Continuous Induction Heating of Aluminum Billets

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A round billet of aluminum enters a line of induction coils.

Induction is a proven, reliable and efficient method of heating aluminum alloys. However, aluminum alloys have material properties that, if unaccounted for, can result in unexpected challenges. Understanding the unique facets of the induction heating of aluminum can be achieved by considering the properties that make aluminum alloys such advantageous materials.

Given that aluminum and its alloys offer numerous advantages over many other metals, it is not surprising that inquiries about induction billet-heating equipment increasingly involve the heating of aluminum alloys. Many of these inquiries focus on how the induction heating of aluminum differs from the induction heating of other materials – typically steels – and how these differences affect heating quality, efficiency and productivity. Electromagnetic induction is well-suited for the heating of aluminum-alloy billets. However, there are some critical, yet easily overlooked, realities of aluminum billet heating that should be considered when designing, operating and maintaining this type of equipment.

Fundamentally, the induction heating of aluminum alloys is no different than that of other common materials (e.g., carbon-steel and stainless steel alloys). It is ultimately material-property differences that set apart the induction heating of aluminum alloys from other metals. These material-property differences, if unaccounted for, can result in unexpected equipment performance and practical challenges. Because the users of most continuous induction billet-heating systems are familiar with the induction heating of steels and carbon-steel and stainless steel alloys, they provide a convenient point of reference in the consideration of the continuous heating of aluminum-alloy billets.

Density

Perhaps the most obvious difference between aluminum and steel alloys is their dramatically different densities. The density of most aluminum alloys is about 2,700-2,800 kg/m^3 (0.097-0.101 lb/in^3), which is far less than the 7,600-8,000 kg/m^3

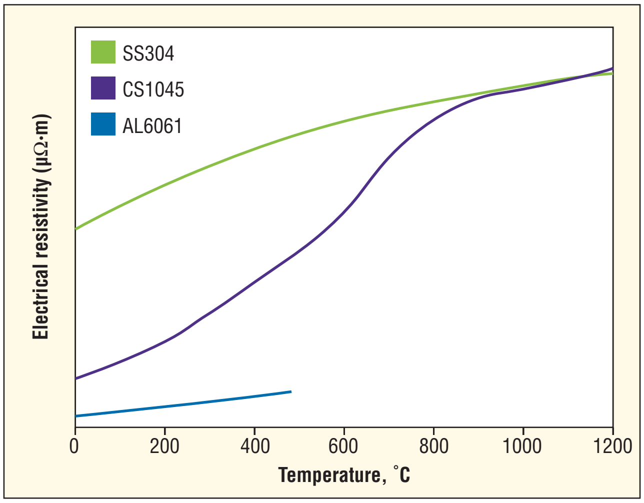

Figure 1. Electrical resistivity vs. temperature

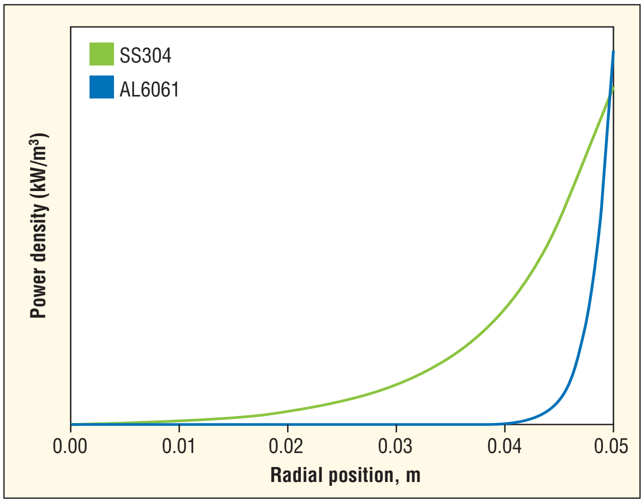

Figure 2. Power density vs. radial position

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(0.275-0.289 lb/in^3) density of typical carbon-steel and stainless steel alloys. Accordingly, the mass of an aluminum billet of a given diameter and length is much less (approximately 2.7-2.9 times) than the mass of an identical carbon-steel or stainless steel billet, implying that:

- For a given billet size and feed rate, the effective production rate (mass flow rate) is much lower for aluminum billets than it is for steel billets.
- Aluminum billets are more susceptible to magnetic forces, especially considering that higher magnetic-field intensities are required for heating aluminum alloys. This topic is revisited in further detail in the discussion of electrical resistivity.

