ELECTROMAGNETIC
PROCESSING OF MATERIALS
TECNOLGIE DEI PROCESSI
ELETTROTERMICI

Induction Heating: fundamentals

Induction heating fundamentals

Summary

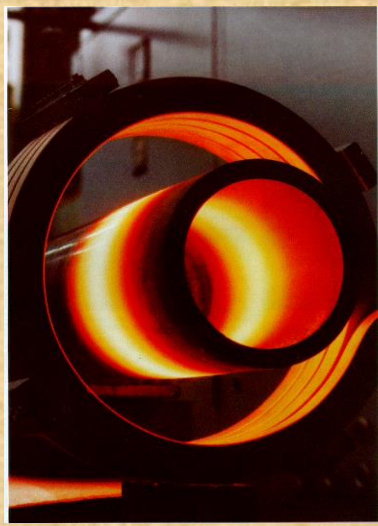
1. Induction heating physical principles
2. Characteristics of the induction heating process
   - Physical parameters that affect induction heating
3. The skin effect:
   - What parameters modify the skin effect?
   - Change of skin effect during the heating
4. Examples:
   - Heating of a magnetic billet
   - Choosing the frequency appropriate to the workpiece
   - Coil thickness as a function of frequency
5. Proximity effect, ring effect, flux concentrators effect

1. Induction heating physical principles

Induction heating physical principles

Characteristics of induction heating

- High temperature in the workpiece (in most cases).
- High power density for a short heating time (in many applications).
- High frequency (in many applications).
- Thermal sources are inside the workpiece.



Induction heating physical principles

Induction heating: fundamental laws

A. Maxwell's equations

3rd Maxwell's equation or Faraday-Neumann-Lenz's law

4th Maxwell's equation or Ampere's law

They state:

- how the electromagnetic (e.m.) field is generated
- how the e.m. field propagates and is distributed in the space
- how the e.m. field interacts with the charged particles.

B. Constitutive relations for materials

- they state what is the (approximate) response of a specific material to an external field or force.

? Ohm's law | Magnetic permeability | Thermal capacity | Fourier's law

Induction heating physical principles

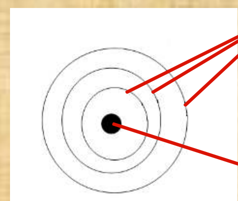
Induction heating fundamental laws: Maxwell's equations

3rd Maxwell's equation or Faraday-Neumann-Lenz's law

4th Maxwell's equation or Ampere's law

TOO BAD TO WRITE!
(in mathematical form)

4th Maxwell's equation (from the induction heating viewpoint):
If an electric current **I** (either DC or time-varying) flows in a conductor, then it generates a magnetic field **H** in the surrounding space.



Magnetic field lines
(always closed loops)

Cross section of a conductor wire (e.g., a copper wire) carrying an electric current **I**

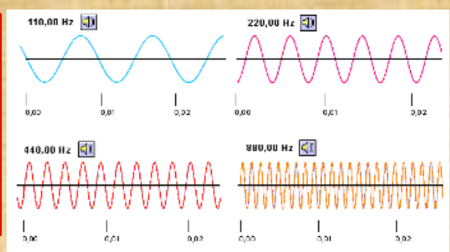
Induction heating physical principles

Induction heating fundamental laws: Maxwell's equations

3rd Maxwell's equation (from the induction heating viewpoint):

The time variation of the **magnetic flux** Φ generates an electromotive force **e.**

- It applies to every time variation (either periodic or non-periodic).
- Periodic time variation à **frequency** is defined.
- Special case: sinusoidal frequency.
- The higher the frequency à the stronger the generated electromotive force.



Induction heating physical principles

Induction heating fundamental laws: Maxwell's equations

Summarizing:

1. Currents generate magnetic fields in the surrounding space (4^{th} **Maxwell's equation**).

2. If the current varies with time, then the magnetic fields vary with time as well.

3. The time variation of magnetic flux generates an electromotive force (3^{rd} **Maxwell's equation**).

4. If any conductor object (i.e. metal) is placed in presence of this electric field, then induced currents are generated in the object itself.

WHY?

Induction heating physical principles

Induction heating: fundamental laws

A. Maxwell's equations

- 3^{rd} Maxwell's equation or Faraday-Neumann-Lenz's law
- 4^{th} Maxwell's equation or Ampere's law

They state:

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- how the e.m. field propagates and is distributed in the space
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B. Constitutive relations for materials

- They state what is the (approximate) response of a specific material to an external field or force.

