Main Applications of Induction Heating

- Hard (Silver) Brazing
- Tin Soldering
- Heat Treatment
  (Hardening, Annealing, Tempering, ...)
- Melting Applications (ferrous and non ferrous metal)
- Forging
Examples of induction heating applications
Advantages of Induction

• Reduced Heating Time
• Localized Heating
• Efficient Energy Consumption
• Heating Process Controllable and Repeatable
• Improved Product Quality
• Safety for User
• Improving of the working condition
Basics of Induction

- INDUCTIVE HEATING is based on the supply of energy by means of electromagnetic induction.

- A *coil*, suitably dimensioned, placed close to the metal parts to be heated, conducting high or medium frequency alternated current, induces on the work piece currents (eddy currents) whose intensity can be controlled and modulated.
Basics of induction

• The heating occurs **without physical contact**, it **involves only the metal parts to be treated** and it is characterized by a high efficiency transfer without loss of heat.

• The depth of penetration of the generated currents is directly correlated to the working frequency of the generator used; higher it is, much more the induced currents concentrate on the surface. In this case, the heating homogeneity on a relevant mass, can be obtained due to the principle of thermal conduction which allows the heating to be transferred in depth.
Basics of Induction

The phenomenon of the electromagnetic induction is therefore based on three physical principles, here below explained:

1) Transfer of energy from the inductor to the piece to be heated, by means of Electromagnetic Fields.

2) Transformation of the electric energy into heat due to Joule effect. \( P = I^2R \)

3) Transmission of the heat inside the mass by means of Thermal Conduction.
Useful Equations

1) Transfer of energy from the inductor to the mass to be heated, by means of **Electromagnetic Fields.**

The electro-magnetic field is generated by a current flowing on a conductor.

**Ampere’s Law:**

\[ \oint B \cdot dl = \mu_0 \cdot I \]

\( \mu_0 = \text{permeability of free space} \)
\( = 4\pi \cdot 10^{-7}[Tm/A] \)
If the conductor has a solenoid shape, the magnetic field generated has the shape as in the pictures below:

![Magnetic Fields Diagram](image)

In this case the magnetic field can be calculated by this simplified equation:

\[ B = \mu_0 \frac{N}{\ell} I \quad \text{where } N = \text{number of loop} \quad \ell = \text{coil length} \]

This simplified equation is correct for calculate B in the middle of the solenoid.
The **Laplace Law** states that the intensity of the magnetic field is reverse proportional to the square of the distance.

In case of a single loop coil, the intensity of the magnetic flow at the point P, whose distance from the coil center is $z$, is given by the simplified equation:

$$B_z = \frac{\mu_0}{4\pi} \left( \frac{2\pi R^2 I}{(z^2 + R^2)^{3/2}} \right)$$
Faraday–Lenz’s Law

\[ \varepsilon [V] = -\frac{d\Phi_B}{dt} \]
\( \Phi_B \) = magnetic flux through the circuit

The induced electromotrice force generated is proportional to the rate of change of the magnet flux.

Eddy currents are currents induced in conductors, opposing the change in flux that generated them. It is caused when a conductor is exposed to a changing magnetic field.

These circulating eddy current create induced magnetic fields that oppose the change of the original magnetic field due to Lenz’ laws, causing repulsive or drag forces between the conductor and the magnet.

The stronger the applied magnetic field, or the greater the electrical conductivity of the conductor, or the faster the field that the conductor is exposed to changes, then the greater the currents that are developed.
The **magnetic permeability** of a material is the capability of this material to channel magnetic induction. In fact, magnetic field $H$ and magnetic induction field $B$ are linked, in a given material, by the equation:

$$B = \mu \cdot H$$

where $\mu$ is the magnetic permeability of the material (in Henry/meter). $\mu = \mu_0 \cdot \mu_r$
- $\mu_0$ is a universal constant, equal to $4 \pi \cdot 10^{-7}$ H/m
- $\mu_r$ depends on the material.

