

Intricacies of Induction Heating of Wires, Rods, Ropes & Cables

by:

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Heating by means of electromagnetic induction has become an increasingly more popular method for heating ferrous and nonferrous wire-type products.

There are several ways to heat wires, ropes, rods and cable products including gas furnaces, electrical resistance heaters, infrared furnaces, electric ovens, molten lead baths, salt baths and induction heaters. Heating by means of electromagnetic induction has become an increasingly more popular method for heating ferrous and nonferrous wire-type products in such applications as heat treatment (hardening, tempering, stress-relieving, annealing, relaxation, etc.), heating before encapsulation, thermal diffusion, wire pre-heating prior to metallic or organic coating, drying, plating, cladding and others (Figure 1).



Fig. 1 — Electromagnetic induction method for heating ferrous and nonferrous wire products in applications such as hardening, tempering, stress-relieving, annealing, relaxation, heating before encapsulation, thermal diffusion, wire pre-heating prior to metallic or organic coating, drying, plating, cladding and others.

Growing environmental concerns for global warming in combination with the requirement of increasing production with reduced equipment footprint have resulted in induction heating (IH) becoming the dominant method for heating of both ferrous and nonferrous wire-like workpieces¹⁻³. Thanks to IH, the use of molten lead and salt baths for heating of wire products has practically been eliminated. Other advantages of IH include instant heat generation and the possibility of incorporating a protective atmosphere (for example, for bright annealing applications).

Quick response and the ability to provide a rapid change in the process operating parameters to accommodate the

required temperature of the wire/cable being processed at speeds up to 5 mps are also noticeable benefits of compact induction systems compared to fluidized beds, infrared heaters and gas furnaces. Frequencies that are in the range of 10 to 800 kHz are commonly applied.

As an example, **Figure 1** (left-bottom image) shows **Radyne's** induction heat treatment line for the hardening and tempering of 1060 carbon steel spring wire in the diameter range of 4 to 8 mm (0.162" to 0.312") using a dual-frequency design concept¹⁻³. Heating below Curie temperature is done using a 400 kW/10 kHz inverter. A 420 kW/200 kHz inverter provides heating above the Curie temperature. Tempering is also carried out by means of electromagnetic induction.

This article reviews subtleties of the most common single- and multi-wire processing applications where the IH is used for the heat generation. Several related case studies will be revealed to illustrate process features.

High Speed Processing of Spring Wires

Some of the most critical properties in manufacturing spring wires are high quality surface finish and integrity, and superior strength while retaining a good ductility. Elimination of traces of alkali and minimization of the carbon deposition on the surface of the wire are essential for manufacturing quality wires^{2,3}.

Materials for spring wire fabrication are commonly ranging from carbon steels and low alloy steels (e.g., *SAE 4140*) through to specialty steels such as *SAE 9254* (Cr-Si alloy) and *SAE 9254V* (Cr-Si-V alloy), for example. Wire diameters are from 1.27 to 15.75 mm being processed at production rates up to 6600 lb/hr (3000 kg/hr) with line speed up to 590 fpm (180 mpm) (**Figure 2**). Combination of tensile strength (greater than 2000 MPa) and ductility (exceeding 40% ROA) are some of critical features. Advanced payoff and take-up systems designed to allow continuous production with maximum uptime.

Wire Annealing Systems

Annealing is a broad term that is used by heat treatment practitioners to describe a variety of processes and properties related to microstructure, machinability, formability, relieving internal stresses, enhancing certain electrical properties and the like¹.

Sometimes, certain corporate terms, or slangs are also used



Fig. 2 — System for processing wire in diameters from 1.27 to 15.75 mm production rates up to 6600 lb/hr (3000 kg/hr) with line speed to 590 fpm (180 mpm).

by steel processing organizations to designate particular process specifics. In carbon steel wire applications, this includes recovery annealing (200°C to 550°C), recrystallization annealing (400°C to 760°C), intermediate annealing (300°C to 760°C) and some others.

The following are some basic forms of annealing related to carbon steels:

- Full annealing
- Intercritical annealing
- Subcritical annealing (process annealing)
- Spheroidized anneal or spheroidizing

Intercritical annealing and subcritical annealing (process annealing) are two of the most typical annealing process where IH is used as the heat source.