? Ohm's law | Magnetic permeability | Thermal capacity | Fourier's law

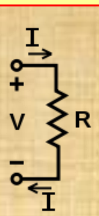
Induction heating physical principles

Induction heating fundamental laws: constitutive relations

Constitutive relations state what is the (approximate) response of a specific material to an external field or force.

Ohm's law **V = R * I**

It states what is the response of any conductor (i.e. metal or alloy) to an **electric** field.



Preliminary remark: the electric (**static**) field **E** is associated to the scalar potential **V**.

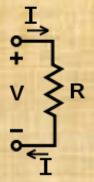
V is related to the potential **energy** of a charged particle in presence of an electric field.

More precisely, Ohm's law states what is the response of any conductor when a potential difference between two points applies.

Induction heating physical principles

Induction heating fundamental laws: constitutive relations

Ohm's law **V = R * I**



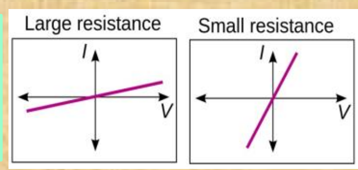
It states that a **current I** flows between two points of any conductor when a **voltage V** is applied.

1. A voltage V is applied to a conductor.

2. Example: a copper wire is connected to a battery.

3. A **current I** flows in the conductor:

- The higher the voltage, the higher the current
- The quantity of current that flows depends on the **resistivity ρ** of the material, and on the geometry of the conductor.



Induction heating physical principles

Induction heating fundamental laws: Maxwell's equations

Summarizing:

1. Currents generate magnetic fields in the surrounding space (4th **Maxwell's equation**).

2. If the current varies with time, then the magnetic fields vary with time as well.

3. The time variation of magnetic flux generates an electromotive force (3rd **Maxwell's equation**).

4. If any conductor object (i.e. metal) is placed in presence of this electric field, then induced currents are generated in the object itself.

according to Ohm's law
WHY ?

Induction heating physical principles

Induction heating fundamental laws: constitutive relations

Constitutive relations state what is the (approximate) response of a specific material to an external field or force.

Magnetic permeability

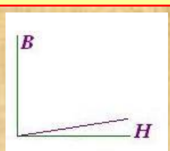
$\mathbf{B} = \mu_0 * \mu_r(\mathbf{H}) * \mathbf{H}$

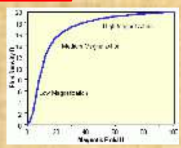
It states what is the response of any material (vacuum included) to a **magnetic** field.

H = magnetic field, magnetic field intensity.

B = magnetic field, magnetic flux density.

μ_0 = physical constant that depends on the physical units (**no** actual physical meaning).





In vacuum:

$\mathbf{B} = \mu_0 * \mathbf{H}$ ($\mu_r = 1$)

In magnetic materials:

$\mathbf{B} = \mu_0 * \mu_r * \mathbf{H}$

($\mu_r >> 1$, μ_r depends on **H**)

Most materials behave similarly to vacuum:

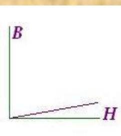
$\mathbf{B} = \mu_0 * \mu_r * \mathbf{H}$ ($\mu_r \approx 1$)

Induction heating physical principles

Induction heating fundamental laws: constitutive relations

Magnetic permeability

$B = \mu_0 * \mu_r(H) * H$



- When a conductive material is placed in a magnetic field, it generates its own bound currents.
- These "bound currents" are due to the interaction between the magnetic field, the bounded electrons (that move around the nucleus) and their spin; they contribute themselves to the total magnetic field in the material.
- **The μ_r value measures the ability of a material to support the formation of a magnetic field within itself**.
- Most materials behave similarly to vacuum:
- Few materials (e.g. **iron, cobalt, nickel** and most of **their alloys**) behave differently:

$B = \mu_0 * \mu_r * H$ ($\mu_r \approx 1$)

(paramagnetic and diamagnetic materials)

$B = \mu_0 * \mu_r * H$

$\mu_r >> 1$ (up to 10^4, μ_r depends on **H**)

(ferromagnetic or **magnetic** materials)

Induction heating physical principles

Induction heating fundamental laws: constitutive relations

Thermal capacity

$Q = m * c * (T_f - T_i)$

It states how much **thermal energy** is needed, for each (homogeneous) material, in order to change the initial **temperature** by a given amount.

- If T_f-T_i is fixed, then the lower the specific heat **c**, the lower the **Q** needed à a little heat **Q** is enough to get the temperature change and vice versa.
- The specific heat is a function of the material's temperature: **c = c(T)**. It is constant on "small" temperature intervals.
- Example: boiling water.

