Induction Heating

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1 Introduction

Electromagnetic induction, simply induction, is a heating technique for electrical conductive materials (metals). **Induction heating** is frequently applied in several thermal processes such as the melting and the heating of metals.

Induction heating has the important characteristic that the heat is generated in the material to be heated itself. Because of this, induction has a number of intrinsic trumps, such as a very quick response and a good efficiency. **Induction heating** also allows heating very locally. The heating speeds are extremely high because of the high power density.

2 Physical principles

The **principle of induction heating** is mainly based on two well-known physical phenomena:

1. **Electromagnetic induction**
2. The Joule effect

2.1 Electromagnetic induction

The energy transfer to the object to be heated occurs by means of electromagnetic induction. It is known that in a loop of conductive material an alternating current is induced, when this loop is placed in an alternating magnetic field (see Figure 1a). The formula is the following:

$$E = \frac{d\Phi}{dt}$$

E	:	Voltage [V]
Φ	:	magnetical flux [Wb]
t	:	time [s]

When the loop is short-circuited, the induced voltage E will cause a current to flow that opposes its cause – the alternating magnetic field. This is Faraday - Lenz's law (see Figure 1b).

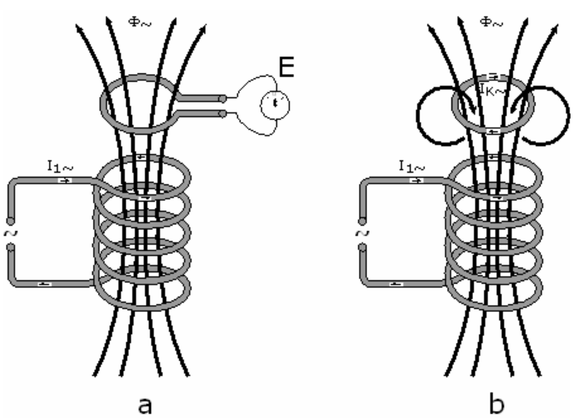

Figure 1: Induction law of Faraday

If a 'massive' conductor (e.g. a cylinder) is placed in the alternating magnetic field instead of the sort-circuited loop, than eddy currents (Foucault currents) will be induced in here (see Figure 2). The eddy currents heat up the conductor according to the Joule effect.

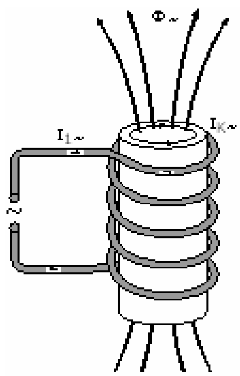

Figure 2: **Induction of eddy currents**

Remark: in practical applications in many cases a solenoid or coil will be used to generate the magnetic field. However, the applications of **induction heating** are not limited to this inductor form.

2.2 The Joule-effect

When a current I [A] flows through a conductor with resistance R [Ω], the power is dissipated in the conductor.

$$P = R \cdot I^2 \quad \text{[W]}$$

In most **applications of induction heating** the resistance R cannot be determined just like that. The reason is the non-uniform distribution of current in the conductor.

2.3 Penetration depth

A general characteristic of alternating currents is that they are concentrated on the outside of a conductor. This is called the *skin effect*. Also the eddy currents, induced in the material to be heated, are the biggest on the outside and diminish towards the centre. So, on the outside most of the heat is generated. The skin effect is characterized by its so-called *penetration depth* δ . The penetration depth is defined as the thickness of the layer, measured from the outside, in which 87% of the power is developed (Figure 3).