In some cases, it might be beneficial to heat a steel to temperatures between the upper critical temperature (A_{c3}) and the lower critical temperature (A_{c1}), obtaining partial austenization (to different degrees), holding the steel at a specified temperature range followed by cooling in air or applying a controlled cooling. This is where the term *intercritical annealing* is derived from. The final multiphase microstructure can be adjusted by changing the time/temperature/cooling rate combinations.

Upon reaching target intercritical temperatures and depending on the application specifics, it might be required to hold the steel at a temperature for some time. IH can be used for intercritical annealing when relatively short holding times are needed or as a booster heater. Whenever long holding times are required, it typical to use holding ovens, which are either gas or electric heated. Although IH at the front end can be very effective at rapidly and efficiently preheating to the hold temperature for these applications.

Subcritical annealing (SA) of carbon steel wires (also called process annealing, recrystallization annealing or tempering) represents a large group of heat-treating processes where

microstructural changes and modification in mechanical properties are achieved without austenization¹. Thus, the temperature range for SA is always below A_{c1} critical temperatures. SA represents an intermittent stage between a fully annealed condition and a cold worked condition (i.e., rolled or drawn). Work hardening takes place as a result of a cold work increasing a number of dislocations (crystal imperfections), changing a dislocation pattern, producing elongated grains and increasing hardness and brittleness.

SA helps to adjust the hardness and grain structure of products processed on previous operations (e.g., cold-worked steels); otherwise, it might be too difficult to continue cold working. Therefore, SA can be applied between certain process stages (e.g., drawn wire/rope) when steel softening is needed. Transforming elongated grains into predominantly equiaxed grains, restoring toughness and ductility of steel, will improve its conditions before the next cold-work process. Several critical engineering properties of steel (e.g., yield strength, fracture resistance, the ductile–brittle transition temperature, etc.) can be enhanced.

According to SA, a carbon steel workpiece is typically heated to temperatures of 20°C to 200°C below the lower critical temperature A_{c1} , held for some time at a temperature (if required), and then cooled in air, gas or using some aqueous medium or their combination. In some cases, the needed time for holding is only a few seconds; however, in other cases, it might be substantially longer. In subcritical annealing of plain carbon and low alloy steels, softening starts with recovery that leads to a redistribution of dislocations. This process intensifies rapidly with a temperature increase.

There are two ways to implement SA of long products: box/batch SA and continuous SA. With batch annealing, a stack of rods or wire coils is heated in an enclosed furnace (e.g., infra-red or resistance furnace); care should be taken to insure that internal areas of a stack are sufficiently heated.

Continuous SA can be done in furnaces (e.g., rotary-hearth or pusher type) or using induction heaters in particular when no holding time is specified or a relatively short holding time is sufficient. At temperatures suitable for SA, carbon steels retain their ferromagnetic properties, allowing extremely energy efficient IH of thin wires at high production rates.

In drawing wires made of austenitic stainless steels, an excessive work hardening might also take place making the wire to be too hard to continue to be drawable. Recrystallization annealing helps to make a stainless steel wire sufficiently soft, improving its drawing capability. In contrast to carbon steels, this is commonly accomplished by heating austenitic stainless steel wire to temperature of the 1050°C or so followed by rapid cooling to avoid precipitation of carbides, which could worsen corrosion resistance properties. Direct water spray quenching does not apply here at first. Instead, specially designed water-cooled tubes/jackets filled with protective gas are used during initial and intermediate cooling stages¹⁻³.

There is a group of applications where IH is effectively used

to heat treat wires or thin-wall tubular products: “black,” “dull” and “bright” annealing of metallic materials including stainless steels.

Stainless steel wire can be heated to temperatures of about 1050°C to 1150°C range and then progresses through a gas quench tunnel filled with a hydrogen-nitrogen atmosphere to prevent surface oxidation and provide a bright appearance. Of course, care should be taken for safe processing because gas mixture can be explosive owing to the presence of hydrogen in an amount greater than 4% or so. In cases where only a nitrogen atmosphere is used, the surface of the product appears dull and the process is called dull annealing. Without using a special atmosphere, the surface will be oxidized and the process is often referred to as “black” annealing. IH can be used for all three processes.