- **T_i =** initial temperature of an object (homogeneous material)
- **m =** mass of that object
- **Q =** heat (thermal energy) given to that object
- **T_f =** final temperature reached by the object, after it received the thermal energy Q
- **c =** specific heat.

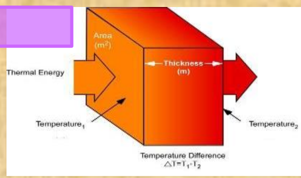
Induction heating physical principles

Induction heating fundamental laws: constitutive relations

Thermal conductivity

(Fourier's law)

$$Q/t = -\lambda * A * (T_2 - T_1)/l$$



Preliminary remark: Heat spontaneously flows from bodies at higher temperature to bodies at lower temperature.

The thermal conductivity states, for each (homogeneous) material, how quickly the heat is transferred, from the higher temperature part to the lower temperature part.

- If T_2-T_1 is fixed, then the lower the thermal conductivity λ, the lower the **Q transfer speed** and vice versa.
- Example: Aluminium cup ↔ ceramic cup.

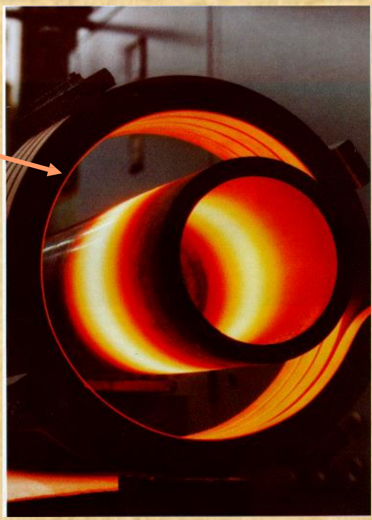
- T_2 = temperature of a body (homogeneous material) on one side.
- T_1 = temperature of the body on the opposite side.
- **A** = area of the body at homogeneous temperature.
- **l** = body's thickness.
- λ = thermal conductivity

2. Characteristics of induction heating process

Characteristics of induction heating process

How is the workpiece heated by means of induction?

1. An electric current (normally high) flows in a conductor (COIL or INDUCTOR).
2. The current generates a magnetic field (4th Maxwell's equation).
3. The **current** in the coil varies with time (normally it has a frequency) à the generated magnetic field (and its flux) have a frequency as well.
4. The time variation of the magnetic flux generates an electromotive force e (3rd Maxwell's equation).
5. The electromotive force can be considered as a voltage V applied to the conductor.



Characteristics of induction heating process

How is the workpiece heated by means of induction?

6. The workpiece (always a conductor, i.e. metal or alloy) is near the coil (electric field more intense).
7. The voltage V between the points of the workpiece generates currents in it (Ohm's law) à

àinduced currents or eddy currents.

8. Eddy currents generate **power** in the workpiece.
9. The power is dissipated in the workpiece and causes its heating.
10. The heat is distributed in the workpiece according to the material's thermal properties. Workpiece's temperature raises.

Characteristics of induction heating process

How is the workpiece heated by means of induction?

Eddy currents generate **power** in the workpiece.

What is power?

Power is the rate at which energy is transferred, used, or transformed:
P = E /t

Why eddy currents generate power?

Because eddy currents (i.e., moving electrons) collide with the metal atoms:
- Because current flowing in a conductor gives rise to heat (Joule effect)

Characteristics of induction heating process

In principle, induction heating is not uniform in the workpiece.

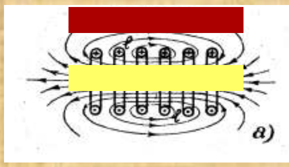
WHY?

Because eddy currents (i.e. the **source** of the heating) aren't uniformly distributed through the workpiece.

WHY?

Many reasons:

1) Magnetic field lines are not uniformly distributed in the space:



à the greater the induced current density

à the greater the induced power density and vice versa.

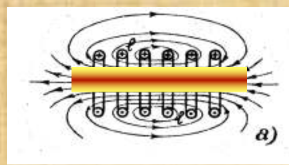
Characteristics of induction heating process

In principle, induction heating is not uniform in the workpiece.

Why aren't eddy currents uniformly distributed through the workpiece?

Many reasons:

1) Magnetic field lines are not uniformly distributed in the space.



Characteristics of induction heating process

2) Even if the magnetic field is uniform, in the conductive workpiece eddy currents are NOT distributed uniformly through the workpiece:

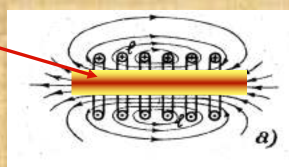
àmost of the current density is close to the workpiece surface

à the higher the frequency, the shallower are the eddy currents.

