Successful Induction Heating of RCS Billets

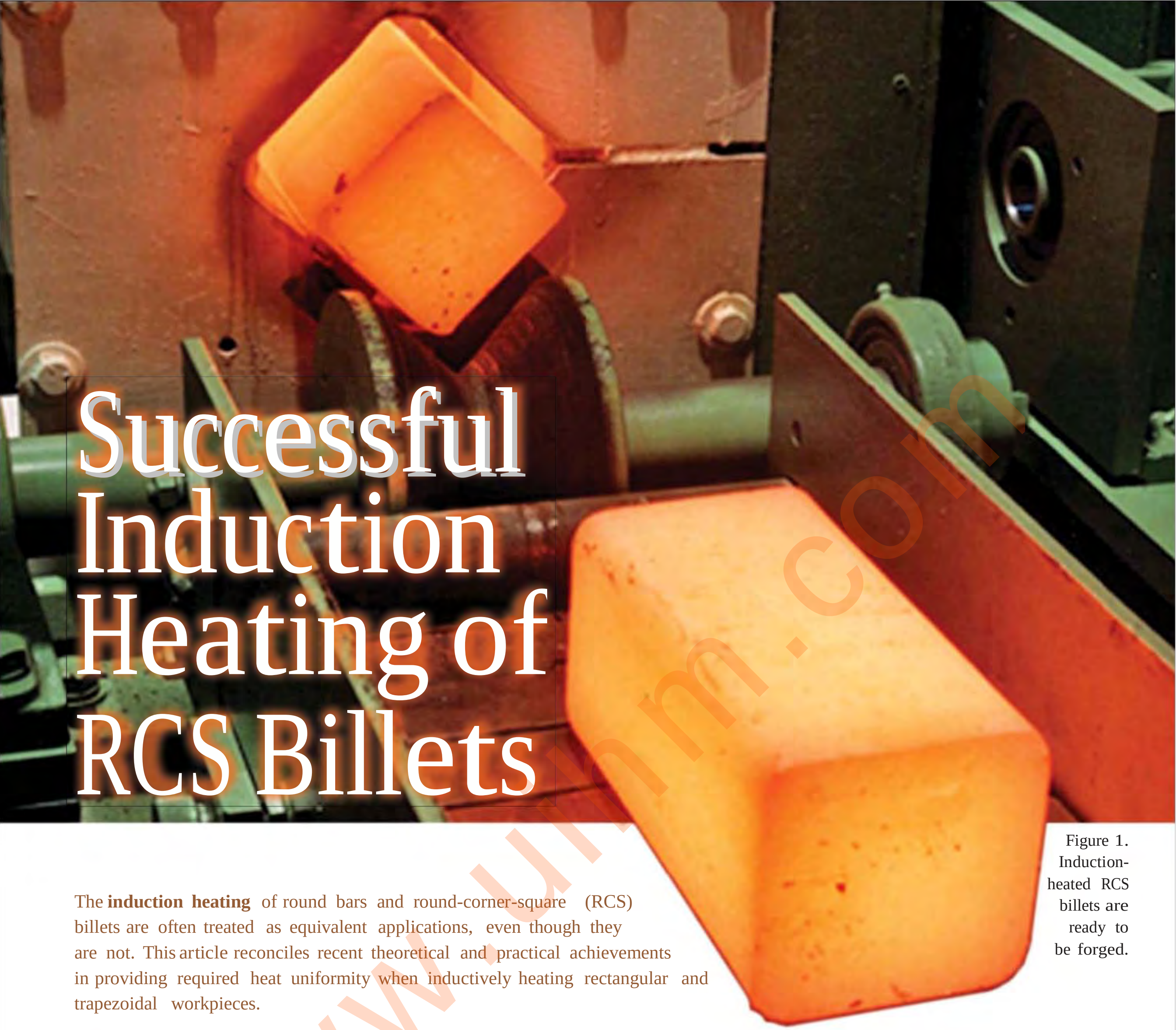

Figure 1. Induction-heated RCS billets are ready to be forged.

The **induction heating** of round bars and round-corner-square (RCS) billets are often treated as equivalent applications, even though they are not. This article reconciles recent theoretical and practical achievements in providing required heat uniformity when inductively heating rectangular and trapezoidal workpieces.