The materials can be classified in:
- **Diamagnetic** (copper, gold, silver, aluminum oxide) $\mu_r \leq 1$
- **Paramagnetic** (aluminum, titanium, molybdenum, stainless steel) $\mu_r \geq 1$
- **Ferromagnetic** (carbon steel) $\mu_r >> 1$

The magnetic permeability of ferromagnetic materials above the **Curie temperature**, suddenly drop down to $\mu_r = 1$

<table>
<thead>
<tr>
<th>Material</th>
<th>Curie Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>1115</td>
</tr>
<tr>
<td>Iron</td>
<td>770</td>
</tr>
<tr>
<td>Nickel</td>
<td>358</td>
</tr>
</tbody>
</table>
2) Transformation of the electric energy into heat due to **Joule Effect.**

The voltage induced in the sample (V) can be controlled by the **intensity** and **frequency** of the current on the coil.

\[ V = R \cdot I \quad I = \frac{V}{R} \quad (Ohm\ Law) \]

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

\[
P[\text{Watt}] = V \cdot I = \frac{V^2}{R} = I^2 \cdot R
\]

\textbf{Material} | \( \rho \) [Ω·m] at 20 °C | \( \sigma \) [S/m] at 20 °C
--- | --- | ---
\textbf{Silver} | 1.59×10⁻⁸ | 6.30×10⁷ |
\textbf{Copper} | 1.68×10⁻⁸ | 5.96×10⁷ |
\textbf{Gold} | 2.44×10⁻⁸ | 4.52×10⁷ |
\textbf{Aluminium} | 2.82×10⁻⁸ | 3.5×10⁷ |
\textbf{Tungsten} | 5.60×10⁻⁸ | 1.79×10⁷ |
\textbf{Iron} | 1.0×10⁻⁷ | 1.00×10⁷ |
\textbf{Platinum} | 1.06×10⁻⁷ | 9.43×10⁶ |
\textbf{Tin} | 1.09×10⁻⁷ | 9.17×10⁶ |
\textbf{Titanium} | 4.20×10⁻⁷ | 2.38×10⁶ |
Skin Effect

Skin effect is the tendency of an alternating electric current (AC) to distribute itself within a conductor with the current density being largest near the surface of the conductor, decreasing at greater depths.

The skin effect is due to opposing eddy currents induced by the changing magnetic field resulting from the alternating current.

The AC current density $I$ in a conductor decrease exponentially from its value at the surface $I_s$ according to the depth $d$ from the surface, as follows:

$$I = I_s e^{-d/\delta}$$

Where $\delta$ is called skin depth (it’s the depth below the surface of the conductor at which the current density decays to $1/e$ of the density at the surface $I_s$)

$$\delta = \sqrt{\frac{2\rho}{\omega \mu}}$$

An alternative definition of skin depth is: the thickness layer from the outside, in which the 87% of the power is developed.

$\rho = $ resistivity of the conductor

$\mu = $ absolute magnetic permeability
We can derive a practical formula for skin depth calculation as follow:

\[ \delta = \frac{1}{\sqrt{\pi f \sigma \mu}} \]

Where

- \( f \)= heating frequency [Hz]
- \( \sigma \)= conductivity of the material [S/m]
- \( \mu \)= absolute magnetic permeability of the material [H/m]
Skin Depth Calculation

Calculation of skin depth at different frequency for magnetic and non-magnetic material

\[ \delta = \frac{1}{\sqrt{\pi f \sigma \mu}} \]

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Steel AISI 316 ((\mu_r = 1))</th>
<th>Copper Cu ((\mu_r \sim 1))</th>
<th>Steel AISI 420 ((\mu_r = 2000))</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>43,32</td>
<td>6,68</td>
<td>0,83</td>
</tr>
<tr>
<td>1,000</td>
<td>13,70</td>
<td>2,11</td>
<td>0,26</td>
</tr>
<tr>
<td>10,000</td>
<td>4,33</td>
<td>0,67</td>
<td>0,08</td>
</tr>
<tr>
<td>100,000</td>
<td>1,37</td>
<td>0,21</td>
<td>0,026</td>
</tr>
<tr>
<td>200,000</td>
<td>0,97</td>
<td>0,15</td>
<td>0,019</td>
</tr>
<tr>
<td>1,000,000</td>
<td>0,43</td>
<td>0,067</td>
<td>0,008</td>
</tr>
</tbody>
</table>
Skin depth versus frequency

- Low conductivity diamagnetic metal (AISI316)
- Good conductivity diamagnetic metal (Cu)
- Ferromagnetic metal (AISI420 - ur 2000)
3) Transmission of the heat inside the mass by means of **Thermal Conduction**.