As an example, **Figure 3** shows two Radyne Bright Annealing Wire Systems implementing a modular and expandable design concept and meeting virtually any line speed and product dimension for heat treating oxygen-free copper, brass, titanium, stainless steel, nickel and other materials. Such systems can either be placed standalone or in-line with reduction equipment to create an inline processing. Innovative design allows for easy operation, maintenance and changeover from product to product. Each system is equipped with automatic and precision process control

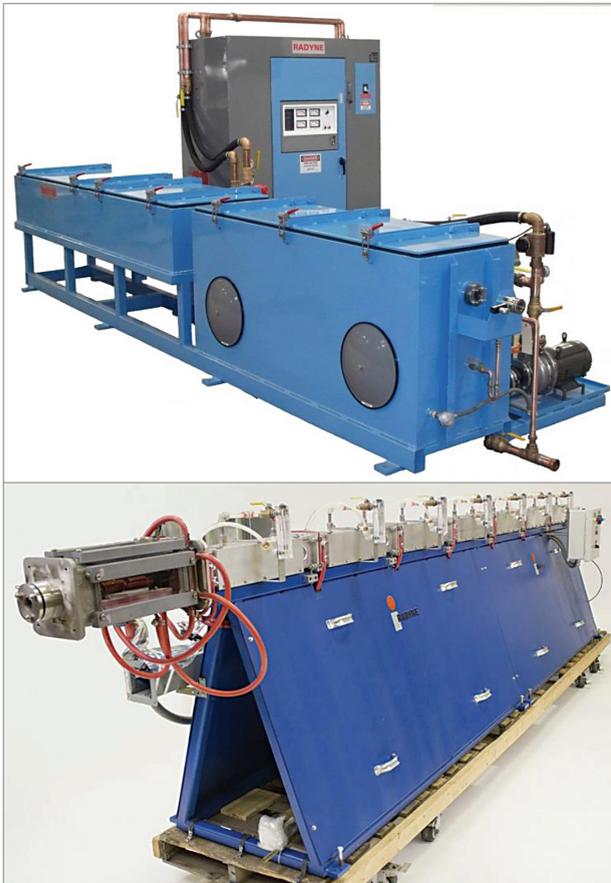


Fig. 3 — Two Radyne Bright Annealing Wire Systems with a modular/expandable design concept and meeting virtually any line speed and product dimension.

containing following features^{2,3}:

- Automatic speed sensor controls power proportionate to line speed. Recipe storage and retrieval. Wire sizes: 2 to 16 mm diameter.
- Integrated temperature sensing.
- High wear resistant tube guides. The ceramic tubes guides allow the surface heat loss to be minimized and somewhat assist with mechanically constraining the movement of the wire.
- Integrated pumping system.
- Solid state inverters, operating in both medium and high frequencies.

Quench details:

- Optional inert gas quench available.
- Optional gas recycling.
- Optional gas manufacturing and mixing systems.
- Contained Atmospheres—Nitrogen, Nitrogen with up to 4% Hydrogen, Helium, Argon, Argon with Hydrogen.
- Gas Impingement Quench—Finished, high quality surface.
- Water Quench – leaves micron level oxidation, acceptable for the majority of inter-process annealing.

Multi-Wire Processing

Besides the case studies discussed above, there are other applications where it is required to heat multiple wires running in parallel or processing cables consisting of many wires and strands or wire bundles. In most cases, a multi-wire induction system utilizes an oval bore coil with multiple openings and individual guides for multiple wires to pass through (**Figure 4**, top). Multi-turn solenoid inductors are commonly used for heating single wires or multi-strand cables (**Figure 4**, bottom).

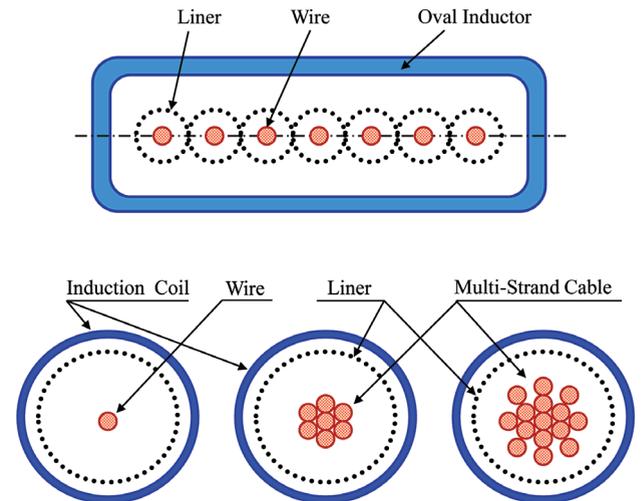


Fig. 4 — Sketch of transverse cross section of inductor for heating multiple wires (top) and multi-strand cables (bottom)¹.