I induction heating, very popular in the heating of cylindrical workpieces, is also commonly used to heat rectangular billets. Workpieces of this general shape include billets, bars, blooms and slabs, which will be referred to in this article as RCS (round-corner-square) billets (Figure 1). In the heating of any shape, it is typically required to not only raise the billet's temperature to a specified level but to also achieve a certain degree of heat uniformity throughout the part. The uniformity specifications may include maximum tolerable thermal gradients: surface-to-core, end-to-end and side-to-side. A billet that is heated non-uniformly can negatively affect the quality of heated products and cause problems for hot-forming machinery.

As a consequence of the non-cylindrical geometry of RCS billets, customers often specify the temperature uniformity in their transverse cross section, including the maximum allowable "central part-to-corner" temperature non-uniformity. Depending upon the specific **induction-heating** parameters used, the edge areas of RCS billets can be under heated, overheated and heated uniformly. The transverse electromagnetic and thermal edge effects are primarily responsible for temperature uniformity within the transverse cross section of the RCS billets, including edges. There are, nonetheless, some misunderstandings among those who use induction heating regarding its ability to provide the required temperature uniformity within RCS billets and factors affecting thermal profiles within a workpiece.

Coil Design

There are three basic induction approaches to heat RCS billets: static, progressive and oscillating heating. The most popular of these is the progressive multi-stage horizontal heating system, in which billets are moved through a single or multi-coil horizontal **induction heater**. As a result, the billet is sequentially (progressively) heated at predetermined positions inside the induction heater. Depending upon application, different in-line coils can have various power levels and frequencies. For this article, we are focused on the progressive multi-stage horizontal-heating design concept because it is the most popular approach.

“Skin” Effect

In discussions about induction heating, reference is often made to the “skin” effect. This is considered a fundamental property of **induction heating** and indicates a non-uniform distribution of an alternating current within the heated workpiece. In this phenomenon, eddy currents induced within the workpiece will primarily flow in the surface layer (skin), where 86% of all the 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.

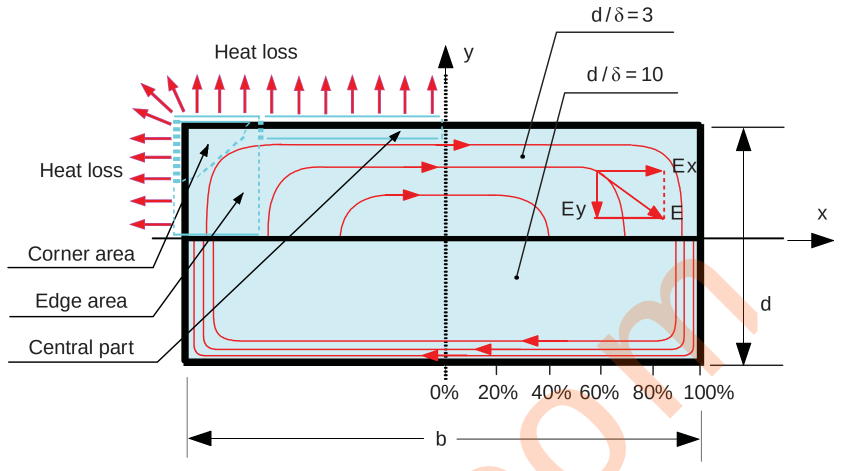

Figure 2. Graphic illustrating the edge effect when heating RCS billets and bars.

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

$$\delta = 503 \times (\rho/\mu_r F)^{1/2}$$

where ρ is the electrical resistivity of the metal (ohm-meters), μ_r is the relative magnetic permeability and F is the frequency (Hertz). In inches, current penetration depth is defined by the following equation:

$$\delta = 3160 \times (\rho/\mu_r F)^{1/2}$$

where electrical resistivity, ρ, is in units of ohm-inches.

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. The value of current penetration depth affects all major induction-heating parameters such as:

- Surface-to-core temperature differential (smaller δ results in greater surface-to-core temperature differential)
- Temperature uniformity along the perimeter of the billet
- Electrical efficiency of the **induction-heating system**
- Required heating time (smaller δ results in a longer heating time and a longer induction line required)

Electromagnetic Transverse Edge Effect

The electromagnetic edge effect represents a distortion of the electromagnetic field and induced eddy current in corner areas of RCS billets. The maximum eddy current density is located on the surface of the central part of the RCS billet. It does not, however, mean that the maximum temperature is always located there. At smaller penetration depths and higher frequencies, the skin effect becomes more pronounced. It is convenient to use the rectangular slab, as an extreme case, when discussing edge-effect appearance. As an example, Figure 2 shows the distribution of the electric-field intensity in the slab’s cross section with pronounced skin effect (d/δ=10, where the slab thickness, d, divided by eddy current penetration depth, δ, is equal to 10), and when skin effect is not pronounced (d/δ=3).