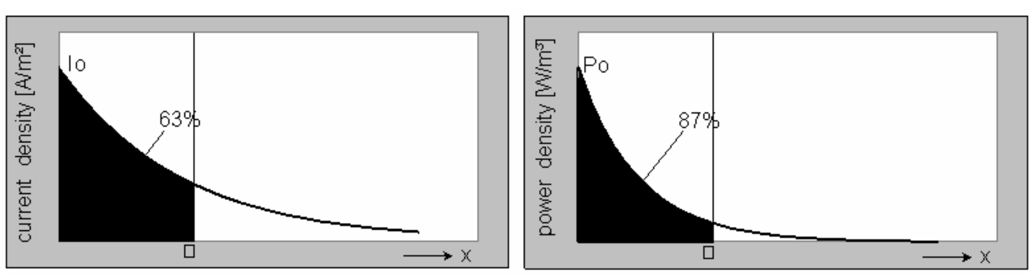

Figure 3: **Penetration depth**

The penetration depth can be deduced from Maxwell's equations. For a cylindrical load with a diameter that is much bigger than δ , the formula is as follows:

$$\delta = \sqrt{\frac{\rho}{\Pi \cdot \mu}} \quad [m]$$

ρ	:	resistivity [Ω .m]
μ	:	magnetical permeability [H/m] (μ=μo.μr)
t	:	frequency [Hz]

We see that the penetration depth, on the one hand, depends on the characteristics of the material to be heated (ρ , μ) and, on the other hand, is also influenced by the frequency. The frequency dependence offers a possibility to control the penetration depth.

The following table gives an idea of the order of magnitude of δ .

Table 1: **Penetration depths**

δ **in [mm]**	Steel 20℃	Steel 20℃	Copper 20℃	Copper 900℃	Graphite 20℃
ρ [μΩ .m] →	0.16	0.16	0.017	0.086	10
μ_r [-] →	40	100	1	1	1
Frequency ↓					
50 Hz	*4.50*	*2.85*	*9.31*	*20.87*	*225.08*
100 Hz	*3.18*	*2.01*	*6.58*	*14.76*	*159.15*
1 kHz	*1.01*	*0.64*	*2.08*	*4.67*	*50.33*
10 kHz	*0.32*	*0.20*	*0.66*	*1.48*	*15.92*
100 kHz	*0.10*	*0.06*	*0.21*	*0.47*	*5.03*
1 MHz	*0.03*	*0.02*	*0.07*	*0.15*	*1.59*

As can be derived from the formula above, the penetration depth is inversely proportional to the square root of μ_r.
For non-magnetic materials like copper or aluminium the relative magnetic permeability is μ_r=1. Ferromagnetic materials (iron, many types of steel) on the contrary, have a μ_r-value that is much higher. Therefore, these materials generally show a more explicit skin effect (smaller δ).

The magnetic permeability of ferromagnetic materials strongly depends on the composition of the materials and on the circumstances (temperature, magnetic field intensity, saturation). Above the Curie temperature μr suddenly drops again to μr=1, which implies a rapid increase of the penetration depth.

3 Induction Heater Installations

3.1 General aspects

The **inductor** and the load behave as an inductive load and are compensated with capacitors. A frequency converter feeds the entirety with a single-phase current at the desired frequency.

An induction installation also contains a cooling system (for frequency converter, inductor), a transport system and the necessary control and measuring apparatus.

3.2 Power supply and generators

The electrical supply can occur in different ways, depending on the frequency at which the installation has to work.

50Hz-installations:

The compensated load is directly connected to the transformer. The transformer can be regulated so that the current can be adjusted to the impedance of the load.

Frequency converters with thyristors:

- efficiency: 90-97%
- frequency range: 100Hz – 10kHz
- power range: up to 10MW

Frequency converters with transistors:

- efficiency: 75-90%
- frequency range: tot 500kHz
- power range: tot 500kW

Frequency converters with vacuum tubes:

- Efficiency 55-70%
- Frequency range: up to 3000kHz
- Power range: up to 1200kW

3.3 Inductors

In most applications the inductor consists of a copper hollow tube. The most simple, often applied configuration consists of one or more windings that surround the workpiece. However, the **inductor** can be placed in many ways, depending on the application.

The inductor is usually made of copper in order to limit the electric losses. Nevertheless, the inductor is in almost all cases internally water-cooled.