The law of Heat Conduction, also known as Fourier’s law, states that the time rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area through which the heat is flowing.

\[ \dot{q} = -k \Delta T \]

- \( \dot{q} \) = Local Heat Flux [W m\(^{-2}\)]
- \( k \) = Thermal conductivity [W/mK]
- \( \Delta T \) = Temperature gradient [K m\(^{-1}\)]

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity [W/m·K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>16</td>
</tr>
<tr>
<td>Carbon Steel</td>
<td>36</td>
</tr>
<tr>
<td>Brass</td>
<td>109</td>
</tr>
<tr>
<td>Aluminum</td>
<td>205</td>
</tr>
<tr>
<td>Copper</td>
<td>385</td>
</tr>
<tr>
<td>Silver</td>
<td>406</td>
</tr>
</tbody>
</table>

The **Thermal conductivity** of a material indicates its ability to conduct heat.
Structure and History of Inductive Heating Generators

An induction heater typically consist of three elements:

- **Power Unit (inverter/generator)**
  This part of the system is used to take the mains frequency and increase it to anywhere between 20÷900 kHz. The typical output power of a unit is from 2 to 500 kW.

- **Work Head**
  This contains a combination of capacitors and transformers and it is used to match the power unit to the work coil

- **Work Coil (inductor)**
  Is used to transfer energy to the piece. Coil design is one of the most important elements of the system as is a science in itself
CLASSIC Structure
Valve Oscillator Generator (1970-1990)

The multi-electrode thermo-ionic vacuum triode (valve) is the heart of the 
**self-oscillator circuit** that is responsible for creating the elevated frequency electrical 
current, that flow on the coil.

Problems:
- Output power instability
  The output power is affected by power supply voltage fluctuation, and the generator 
is not able to follow the set power in case of load variation (i.e. heating over Curie Point)
- Difficult power regulation
- Low efficiency (nearly 60 %)
- Valve lifetime
- Very High anodic voltage
  (Danger for operator safety)
- Large Overall Dimensions
Conventional Structure  (1990 – Today)
Solid State Transistor Generators

Nowadays the use of MOSFET or IGBT transistors has replaced the use vacuum valves, and is become the heart of all conventional inductive heating generators in the market.

Main Features:
- Overall dimensions smaller than valve generators
- Higher efficiency
- Higher working frequency range

Problems:
- High current flow from generator to Heating Head
- Output power instability in case of mains voltage fluctuation, or load variation

The use of the conventional generator is possible in heating process with large admitted tolerances.
CEIA Induction Heating Generators

Main Features and Difference vs. conventional generators
- Real-Time Micro processor control of the power generation
- Extremely compact design
- Coil voltage feedback sensors
- Resonant Heating Head (low current flow from generator to heating head)
- Maintains stable output power even as working conditions change (calibration report)
- Specific Control unit for output power control
- EMC and CE certified

Accurate Control Loop through feedback of:
- Coil Voltage
- Coil Current
- RF Output Phase
- Input Current
- Optical pyrometer for temperature control
- (80÷2000 °C) (175÷3630 °F)

Total of 5 feedback parameters to ensure a precise and consistent heating process.
The CEIA inductive heating system allows for very fast and accurate temperature control. They are suitable for industrial and automatic processes, and they are also installed on robotic systems where:

- Extremely high repeatability
- No tolerance admitted

Thermal Profile Monitoring
Heating Head Structure

The Quality factor $Q$ is defined in terms of the ratio of the energy stored in the resonator to the energy supplied by a generator.

The coil shape and the gap between coil and sample is extremely important in order to maximize the power transfer.

The goal is to maximize the current flow on $R_{\text{load}}$ building the most suitable coil.

$$f = \frac{1}{2\pi \sqrt{LC}} = \text{Resonance frequency}$$

$$Q = R \sqrt{\frac{C}{L}} = \text{Quality factor}$$
Heating Head and Sample to be heated: Equivalent Circuit

\[ C_1 = \text{Heating Head Capacity} \ (\mu F) \]

\[ L_1 = \text{Coil Inductivity} \ (\mu H) \]

\[ R_1 = \text{Coil resistance} \ (\Omega) \]

\[ R_2 = \text{Sample resistance} \ (\Omega) \]

The voltage induced on the sample by the current flowing on the coil, depends on the coil shape, on gap between coil and sample, and on material to be heated.

In the circuit above it’s resumed by the Coefficient of Mutual Induction (M)

\[ v_2[Volt] = -N_2 \frac{d\phi_{12}}{dt} = -M \frac{di_1}{dt} \quad \text{where} \ M = N_2 \frac{\phi_{12}}{i_1} \]
Types of Heating Coils

- **Open Shape coil**

- **Closed Shape, multiple loop coil**

- **Complex Shape coil**
Example of induction heating applications
Thank you for your attention