If the skin effect is pronounced (d/δ>5), then the current and power density are approximately the same along the slab perimeter, except in the edge areas (Figure 2, bottom half of the slab cross section), where the distortion of induced power takes place.

Even though heat losses at the edge (corner) area are higher than those at the central part, the edge areas can be overheated compared to the central part. This occurs because in the central part the heat sources penetrate from two sides (from two surfaces), and at the edge (corner) areas the heat sources penetrate from three sides (two surfaces and butt-edge). The phenomenon of edge overheating usually occurs in the induction heating of magnetic steel, aluminum, silver or copper slabs, where skin effect is typically pronounced.

If the skin effect is not pronounced (d/δ<3), then under heating of the edge areas will occur. In this case, the path of eddy currents in slab cross section does not match the contour of the slab, and most of the induced currents close their loops earlier without reaching the corners and the edge areas (Figure 2, top half of the slab cross section). As a result, the power densities and heat sources in edge areas will be less than corresponding values in the central part. For example, in induction heating of large titanium or stainless steel slabs using relatively low frequency, the temperature of the corners and edge areas at the end of heating could often be noticeably lower compared to the temperature of its central part, requiring using dual- or multiple-frequency designs.

Induction Heating of Magnetic Materials.

The induction heating of carbon steel RCS billets or slabs from an ambient temperature or a temperature below Curie point (1414˚F for low-carbon steel and 1350˚F for high-carbon steel) to a temperature above it involves several features. In the initial stage of heating, the entire body is magnetic and the skin effect is pronounced, causing the heat sources to be concentrated within a very thin surface layer.

Surface heat losses are relatively low in this stage. Due to the transverse edge effect, the edge area and particularly the corner region will be heated much faster than any other areas, including the surface of its central region.

During an initial heating stage, the maximum temperature will be located near the corner despite the fact that there is not any current induced in the actual corner.

The beginning of the intermediate stage of heating is characterized by a continued temperature increase. The corner area reaches the Curie temperature first, beyond which the heat intensity in this area significantly decreases. This takes place due to the following reasons:

- Specific heat has its maximum value (peak) near the Curie point. The specific heat value denotes the amount of energy necessary to be absorbed by metal to achieve the required temperature. Therefore, this peak leads to a reduction of heat intensity in the corner when RCS billet temperature approaches the Curie point.
- Steel in the corner area loses its magnetic properties and μ_r drops to 1. In addition, during the heating cycle, the electrical resistivity of the carbon steel increases approximately two to three times relative to its initial stage value. Both factors (the reduction of μ_r and the increase of electrical resistivity, ρ) cause an increase of current penetration depth δ. As a result, skin effect in the corner area becomes less pronounced and heat sources will be redistributed.
- Surface heat losses (due to thermal radiation and convection) increase with temperature. Since the corner (edge area) became the hottest, the surface heat losses in that area will also be the greatest.

During the intermediate heating stage, the temperature of the subsurface area rises more rapidly than in the initial stage of heating. This occurs because of thermal conductivity and increased penetration depth and causes the rest of the workpiece to catch up with the corners as the hottest regions. Therefore, during the intermediate heating stage certain parts of the billet (for example, its corners, edge region, surface and/or subsurface areas) are nonmagnetic, being heated above the Curie point, though the rest is magnetic.

Eventually, the final heating stage takes place. The heat sources at the central part of the slab will be greater than in its edge area. In addition, the heat losses at the edge area are greater than the heat losses in the central part of the slab. As a result, the temperature in the slab central part will start to rise much faster than in its corner.

Finally, the slab edges can be under heated compared to its central region, potentially causing the corners to become the coldest area within the billet. Even its core could be heated to the higher temperature than its sharp corners.

The radius of an RCS billet's corners has an appreciable effect on providing required temperature uniformity across a cross section of billets and slabs.

Computer Modeling

Experience gained on different applications and the computer modeling of induction processes provides a comfort zone in designing new induction billet-heating systems. The combination of advanced software and engineering enables manufacturers of induction-heating equipment to quickly determine details of the process that could be costly, time-consuming and, in some cases, extremely difficult (or impossible) to determine experimentally.

