Journal of Engineering and Applied Sciences 2 (7): 1178-1182, 2007
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Industrial Applications for Induction Heating

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Abstract: This research 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.

Key words: Electromagnetic induction, energy transfer, power dissipation, ristrictions, inductor and load

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.

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

- Electromagnetic induction
- The Joule effect

ELECTROMAGNETIC INDUCTION

The energy transfer to the object to be heated occurs by means of electromagnetic induction (Metaxas, 1996).

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 (Fig. 1a).
The formula is the following:

$$E = \frac{d\theta}{dt} \qquad (1)$$

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 (Fig. 1b).

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

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.

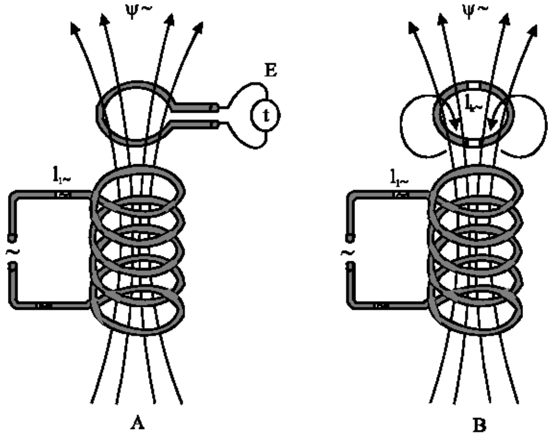

Fig. 1: Induction law of Faraday

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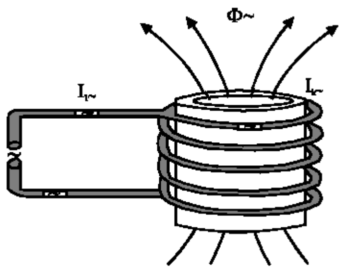

Fig. 2: Induction of Eddy currents

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

$$P = R \times I^2 \, [W] \qquad (2)$$

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.

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 d. The penetration depth is defined as the thickness of the layer, measured from the outside, in which 87% of the power is developed (Fig. 3).

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

$$\delta = \sqrt{\frac{\rho}{\pi . \mu . f}} \qquad (3)$$

ρ : Resistivity [Ω.m]
μ : Magnetical permeability [H m^{-1}] (μ = μo.μr)
f : Frequency [Hz]

We see that the penetration depth, on the one hand, depends on the characteristics of the material to be heated (r, m) and, on the other hand, is also influenced by the frequency.

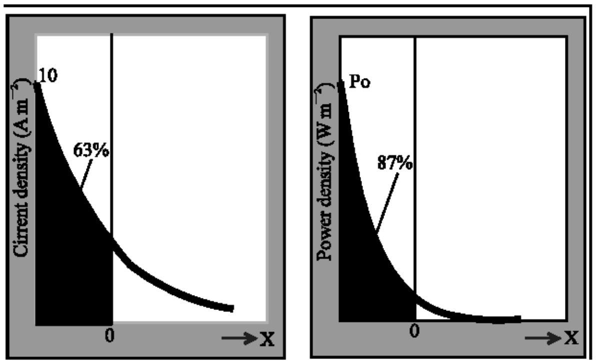

Fig. 3: Penetration depth

Table 1: Penetration depths

			Frequency [Hz]					
δ	ρ	μr	50	10^2	10^3	10^4	10^5	10^6
Steel 20°C	0.160	40	4.5	3.1	1.0	0.3	0.10	0.03
	0.160	100	2.8	2.0	0.6	0.2	0.06	0.02
Copper 20°C	0.017	1	9.3	6.5	2.0	0.6	0.20	0.17
Copper 900°C	0.086	1	21.0	15.0	4.6	1.5	0.50	0.10
Graphite 20°C	10.00	1	225.0	159.0	50.0	16.0	5.00	1.90

The frequency dependence offers a possibility to control the penetration depth.

The Table 1 gives an idea of the order of magnitude of d.

As can be derived from the formula above, the penetration depth is inversely proportional to the square root of μr.

For non-magnetic materials like copper or aluminium the relative magnetic permeability is μr = 1.

Ferromagnetic materials (iron, many types of steel) on the contrary, have a μr-value that is much higher. Therefore, these materials generally show a more explicit skin effect (smaller d).

The magnetic permeability of ferromagnetic materials strongly depends on the composition of the materials and on the circumstances (temperature, magnetic field intensity, saturation) (Davidson, 2006). Above the Curie temperature μr suddenly drops again to μr = 1, which implies a rapid increase of the penetration depth.

INDUCTION INSTALLATIONS

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.

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

50 Hz-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: 100-10 kHz
- Power range: Up to 10MW

Frequency converters with transistors:

- Efficiency: 75-90%
- Frequency range: Tot 500 kHz
- Power range: Tot 500 kW

Frequency converters with vacuum tubes:

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

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 work piece. 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.

PROPERTIES OF INDUCTION HEATING

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 $P=R\times I^2$ cannot be used because the distribution of the currents over the conductor is not uniform.

In general, one can state:

$$P = \pi.d.h.H^2.\sqrt{\pi.\rho.\mu_0.\mu_r.f}.C.F \qquad (4)$$

d : Diameter of the cylinder [m]
h : Height of the cylinder [m]
H : Magnetic field intensity [A m^{-1}]
ρ : Resistivity [W.m]
μo : Magnetic permeability of vacuum (4p.10-7 H m^{-1})
μr : 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 air gap 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 (r and especially μr). For ferromagnetic materials the added power drops when the Curie temperature is exceeded ($\mu r = 1$ if $T>T_{Curie}$).

Electrical efficiency: The electrical efficiency is defined as follows:

$$\eta_e = \frac{P}{P + Pi} \qquad (5)$$

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 air gap, make the inductor sufficiently long).

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/d (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.

Characteristics of induction heating

Technical process:

- 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.

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.

Melting of metals by means of induct ion 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 (ISEPM, 2006). 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^{-1}) are extremely high. The melting can therefore occur very quickly.

Low-frequency induction crucible furnaces (50 Hz) 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.

Brazing: Brazing is an assembly technique where 2 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 (Rudnov *et al.*, 2003). Induction heating is suited for high production speeds in automatized production lines.

Inductive hardening of steel: Steel with a carbon percentage of at least 0.3% is qualified for surface hardening. For this the work piece 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.

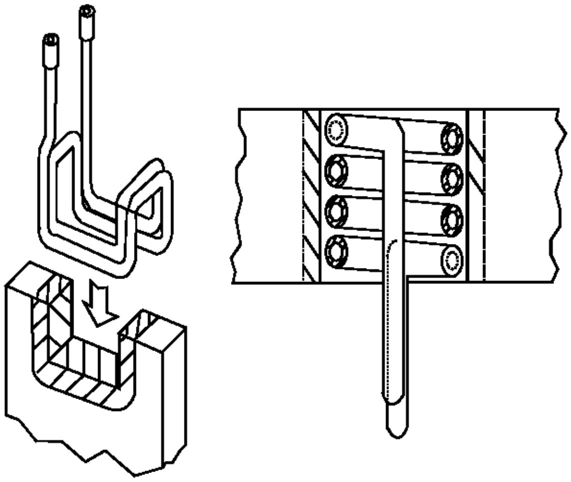

Fig. 4: Inductors for hardening

Typical for inductive hardening are the very high energy densities (1.5-5kW cm^{-2}) and the short treatment times (2 sec).

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

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.

CONCLUSION

This research 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.

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