WHY?

As a result of solving Maxwell's equations

SKIN EFFECT



Characteristics of induction heating process

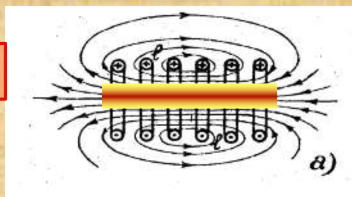
Writing down Maxwell's equations is one thing…

…**solving** them is quite another story!

- The exact mathematical solution is found in very few cases (e.g. the billet in a solenoidal inductor sketched below)
- In all the remaining cases, approximate solutions (e.g. by means of simulations) are found.
- Good news:

Both simple and complex cases are affected by the same (few) physical parameters.

- Then, the billet (easy case) is considered in order to understand **how stuff works**.



Characteristics of induction heating process

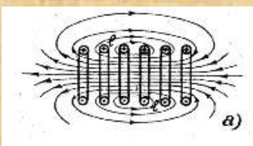
What physical parameters affect the workpiece's heating by induction?

PROCESS

- Frequency **f**
- Current intensity **I** of inductor
- Total heating time **t**

COIL

- Geometry of coil (e.g. air gap)



WORKPIECE

- Relative magnetic permeability μ_r
- Electric resistivity ρ
- Heat capacity C_p
- Thermal conductivity λ
- Geometry of workpiece (e.g. diam.)

Characteristics of induction heating process

PROCESS AND COIL GEOMETRYPARAMETERS:

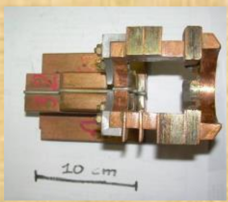
PROCESS

- Frequency **f**
- Current intensity **I** of inductor
- Total heating time **t**

COIL

- Geometry of coil

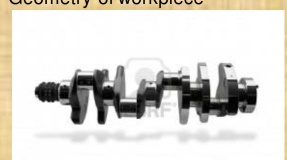
- The coil is connected to a power supply (see below).
- Choice of parameters: upon user's experience.

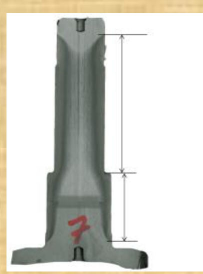


Characteristics of induction heating process

WORKPIECE

- Relative magnetic permeability μ_r
- Electric resistivity ρ
- Heat capacity C_p
- Thermal conductivity λ
- Geometry of workpiece





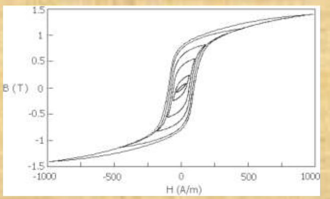
Characteristics of induction heating process

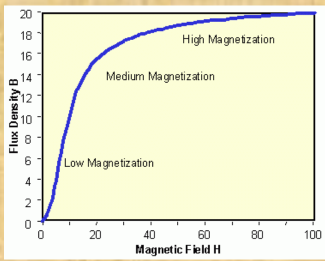
WORKPIECE:

- Relative magnetic permeability μ_r
- Electric resistivity ρ
- Heat capacity C_p
- Thermal conductivity λ
- Geometry of workpiece

For magnetic materials, μ_r depends also on **H**, i.e. on the process parameters

$B = \mu_0 * \mu_r(H) * H$





3.The skin effect

The skin effect

"SKIN EFFECT" = tendency of any AC current (<u>either induced or not</u>) to distribute itself within any conductor:

- **Maximum current density on the conductor external surface**
- **Exponential decay of current density toward the conductor's center**

$$\vec{J}(r) = \vec{J}_0 e^{-r/\delta}$$

δ = penetration depth.

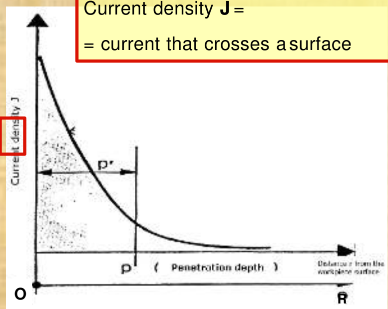
δ depends on material and process.

Current density **J** =

= current that crosses a surface

Cross section of a billet (R>>δ).