Figure 3 shows two-dimensional temperature profiles representing the dynamics of induction heating a rectangular, round-cornered carbon-steel bar of 0.1-meter (4-inch) cross section using a frequency of 500Hz. Significant temperature gradients occur within the bar cross section. It is important to have a clear understanding of the magnitude of these gradients during initial and intermediate heating stages. With intensive heating, longitudinal and transverse cracks may occur as a result of significant thermal stresses caused by different magnitudes of temperature and temperature gradients.

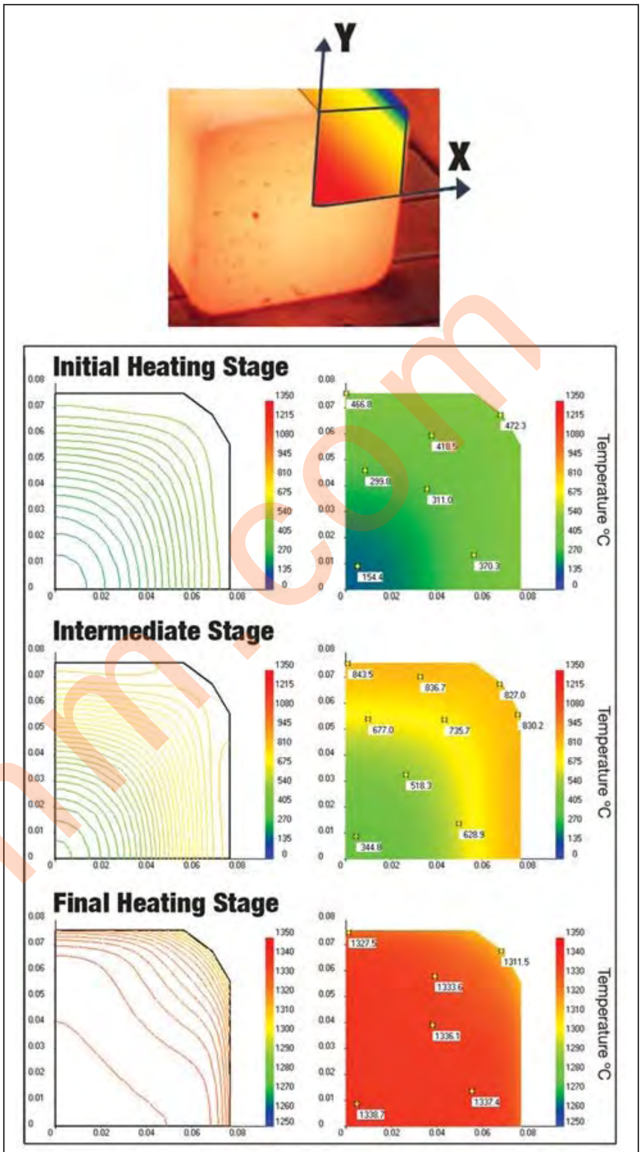

Figure 3. Illustrated dynamics of heating a rectangular, round-cornered steel bar.

Dual- and Multiple-Frequency Approach

In order to avoid undesirable temperature non-uniformity along the perimeter of an RCS billet or slab, it is advantageous to use a dual-frequency approach, in which a low frequency is used in the initial heating stage when the whole slab or most of the billet remains magnetic. Then, when the surface temperature of the billet and/or the temperature of an appreciable portion of its corner exceed the Curie point, a higher frequency is applied.

When heating solid cylinders, the principle reason for using a dual-frequency approach is to avoid an eddy current cancellation when heating billets above the Curie temperature. When heating rectangular workpieces, however, there is an additional criterion for using a dual- or multiple-frequency approach that deals with the necessity to control electromagnetic transverse edge effect as well as thermal edge effect and, therefore, an ability to provide a required temperature distribution along the perimeter.

Therefore, in RCS billets, bars or slabs, a dual- or a multi-frequency design concept allows one to combine the high overall electrical efficiency and short cycle time with required temperature uniformity within the perimeter of a non-cylindrical workpiece.

For example, a dual-frequency design has been successfully used in the induction heating of carbon steel RCS bars (Figure 4). The bars are 4 inches square and 3 meters (10 feet) long with the overall length of the coil assembly being 9 meters (30 feet). The induction-heating coil assembly consists of nine in-line coils and two power supplies – a 600 kW/0.5 kHz and a 300 kW/1 kHz. The bars are heated from ambient temperature by using 0.5kHz up to 650˚C (1200˚F) and then 1 kHz, to increase the temperature to 1120˚C (2050˚F). The production rate is one bar every three minutes. ◆

Figure 4. Dual-frequency induction heating of 4-inch x 4-inch x 10-foot bars has proved successful.