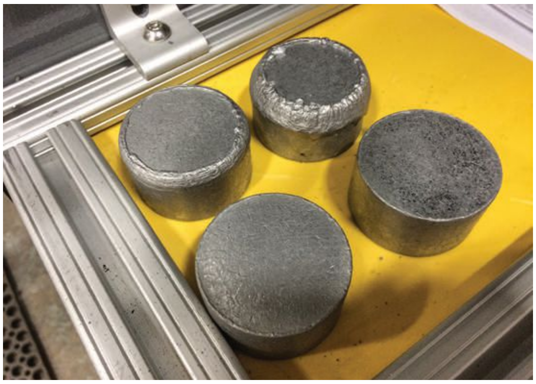


Figure 3. If unaccounted for, electromagnetic end effects can result in localized melting of aluminum billet ends in both continuous and static billet heating processes.

Forging Temperature

Hot-forging temperatures for commonly forged aluminum alloys are generally on the order of 400-480°C (752-896°F), while hot-forging temperatures for most carbon steels are on the order of 1200-1290°C (2192-2354°F). From an induction heating perspective, this means that:

- Despite the fact that aluminum alloys have a substantially higher specific heat (per unit mass) than steel alloys, the theoretical amount of thermal energy required to heat an aluminum body of a given mass to its hot-forging temperature is considerably less than that required to heat a steel body of identical mass to its (much higher) hot-forging temperature. This, however, does not take into account the inherent efficiency differences between the induction heating of aluminum and steel alloys, which are discussed in subsequent sections.
- The thermal efficiency of induction heating aluminum alloys is high (exceeding 95% in many cases) because thermal losses due to convection and radiation are relatively small due

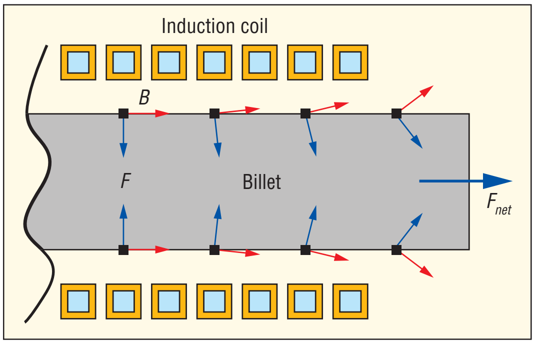


Figure 4. A schematic of the physical forces acting on an aluminum billet as it travels through an induction coil.

to the reduced maximum surface temperature. Aluminum's relatively low emissivity further reduces radiation losses.

- The forging temperature for some aluminum alloys (e.g., alloy 7075) is very close to its solidus temperature, meaning that frequency and power density must be carefully selected in order to mitigate the risk of melting the material during heating.

Electrical Resistivity

Electrical resistivity, a material property indicative of how strongly the material resists current flow, dramatically differentiates aluminum alloys from carbon-steel and stainless steel alloys. The resistivity of aluminum is quite low relative to carbon steel and stainless steels, as shown in Figure 1. At their respective hot-forging temperatures, the electrical resistivity of aluminum alloy 6061 is approximately one-tenth that of carbon-steel alloy 1045 and stainless steel alloy 304. Aluminum's low electrical resistivity is significant for a number of reasons.

As illustrated mathematically, the skin depth δ (m) – the depth in which the majority of alternating current flows in a conductive material – is a function of the material's electrical resistivity ρ (Ω·m) and relative magnetic permeability μ_r, as well as the frequency F (Hz) of the current flowing through it.

$$\delta = 503\left(\frac{\rho}{\mu_r F}\right)^{0.5}$$

Accordingly, high-resistivity materials have larger skin depths than low-resistivity materials. For example, consider independently the heating (from room temperature) of two equally long, round 70-mm billets – one aluminum alloy 6061 (AL6061) and the other stainless steel alloy 304 (SS304).