Sketch of induced currents distribution



The skin effect

- **Maximum current density on the conductor external surface**
- **Exponential decay of current density toward the conductor's center**

$$\vec{J}(r) = \vec{J}_0 e^{-r/\delta}$$

δ = penetration depth

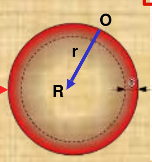
r value	% of $\mathbf{J_0}$	Formula
r = 0	100%	$J(0)=J_0$
r = δ	37%	$J(\delta)=J_0/2.72$
r = 2*δ	14%	J(2*δd)=J_0/7.39
r = 3*δ	5%	$J(3^*\delta)=J_0/20.1$
r = 5*δ	0.7%	$J(5^*\delta)=J_0/148$

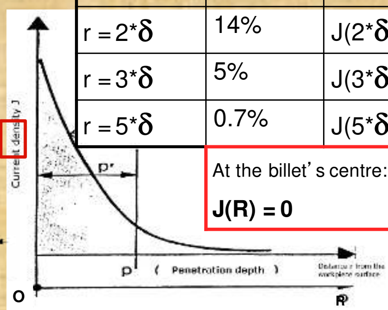
At the billet's centre:

J(R) = 0

Cross section of a billet.

Sketch of induced currents distribution





The skin effect

- Maximum current density on the conductor external surface
- Exponential decay of current density toward the conductor's center

$$\vec{J}(r) = \vec{J}_0 e^{-r/\delta}$$

$$\delta = \sqrt{\frac{\rho}{\pi\mu_0\mu_r f}}$$

δ is function of the process and of the material:

- f = frequency à process parameter
- ρ=ρ (T) resistivity à function of temperature
- $\mu_r = \mu_r(H,T)$ magnetic permeability à function of magnetic field and temperature

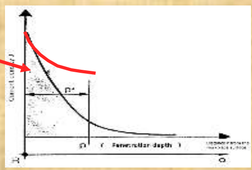
Smaller δ

Current squeezed on the surface

Bigger δ

Current distributed in the workpiece

$$P(r) = P_0 e^{-2r/\delta}$$



The skin effect

$$\delta = \sqrt{\frac{\rho}{\pi\mu_0\mu_r f}}$$

ρ= resistivity à material parameter

Material	Resistivity [Ohm*m] – reference values		
	@ T_{amb}	T ≈ 700 °C	T ≈ 1000 °C
Copper	$2*10^{-8}$	$6*10^{-8}$	$15*10^{-8}$
Carbon (magnetic) steel	$20*10^{-8}$	$100*10^{-8}$	$120*10^{-8}$
Stainless (non-magnetic) steel	$80*10^{-8}$	$120*10^{-8}$	$140*10^{-8}$
Brass	$7*10^{-8}$	$13*10^{-8}$	$16*10^{-8}$

@ T_{amb}:

$\delta_{stainless\_steel} \approx 6 * \delta_{copper}$

Smaller δ

Current squeezed on the surface

Bigger δ

Current distributed in the workpiece

The skin effect

$$\delta = \sqrt{\frac{\rho}{\pi \mu_0 \mu_r f}}$$

f = frequency à process parameter

Example:

- f = 50 Hz à very low frequency
- f = 500000 Hz à very high frequency

à $\delta_{low\_freq} \approx 100 * \delta_{high\_freq}$

Typical frequency range:

1 kHz ÷ 300 kHz

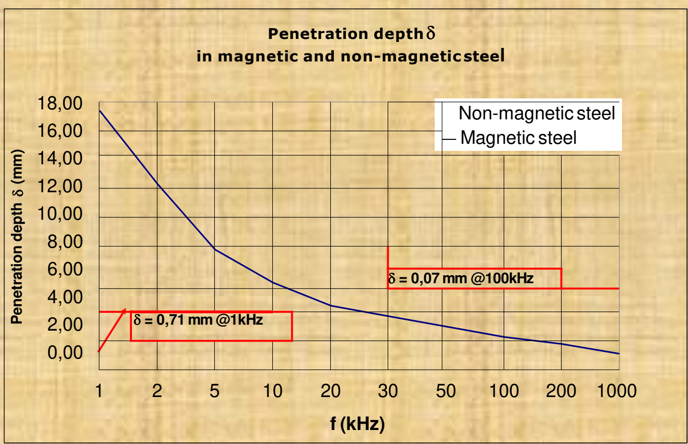
Smaller δ

Current squeezed on the surface

Bigger δ

Current distributed in the workpiece

The skin effect



The skin effect

$$\delta = \sqrt{\frac{\rho}{\pi \mu_0 \mu_r f}}$$

$\mu_r = \mu_r(H,T)$ magnetic permeability à function of magnetic field and temperature (material **and** process parameter)