4 Properties of induction heating

4.1 Power Transfer: simplified calculation

The load of an induction installation is heated because of the Joule effect as a result of induced eddy currents. The simple formula $P=R \cdot I^2$ cannot be used because the distribution of the currents over the conductor is not uniform.

In General, one can state:

$$P = \pi \cdot d \cdot h \cdot H^2 \cdot \sqrt{\pi \cdot \rho \cdot \mu_0 \cdot \mu_r}$$

d	:	diameter of the cylinder [m]
h	:	height of the cylinder [m]
H	:	magnetic field intensity [A/m]
ρ	:	resistivity [Ω .m]
μ_o	:	magnetic permeabity of vacuum ($4\pi \cdot 10^{-7}$ H/m)
μ_r	:	relative permeability
f	:	frequency [Hz]
C	:	coupling factor
F	:	power transmission factor

The last two terms in the formula are correction factors:

- F (power transmission factor):
  - Takes into account the relation between the penetration depth and the external dimensions of the load. *F* depends on the geometry of the load;
- C (coupling factor):
  - Corrects for the relative dimensions of the inductor and the load. The correction is smaller as the inductor is longer and the airgap between the inductor and the load is smaller.

Conclusions resulting from these formulas:

- the power can be increased by an increase in the magnetic field intensity *H*. This means increasing the number of ampere-windings of the inductor;
- an increase of the frequency only leads to a relative small increase in the power. Moreover, the losses in the supply increase and the penetration depth gets smaller;
- material characteristics play an important part (ρ and especially μ_r). For ferromagnetic materials the added power drops when the Curie temperature is exceeded ($\mu_r=1$ if $T>T_{Curie}$).

4.2 Electrical Efficiency

The electrical efficiency is defined as follows:

$$\eta_e = \frac{P}{P + P_i}$$

P	:	power, induced in the load
Pi	:	power, dissipated in the inductor

Also the efficiency is strongly influenced by the relation diameter/penetration depth (in case of cylindrical load). Finally, also the design of the inductor is important. Here, the following points of attention apply:

- For the inductor, use a material with small resistance. Usually, electrolytic copper is applied;
- Use an inductor with a small distance between the windings;
- Provide a good connection between the inductor and the load (limitation of the airgap, make the inductor sufficiently long).

4.3 Power factor

The whole of the **inductor** and the load usually represents an important reactive power. On the one hand, there is the air gap between the inductor and the load and on the other hand, the load itself also has an inductive character, depending on the relation d/δ (in case of a cylinder).

The power factor of the inductor and the load usually lies around 0.05-0.6. In all cases, compensation by means of condensers is required.

4.4 Characteristics of Induction Heating

Process technical

- Because of the high power density an induction installation can be compact and realise a quick heating.
- Induction offers the possibility to reach very high temperatures
- **Induction heating** can be applied very locally
- Induction installations are suited for automation

Energy consumption

- Induction installations generally have a good efficiency. However, the efficiency also depends on the characteristics of the material to be heated.
- An important part of the heat losses can be recuperated

Quality

- Extreme purity is possible by working under vacuum or inert atmospheres
- The place of heating can be determined accurately
- The heating can be regulated precisely

Environment and working conditions

- No production of flue gasses

Limitations

- An induction installation usually implies a big investment that must be considered and compared to alternative heating techniques.
- Induction heating is preferably used for heating relatively simple shapes.

5 Industrial Applications

Typical applications of induction are the **melting of metals**, the **heating of metals for design**, the brazing and welding and all sorts of **surface treatments**. However, by using electric conductive recipients (e.g. graphite) also other materials like glass can be heated.

5.1 Melting of metals by means of induction crucible furnaces

An **induction crucible furnace** essentially consists of a crucible with refractory lining, that contains the material to be melted and that is surrounded by the induction coil. The coil is water-cooled and is surrounded by an iron core, in order to improve magnetic coupling.