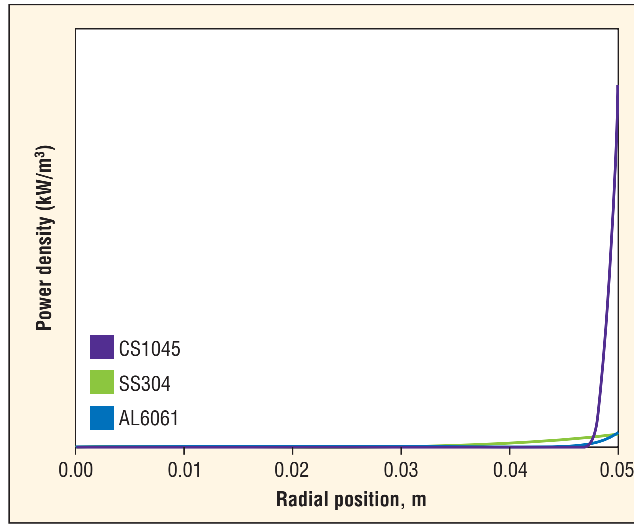


Figure 5. Power density vs. radial position

As shown in Figure 2, assuming identical induction-coil geometries and process parameters (e.g., electrical frequency and magnetic-field intensity), induced power density is much more concentrated near the surface of the aluminum billet than the austenitic stainless steel billet. This is an intrinsic characteristic of induction heating aluminum alloys. Consequently, the overheating of the surface of billets is a legitimate concern in aluminum induction heating processes.

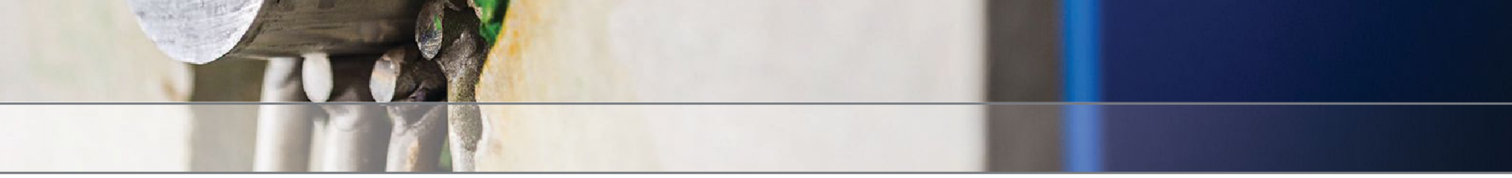
Aluminum alloys' typically high thermal conductivity does mitigate this risk substantially. It should always be considered, however, particularly when heating large-diameter billets very close to their solidus temperature. Coupled electromagnetic-thermal computer simulation software is very useful in foreseeing and avoiding these potential problems.

The concentration of magnetic flux lines near the surface of aluminum billets also creates the potential for localized overheating of billet ends. This phenomenon occurs because of the distortion of magnetic-field lines that results at the end of a billet (when there is not another billet in close proximity).

Because billets are fed end-to-end through continuous billet-heating systems, it is commonly thought that the overheating of billet ends is not an issue in continuous aluminum billet-heating processes. However, this is a dangerous assumption to make. This notion is actually reasonably accurate in steady-state production (assuming the billet extraction mechanism at the end of the induction coil line is properly designed and positioned), but major problems can occur if this phenomenon is not taken into account in transient conditions such as an empty coil start-up.

In an empty-coil start-up, the leading end of the first billet experiences substantial magnetic-field distortion and, in some cases, can exceed the melting temperature inside the induction coil(s), the implications of which are shown in Figure 3. The use of "dummy" billets and the variation of power-supply output and control modes are some of the ways this risk can be mitigated.