Example:

- Magnetic steel @T_{amb}à — $\mu_r \approx 10^3$
- Non-magnetic steel @T_{amb}à — $\mu_r = 1$
- **Magnetic steel @ T ≥ 760 ° C**à — $\mu_r = 1$

à $\delta_{nonmagn} \approx 30 * \delta_{magn}$

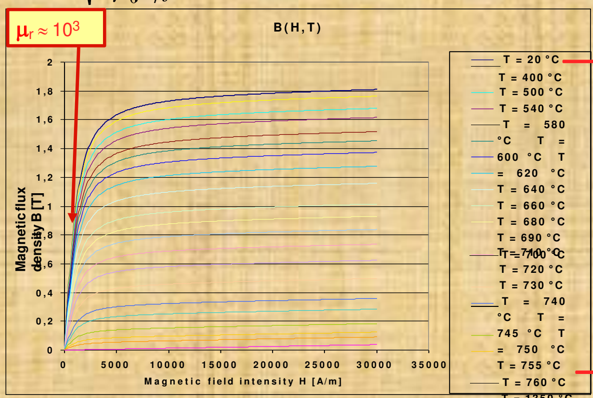
Smaller δ
Current squeezed on the surface
Bigger δ
Current distributed in the workpiece

The skin effect

$$\delta = \sqrt{\frac{\rho}{\pi \mu_0 \mu_r f}}$$

$\mu_r = \mu_r(H,T)$ magnetic permeability à function of magnetic field and temperature (material **and** process parameter)

$\mu_r \approx 10^3$



μ_r @ T_{amb}

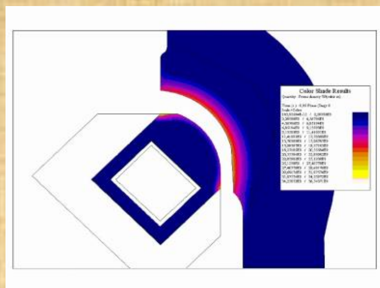
Curie temperature for soft steel (magnetic material) ≈ 760° C

μ_r = 1 @ T≥760° C

The skin effect

$$\delta = \sqrt{\frac{\rho}{\pi \mu_0 \mu_r f}}$$

$\mu_r = \mu_r(H,T)$ magnetic permeability à function of magnetic field and temperature (material **and** process parameter)



Examples

Examples

Heating of a magnetic billet from T_{amb} up to 1200° C

1. Heating starts:
   - Billet fully magnetic
   - Induced currents squeezed on the surface
2. Only surface layers of the billet heat up à the inside remains cold.
3. Surface temperature ≈ Curie temperature (760 ° C) à induced currents spread more within the billet (where the material is still magnetic)
4. At the same time, the **phase transition** between magnetic and non-magnetic material takes place:
   - All the energy from induced currents is used for breaking magnetic domains
   - The surface temperature does not increase any longer
5. Phase transition completed à the surface temperature rises again.

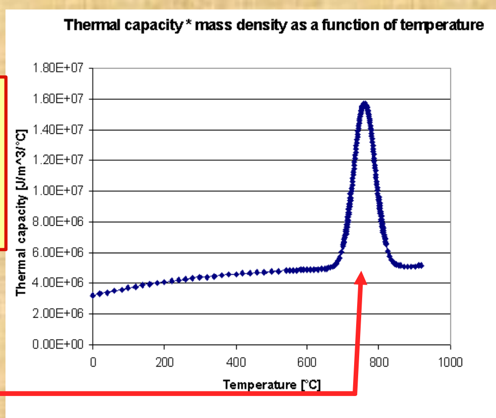
Examples

Heating of a magnetic billet from T_{amb} up to 1200° C

At Curie temperature (≈ 760 ° C):

•All the energy from induced currents is used for breaking magnetic domains

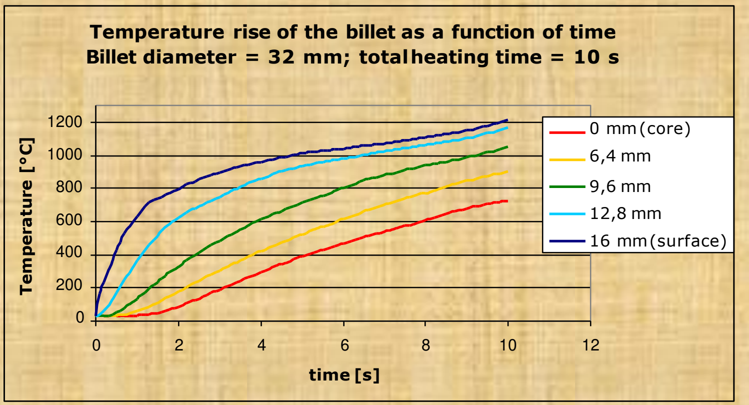
•The surface temperature does not increase any longer



