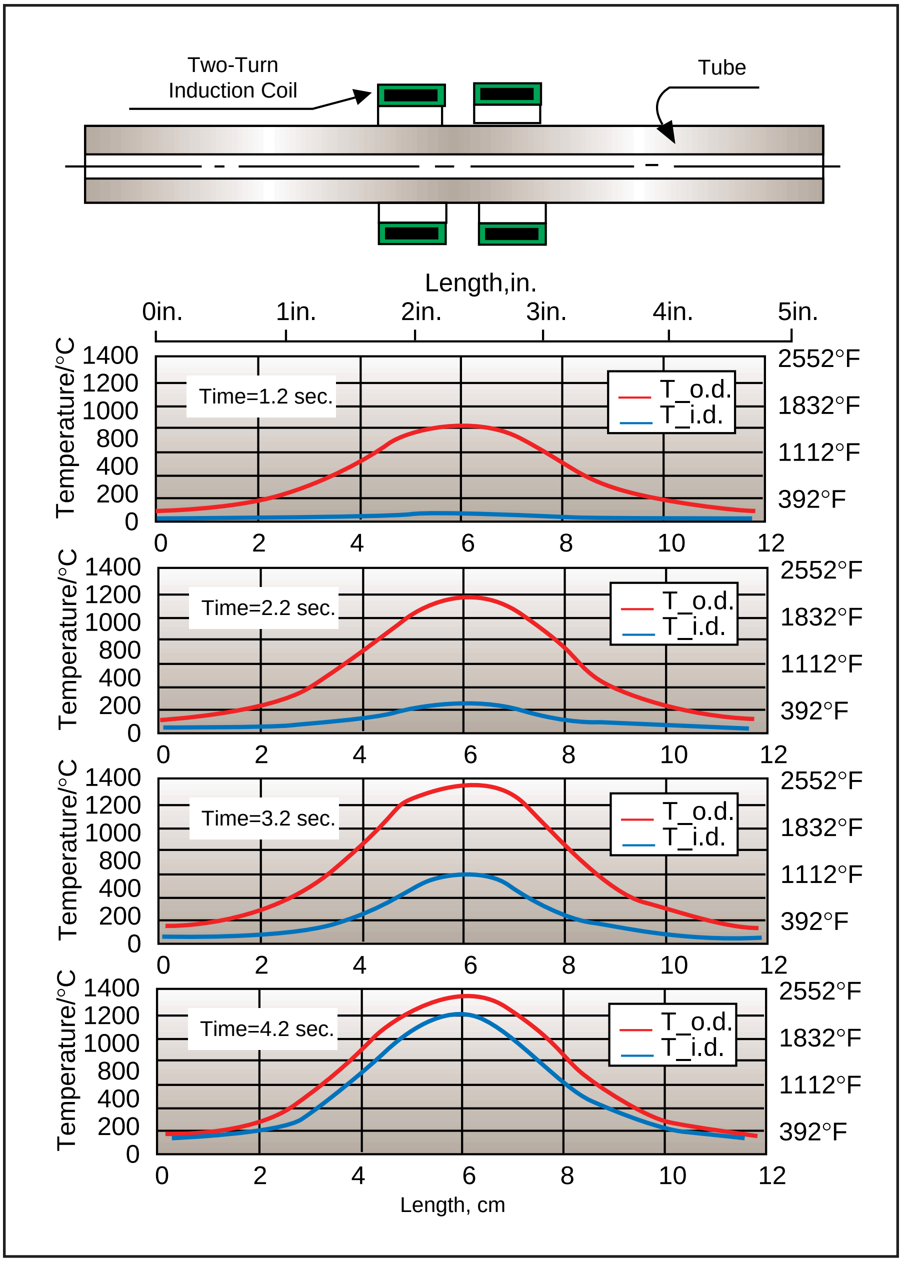

Fig. 7 Temperature profiles at different stages of induction heating of 1045 carbon steel tube with tube O.D. = 6 inches (152.4 mm) and wall = 0.6 inches (15.24 mm) at 1 kHz.

Therefore, the choice of the coil length is also a well understood compromise.

Magnetic Flux Concentrators in Induction Tube and Pipe Heating

Magnetic flux concentrators are often used in induction heating design.[1] Materials most commonly used for flux concentrators are laminations, iron powder-based and ferrite powder-based materials. A traditional function of flux concentrators has been to improve coil efficiency and to obtain a selective heating pattern. However, the use of magnetic flux concentrators does not automatically mean an increase in coil efficiency. In some applications, coil efficiency can be noticeably improved by applying a flux concentrator and in others, efficiency can actually fall.