In most single wire processing applications with wire diameters less than 3 mm, the entire wire is usually heated through and the criterion of obtaining surface-to-core temperature uniformity is not an issue unless extremely short heat times are used. Therefore, when heating multiple wires running in parallel or multi-strand cables, the criterion of providing an equal temperature in all wires regardless of their position inside the inductor becomes critical. The former is a result of the fact that external and internal wires of the cable may be heated differently because of the electromagnetic proximity effect and electromagnetic shielding of the external vs. internal wires.

Figure 5 shows an example of the Radyne multi-wire or strand induction heater that offers a high-production and cost-effective solution^{2,3}. System can heat from two to 40 carbon steel wires to Curie temperatures delivering a throughput of 4400 lb/hr (2000 kg/hr).



Fig. 5 – Radyne multi-wire or strand induction heater that offers high-production and cost-effective operation.

Another example is a tire cord diffusion, which may require simultaneous heating of 10 to 24 wires running in parallel and being heated to a temperature up to 600°C to melt the surface alloy coatings (e.g., zinc alloys) that diffuse into the base steel wire to provide a barrier for rust and corrosion. Wire diameters typically range from 0.8 to 2 mm.

Several process features and physical phenomena distinguish IH of multiple wires and cables from IH of single solid cylinders, bars and single wire heating.

Frequency Selection and Energy Efficiency

Coil electrical efficiency is a complex function of several design parameters including the gap between coil copper and wire, electro-thermal properties of heated metal, coil length, number of wires/strands, and frequency, with the former being the most prominent¹.

In the case of IH of a single wire, there will be higher coil efficiency when the applied frequency corresponds to a ratio of “wire diameter-to-current penetration depth (δ)” greater than four. If the chosen frequency results in that ratio of less than 3.2, the coil electrical efficiency will dramatically decrease or heating can be even halt without reaching needed temperatures. This is attributed to the cancellation of induced eddy currents circulating in the opposite sides of the wire¹.

In the case of heating multiple wires or multi-strand cables, efficient heating can be achieved using lower frequencies or smaller-sized wires compared to the heating of a single wire. **Figure 6** reveals that efficiency may increase with the number of wires/strands heated in the same coil (assuming relatively tight positioning of wires). In some instances, it is possible to gain an improvement in coil electrical efficiency that can approach 15% to 20% compared to the heating of a single wire.

Since the capital cost of a power supply usually decreases with a frequency reduction, the ability to use lower-frequency inverters can result in considerable cost savings for the user.

As shown in **Figure 6**, the minimum frequency for efficient heating of multiple wires (frequency F3) is shifted toward the use of lower frequencies compared to heating of a single wire (frequency F1).

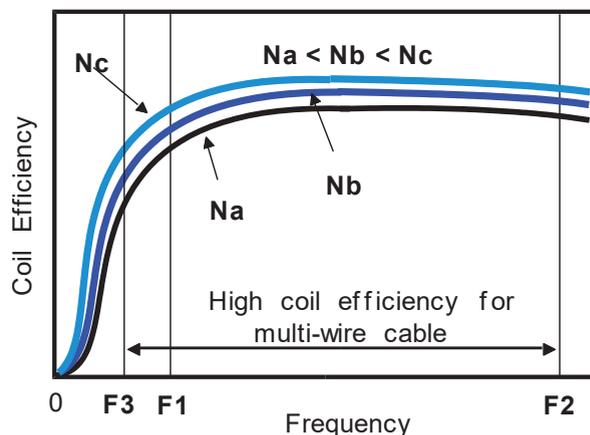


Fig. 6 – Minimum frequency for efficient heating of multiple wires (frequency F3) is shifted toward the use of lower frequencies compared to heating of a single wire (frequency F1).

Metallic materials with high electrical resistivities (ρ) are commonly heated with higher coil efficiency than metals with low ρ (assuming no eddy current cancellation).