Curie's transition (from magnetic to non-magnetic steel)

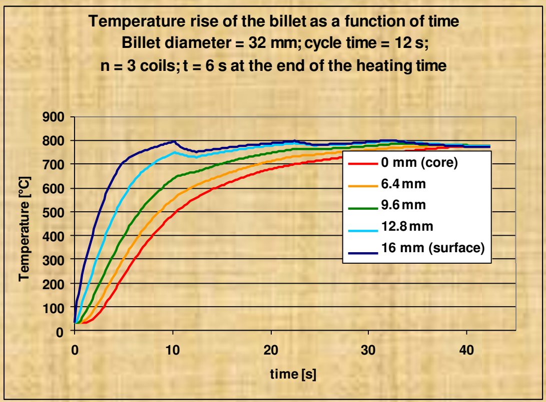
Examples

Heating of a magnetic billet from T_{amb} up to 1200° C



Examples

How shall we get an uniform heating of the billet?



Examples

Rule-of-thumb in the choice of frequency

Lower frequency (1÷2 kHz)

- Through heating
- Good performance on big parts

Medium frequency (2÷50 kHz)

- More often used: surface heating of average parts, annealing, stress relieving…

Higher frequency (50÷500 kHz)

- Surface heating (< 1 mm case depth), welding
- Good performance on small parts.

Examples

Choice of appropriate frequency:

First example. Small magnetic steel tube (diam. 5 mm, wall 0.5 mm). Through heating.

Multi-turn coil. Internal diam. 20 mm. Total heating time = 10 s.

Frequency [kHz]	Magnetic field intensity [A/m]	Average final temperature [° C]	Total power (coil + tube) [kW]	Electrical efficiency
1	1’000’000	520	800	0.009
100	10’000	740	4	0.67
100	30’000	1220	13	0.37
400	**12’500**	**1230**	**9**	**0.65**

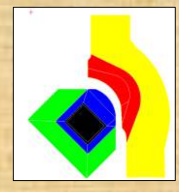
Examples

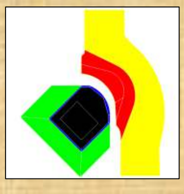
Coil thickness as a function of frequency

Multi-turn coil. Internal diam. 1100 mm. Total heating time = 200 s.

I_{COIL}=12000 A
f = 4800 Hz
t = 0s

→ δ_{Cu} = 1 mm → Minimum acceptable coil thickness ≈ 2 δ_{Cu} = 2 mm





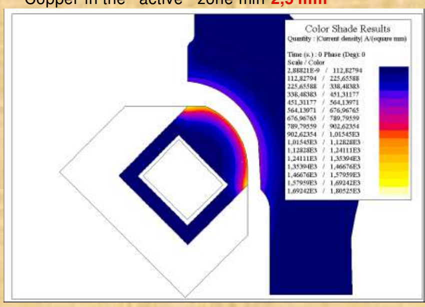
Current density is greater on "open surface" of inductor

Examples

Coil thickness as a function of frequency

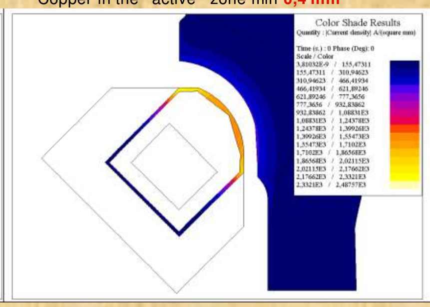
THICK COIL I_{COIL}= 12000 A f = 4800 Hz t = 0s **THIN COIL**

Copper in the "active" zone min **2,5 mm**



P_{TOT}=288 KW P_{COIL}=54 KW h =

Copper in the "active" zone min **0,4 mm**



P_{TOT}=341 KW P_{COIL}=107 KW h =

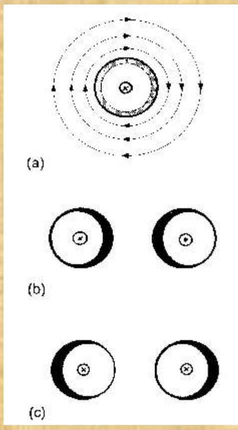
5.Proximity effect, ring effect, flux concentrators effect