The electromagnetic efficiency of induction heating is



influenced substantially by the resistance of the load (billet, bar, tube, etc.). Accordingly, high-resistivity materials tend to heat more efficiently because they inherently have a higher electrical resistance (assuming all other material properties and process parameters are identical). This can be illustrated quite clearly by integrating the power-density curves shown in Figure 2. The result of this integration represents the total induced power per unit length in each billet at the start of the heating processes (assuming electromagnetic end effects are negligible). The total induced power per unit length for the AL6061 billet is 112 kW/m and 484 kW/m for the SS304 billet.

This dramatic difference helps to explain why the attainable electromagnetic efficiency for induction heating aluminum alloys to typical forging temperatures is noticeably lower than that of austenitic stainless steel alloys (approximately 40-45% versus 70-75%). Despite this, electromagnetic induction can still provide substantial efficiency advantages over other methods of heating aluminum alloys.

The low resistivity of aluminum also means that relatively high magnetic-field intensities are often needed to meet production-rate requirements, particularly when using lower frequencies. As a result, magnetic forces can be high in aluminum billet heating. In continuous billet heating, when a billet approaches and passes through the final coil exit, it is subjected to a distorted magnetic field.

This distortion is a product of the fact that magnetic flux lines must form a continuous loop around the inductor. In the end region of the coil (Figure 4), the appreciable radial component of the magnetic field can exert a net longitudinal force that, in some cases, can overcome frictional forces and project the billet out of the coil. In such cases, additional design approaches or material-handling schemes must be considered. Computer simulation is an effective way to predict magnetic forces and determine whether such considerations are necessary.

Aluminum alloys' low resistivity also reduces the coil power factor, the ratio of real power (kW) and apparent power (kVA) at the coil terminals. Practically speaking, a low coil power factor means that the power supply must be capable of providing a very high apparent power (kVA) to the coil and/or more load-matching capacitors are used to offset the high inductive reactance of the circuit. In some cases, low coil power factor can also create some coil design challenges because of practical copper-tube size limitations.

Magnetic Permeability

Unlike carbon-steel and ferritic and martensitic stainless steel alloys, aluminum alloys are effectively nonmagnetic. (Technically aluminum alloys are paramagnetic materials.) Accordingly, aluminum alloys do not strongly "attract" magnetic flux lines like the aforementioned ferromagnetic materials, which has some important implications:

- The reality that magnetic materials (materials with a relative magnetic permeability greater than 1) "attract" magnetic flux lines results in very small skin depths and increased electromagnetic efficiency. Consider again the example of heating an AL6061 and SS304 70-mm-diameter billet, except now consider an additional carbon-steel alloy 1045 (CS1045) billet. Figure 5 reflects the addition of this billet and illustrates the pronounced skin effect and very high power density near the surface commonly associated with the induction heating of carbon-steel alloys. Again, integrating this curve reveals a total induced power per unit length (neglecting electromagnetic end effects) of 1,299 kW/m. This comparatively large figure mathematically illustrates why very high electromagnetic efficiencies can be obtained when heating carbon steels below the Curie temperature (over 90% in many cases) and also further differentiates the induction heating of aluminum alloys from that of ferromagnetic steel alloys.
- Aluminum billets do not experience a magnetizing force when subjected to a magnetic field and are therefore never longitudinally "pulled" toward (into) the induction entrance coil, as is the case with magnetic steel billets. This is a relatively minor point because this force typically does not result in any heating or material-handling issues, but it is a physical difference seen from time to time.

Conclusion

Induction is a proven, reliable and efficient method of heating many different materials – aluminum alloys included. While the induction heating of aluminum is fundamentally no different than the heating of other commonly induction heated metals, aluminum alloys have distinct material properties that, if unaccounted for, can result in unexpected challenges. Computer simulation is a valuable tool in the design of aluminum billet-heating equipment and processes. For equipment users, however, better understanding of the unique facets of induction heating aluminum can often be achieved by simply considering the properties that make aluminum alloys such advantageous materials.

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