It is often required that the single wire induction heater be able to heat a variety of wire sizes to different target temperatures using a single frequency. It is imperative to choose a frequency, which would guarantee that for any combination of wire sizes, materials and target temperatures, severe current cancellation would not occur. It is wise to remember that while calculating the δ , the values of ρ and μ should correspond to their values at the highest temperature expected to be reached during the heating¹.

In some cases, it makes economic sense to choose the frequency based on the so-called big runners (wire sizes that represent the highest production). If there is an insignificant difference in the sizes of the big runners and smaller wires, then, in order to minimize the capital cost of the system, the choice of frequency can be determined by maximizing coil efficiency when heating the big runners with an accepted minor efficiency reduction while processing the smaller sizes.

Continued...

Intricacies of Induction Heating of Wires, Rods, Ropes & Cables ...continued

For some coating lines where gas or electric heating capacity has been reached in a fluidized bed or coating tank, it is desired to preheat various mixed wire diameters prior to their entry into the coating tank. The requirement is for injection of additional thermal energy to maintain overall process thermal equilibrium. In this case, Radyne has developed and patented a multi-channel inductor that allows for the simultaneous heating of various different wires, adding thermal energy to the process allowing for higher throughput than the original coating tank design. This innovative approach allows the wires to be strung above the channel coil until movement and heating is required at which point the wire is lowered into the heating zone. This technique can simplify changeover and setup for coated wire producers and depending upon the size range, can be similarly efficient for heating ferrous alloys below Curie temperature.

Nonferrous wires/cable/ropes such as aluminum, copper, tungsten, titanium and their alloys (for example, brass, Nitinol, etc.) can also be successfully heated using electromagnetic induction. However, coil efficiency when heating nonferrous wires and particularly those made of low-resistance materials is noticeably lower compared to heating ferromagnetic alloys.

Space limits to provide an exhausted description of wire applications as well as electromagnetic and thermal subtleties of applying induction heating. We suggest interested

professionals visit the following websites:

www.inductothermhw.com

www.radyne.com

Or review a content of newly published the second edition of the *Handbook of Induction Heating*, CRC Press, 2017¹.

WFTI

References:

¹ Rudnev, V., Loveless, D., Cook, R., *Handbook of Induction Heating, 2nd Edition*, CRC Press, 2017.

² www.inductothermhw.com

³ www.radyne.com

Company Profile:

Radyne has developed unmatched skill and facilities in the field of induction heating. Radyne maintains a dynamic, integrated, solutions-driven team equipped with the tools essential for rapidly delivering innovative products, services and engineered solutions. The company is a world leading manufacturer and pioneer in the development of advanced induction and controlled atmosphere heating equipment. Offering general-purpose to full-turnkey induction systems for almost every industry, Radyne offers customers industry expertise, process engineering, induction equipment, inductor design and development and 24/7 service and support in one location. www.radyne.com



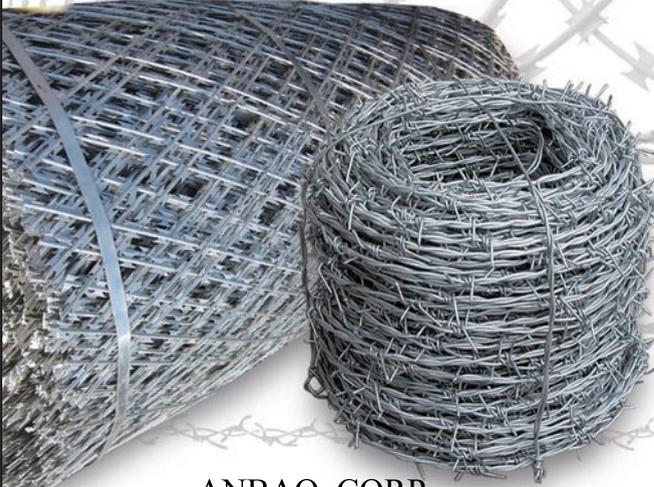
ANBAO

Razor Wire & Barbed Wire

Wire Materials: Galvanized steel wire, PVC coated iron wire
in blue, green, yellow and other colors

Razor type: BTO-10/12/18/22/28/30/36/65

Barbed wire: 1PLY AND 2PLY



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