Proximity effect, ring effect, flux concentrators effect

Proximity effect

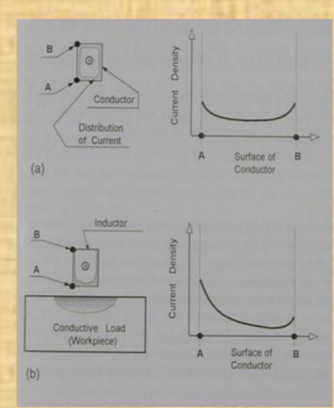
If there are two (or more) conductors in close proximity:

- Eddy currents and inductor current have opposite directions.
- Coil and workpiece current will concentrate in poor coil-to-workpiece areas.
- b) Currents have opposite directions à currents concentrate in the areas facing each other.
- c) Currents have the same direction à currents concentrate on opposite sides of the conductors.



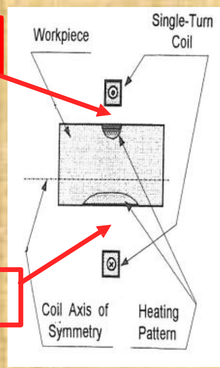
Proximity effect, ring effect, flux concentrators effect

Proximity effect



Small air gap à better coupling

Big air gap à worse coupling

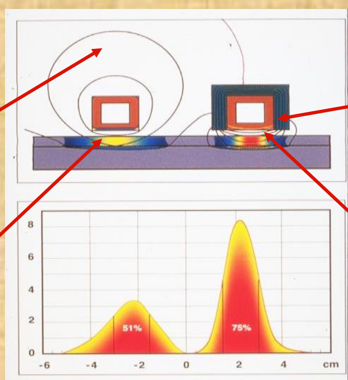


Proximity effect, ring effect, flux concentrators effect

Flux concentrator

"squeezes" the current to the "open surface" of the coil

optimizes the inductor-workpiece coupling

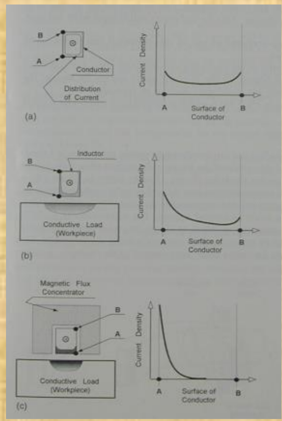


shields some parts to decrease or to avoid heating

directs the magnetic flux to parts hard to heat

Proximity effect, ring effect, flux concentrators effect

Flux concentrator

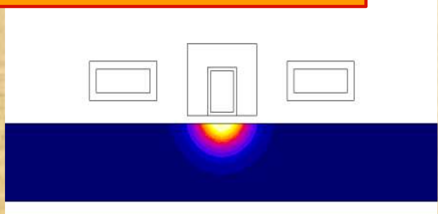


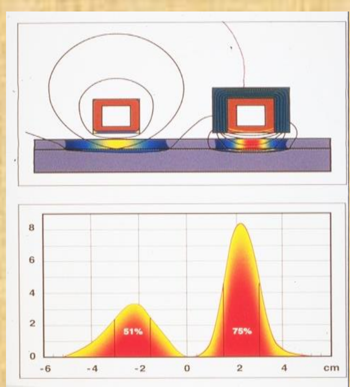
Proximity effect, ring effect, flux concentrators effect

Flux concentrator

Most common materials: Fe-Si electrical sheets, Commercial “magnetic-dielectric” materials.

Fe-Si thin sheet , magnetodielectric or Soft Magnetic Composites, ferrite-based





Proximity effect, ring effect, flux concentrators effect

Ring effect

- In a ring shaped inductor, magnetic flux lines are concentrated inside the ring.
- The workpiece is inside the induction coil, à close coil-workpiece coupling à good coil efficiency.
- The workpiece is outside the induction coil à poor coil-workpiece coupling à bad coil efficiency.

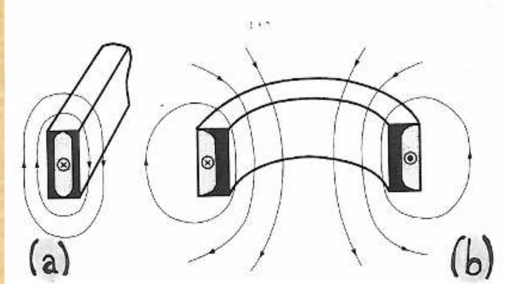


Figure 25 Ring effect in rectangular conductors.

Induction Heating: Fundamentals