As shown in Fig. 3, an optimal frequency for induction tube and pipe heating is lower than the optimal frequency for heating of solid cylinders. Typically, it is less than 10kHz for medium size walls, and is often less than 1kHz for heavy wall tubes. A relatively low frequency range, simple coil shape and the absence of an aggressive environment often makes laminations preferable for tube heating applications. At the same time, there are cases (especially when using high frequencies) where powder-based flux concentrators can be preferable.

When heating selective areas of a tube, the coil length typically is relatively short compared to its diameter. The effectiveness of using magnetic flux concentrators is more pronounced when applied to short coils. Conversely, if the coil length is six times greater than the diameter, there typically will not be a noticeable improvement in coil efficiency when using magnetic flux concentrators. When induction heating of selective areas of tubes and pipe, it is sometimes desirable to have a short longitudinal transition zone. In this case, a flux concentrator's ability to localize the magnetic field in the required area is a definite benefit.

Space Saving Power Supplies for Induction Tube and Pipe Heating

Many new induction heating power supply designs using MOSFET or IGBT fast switching power transistors have been introduced in the past few years. In general, transistorized power supplies are much more compact than the equivalent thyristor or vacuum tube equipment. For example, a 150 kW, 30 kHz, IGBT power supply (including the inverter, heat station, load matching transformer and capacitors) measures on 24" x 24" x 51" and mounts on a standard heat station base. Solid state power supplies can be effectively used for thin wall tubing applications, such as brazing, soldering, bending, coating, and annealing. IGBT and MOSFET power supplies are most effective at frequencies above 10kHz. The space-saving features of these new power supplies has made a huge difference in the space requirements for modern induction heating machines.

Fig. 8 shows a thyristorized power supply and induction coils for heating of pipes used for oil and gas lines prior to the application of three layer polythelene coating. The thyristorized-type inverters are typically used at frequencies below 10kHz. This particular system is quite large and coils are normally maneuvered into the heating position with the aid of casters or wheels, and jacked for correct pass line height. They are housed in a steel frame to ensure robust presentation and long life. Typically, one coil is designed with an ability to heat several different tube sizes. Flexibility of a power supply to

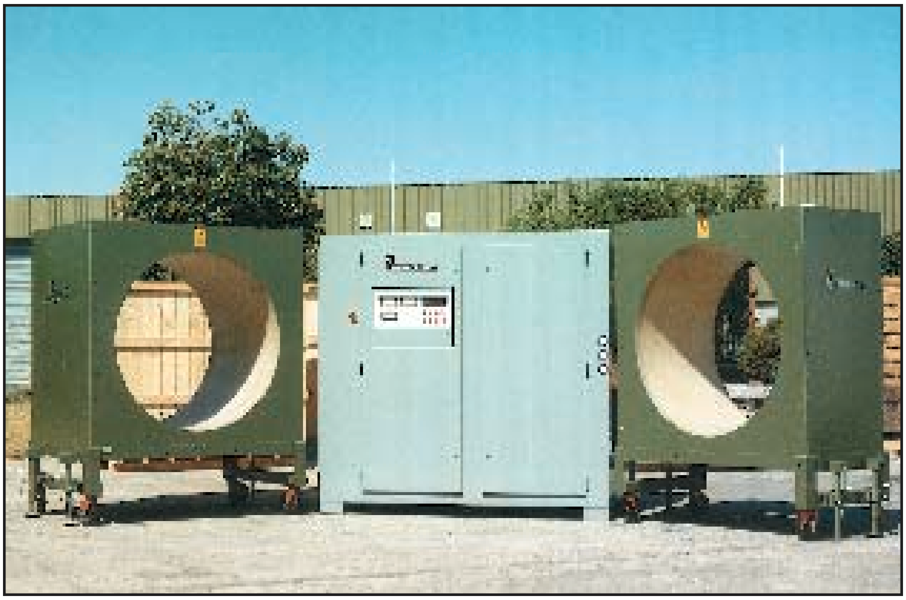

Fig. 8 Induction heating system for pipe coating.

operate under varying load conditions or on different applications is an important factor. It is imperative that power supply tolerance to load perturbations is a function of power component design margin and control circuit design.

CONCLUSION

Induction processes provide improved capability for many of the current and innovative tube and pipe products. In order to be efficient and competitive, manufacturers should understand the physical, electrical and metallurgical ramifications of their heating process. The newer power supply design, inductor concepts and computer-based analytical techniques will provide the basis for robust and successful induction tube and pipe heating applications.

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