Dr. **Valery Rudnev,** known as "Professor Induction", discusses in the heat processing different aspects of induction heating, novel theoretical and practical knowledge related to different heat treating technologies accumulated in the North America and around the globe.

Subtleties of induction heating of aluminum, magnesium and copper alloys

Steel components by far represent the majority of hot worked and heat-treated parts for which electromagnetic induction is used as a source of heat generation. At the same time, aluminum, magnesium, titanium, copper as well as many other non-ferrous metals and alloys are also inductively heated for a number of commercial applications producing various properties and microstructures (**Fig.1**).

Popularity of using non-ferrous metallic alloys has been dramatically increased in the last decade chiefly due to an implementation of light-weight initiatives by automotive industry to meet more stringent federal Corporate Average Fuel Economy regulations. Similar changes are occurring in aerospace and other industries. Practically every metallic part is in process of being revised to optimize engineering properties including weight-to-strength ratio, resistance to specific corrosion media, yet satisfying stringent safety requirements and maximizing process effectiveness. Enhanced thermal and electrical conductivities, thermal stability and appropriate grain structures are other properties that can be also critical in certain applications.

Piece-by-piece processing capabilities with individual component traceability, consistent product quality and environmental friendliness (no combustion or environmental contaminants) are among of the most attractive features of induction heating (IH).

Common applications of IH of non-ferrous metals include annealing and re-crystallization after cold working and casting, metal softening prior to cold forging, heating prior to warm and hot working (e. g. extrusion, forging, heading etc.), drawing, coating and joining applications (e. g. bonding, sealing, brazing, shrink fitting), corrosion-resistance lining for pressure vessels and pipes, just to name a few.

One of the most distinguished features of IH compared to alternative heating methods (e. g. gas-fired furnaces, fluidized beds and infrared heaters) is an impact of electrical resistivity ρ on practically all important parameters of an induction system including depth of heat generation, temperature distribution, heating efficiency etc.

Although metallic materials are known to be good electrical conductors, they are, in turn, also divided on several subgroups

Fig. 1: Electromagnetic induction is widely used for heating aluminum, magnesium, titanium, copper as well as many other non-ferrous metals and alloys for a number of commercial applications (Courtesy of Inductotherm Group)

based on their electrical resistivity ρ. There are metals and alloys that are considered being low-resistive metals (e. g. Al, Mg, Ag, Cu) and high-resistive metals and alloys (e. g. Ti, W, stainless steel, superalloys).

IH of low-resistive metals and alloys such as Al, Mg and Cu requires special design considerations because those materials are better electrical and thermal conductors. For example, the electrical resistivity of Cu is 38 times (at 20 °C) to 15 times (at 900 °C) lower than that of austenitic stainless steel. In contrast, its thermal conductivity is 15 to 20 times higher compared to stainless steel. The lower value of ρ results in smaller depth of heat source generation δ, making it possible to apply much lower frequencies without facing the danger of eddy current cancellation.

IH of low electrically resistive metals are typically associated with lower electrical efficiencies compared to metallic alloys that exhibit higher ρ. The power loss in any IH system includes losses in power supply, capacitors, and transmission; loss of power generated in the coil surroundings (i. e. fixture, support rails etc.); thermal losses from the workpiece's surface; and kW losses in the coil copper windings. When heating low-resistive metals such as Al, Mg or Cu, the power loss in the coil copper windings is usually greater than all other losses combined. Therefore, the ability to reduce losses in coil turns represents the main avenue toward improving the process efficiency.

Impurities observed in metals and alloying elements distort the lattice and can affect the behavior of ρ to a considerable extent. Heating using gas furnaces is practically immune to a variation of ρ. In contrast, implications of using IH when dealing with alloys are noticeably different and associated with deviations in both thermal conduction and electrical resistance of heated material. It would be appropriate to illustrate this statement reviewing a case study of IH copper alloy billets prior to hot working.

CASE STUDY

The challenges with the IH of some Cu alloys, for example, C71500 vs. pure Cu are associated with extremely low thermal conductivity that is approximately 14 times lower than that of pure Cu producing respected "surface-to-core" heat transfer reduction. Regardless of heating method, this will require an additional process time for obtaining needed temperature uniformity, though the extent of

the required heat time increase with IH is much shorter compared to alternative heating methods.

In addition, an electrical conductivity of copper alloy C71500 is only 4.6 % that of pure copper. This increases both electrical efficiency and depth of heat generation, which is positive and may compensate to some degree for the lack of thermal conduction. The ρ of C71500 is only about 54 % and thermal conductivity is about 1.6 times of austenitic stainless steel. Therefore, a response of copper alloy C71500 to IH is closer to the response of stainless steel than pure copper. Some Al and Mg alloys exhibit similar trends to their respond to IH.

Prior microstructure and a degree of previous cold work may also noticeably affect ρ, a respond of alloys to IH. In such applications as recrystallization, this might require to noticeably modify process protocol for producing needed metallurgical results.

In some applications, obtaining a uniform heat distribution is not desirable and certain temperature gradients are specified. For example, depending on the Al alloy and the specifics of the extrusion press, the temperature of the leading end of the billet might be specified approx. 40–80 °C higher than its trailing end. Banyard Zero Friction precision taper heaters using multi zone induction coil technology powered by Inductotherm LFi series low frequency IGBT inverters (**Fig. 1**, middle) provides needed thermal gradients helping to achieve close to isothermal extrusion conditions of the taper-heated billets. This positively affects the quality of extruded aluminum products, while ensuring high production rate.

Regardless of the fact that some of newly developed Mg alloys are not as flammable as pure Mg, precautions must be taken when dealing with any Mg alloys due to potential hazards, explosiveness, and highly flammable nature when in powder, small particles or chips.

Critical temperatures of pure Mg are:

- Autoignition temperature is about 473 °C
- Melting point is 650 °C
- When burning, its flame temperature could exceed 2,100 °C.

When heating Mg alloys, target temperatures often exceed the autoignition temperature, and in some cases, it is even higher than the flash point. Bulk metal is not nearly as flammable or explosive. Of course, during the processing/handling of Mg components, there might be some inevitable small particles and dust accumulations, which could raise a concern. Water cannot be used to extinguish Mg fires because it reacts violently with water. Special fire extinguishers should be applied (Fig.1, bottom-left). Preventive measures should be used to eliminate the possibility of occurring arcing or sparking when using electromagnetic induction. Safety requirements when dealing with Mg and its alloys can be reviewed at www.gov.uk or your national occupational safety office.

More information related to discussed subjects can be found in [1].

LITERATURE

[1] Rudnev, V.; Loveless, D.; Cook, R.: Handbook of induction heating. 2nd Edition, CRC press, 2017

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