There are applications at 50Hz as well as mid-frequency applications. The power range (up to 10MW and more) and the specific powers (up to 1200 kW/ton) are extremely high. The melting can therefore occur very quickly.

Low-frequency **induction crucible furnaces** (50Hz) are usually applied for big applications (large power and large capacity). Mid-frequency furnaces are rather used in smaller applications. They offer more flexibility and are more compact. In general there is a trend towards using mid-frequency furnaces at the expense of low-frequency furnaces.

5.2 Induction Brazing

Induction Brazing is an assembly technique where two pieces are joined together by means of a third material that is brought to its melting temperature. In the connection zone both pieces are heated up to a temperature higher than the melting temperature of the third material.

Induction is frequently applied because of the precise localisation of the heating. Moreover the heating happens very quickly which makes that the oxidation or structural or compositional changes can be controlled. Brazing under inert atmosphere is possible. Induction heating is suited for high production speeds in automatized production lines.

5.3 Inductve hardening of steel

Steel with a carbon percentage of at least 0.3% is qualified for **surface hardening**. For this the workpiece is heated up to approximately 900°C and after that it is chilled. The technique is used for the hardening of gear wheels, crankshafts, valve stems, saw blades, spades, rails, and many other things.

The inductive process has the advantage that the treatment can be localised very accurately. Moreover, the chemical composition of the surface layer doesn't change, which is the case for other surface hardening techniques. Because of the selective heating less energy is required than for a complete heating of the product and distortion can be avoided. Typical for inductive hardening are the very high energy densities (1.5 to 5kW/cm²) and the short treatment times (2 seconds).

Figure 4 shows some realisations of inductors. Some inductors are equipped with a spraying system that allows chilling of the workpiece right after the heating.

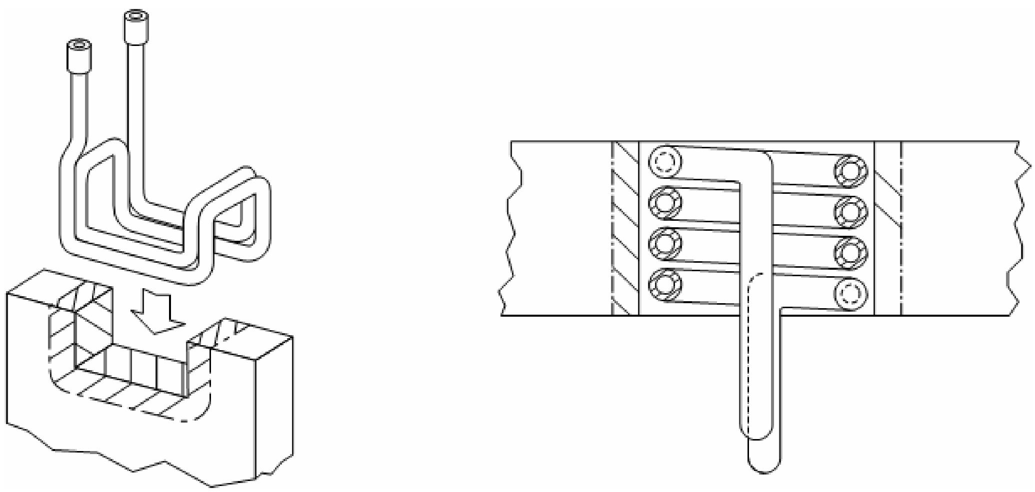

Figure 4: Inductors for hardening

Inductive hardening is especially applied in automated production processes with sufficient production volume. With induction heating a constant, high production quality can be reached. The energy consumption and the production losses are lower than for conventional techniques.

6 Conclusions

This application guide shows the advantages of a less conventional heating technique. As was explained throughout this document, the primary advantage of induction heating is that the heat is generated within the material to be heated. This results in a very quick response, good efficiency and local heating possibilities.

On the downside, because of the desired coupling between inductor and load, restrictions concerning size and geometry have to be taken into account. However, there are many applications possible in the field of heating or melting of metals.

7 Reference

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