ELECTROMETALLURGY AND FERROALLOYS
PRODUCTION

Didactic Text

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Subject synopsis „Electrometallurgy and Ferroalloys Production“

1. The present state and perspectives of steel production in electric furnaces. Division of electric furnaces. The basics of heavy-current electrotechnics of alternate current.

2. Theory of electric arc. Electric arc in direct current. The stabilization of arc burning.

3. Electric and thermal mode of EAF. Working electric characteristics of EAF. Dynamic, physical and chemical effects of arcs. UHP and SUHP furnaces.

4. Other sources of heat in EAF. Melting intensification. Using gaseous oxygen, oxyfuel burners. Frothing nozzles. Injection of inert gas through the floor of EAF. Productivity of EAF.

5. Basic parts of EAF construction. EAF transformer, inductor, power factor compensation, short net EAF, EAF electrodes. The production of graphite electrodes.


7. Technology of steel production in EAF. Two-slag technology. One-slag technology. The importance of oxidation and reduction periods of the melting. The technology of remelting.

8. The production of alloyed and highly alloyed steels. The thermodynamics of metallurgical processes during the oxidation refining of the pool. Dephosphorization during the production of alloyed steels. Reduction of oxides of alloying elements from the slag to the pool. Alloying by titanium. The production of steels in acidic arc furnaces. Combined processes of EAF-DH, EAF-AOD, EAF-VOD, EAF-VD.

9. The behavior of hydrogen and nitrogen during the process of melting in EAF. Measuring the temperature of the pool. Determining the activity of the oxygen, content of hydrogen and nitrogen in the pool. Automatization of the production control in the EAF.

10. DC arc furnaces. Peculiarities and differences in the construction of furnaces. Soil anodes. The course of melting in a DC arc furnace. Advantages of DC furnaces compared to AC furnaces.


14. The basics of thermodynamics of ferroalloys production. Carbothermical, silicotherrmal and aluminothermical methods of ferroalloys production. The production of main types of ferroalloys: FeMn, FeCr, FeSi, FeTi, FeW.
PREFACE

Study support to the subject **Electrometallurgy and Ferroalloys Production** is primarily intended for students of combined studies. In the combined form of study, there is a much smaller proportion of direct contact teaching, which makes this study much more difficult for students. Our study support to the subject **Electrometallurgy and Ferroalloys Production** can help you to eliminate this handicap to a certain extent. These is not a new textbook, there are enough of those. The study support is a replacement, if possible, for the lack of direct instruction and interlink to a subsequent study of professional literature itself, whether it be textbooks or other publications.

When writing this support I have tried to maximize the clarity of the text. This cannot be achieved, at least in my opinion, without some simplification, reduction and sometimes even inaccuracy. If someone feels that simplification is too much, I apologize in advance. But my experiences in teaching this subject led me to a result which is just this text.

Despite careful checking of the text, it is almost certain that I did not avoid errors, typing errors, etc., maybe even factual mistakes. I will be most grateful, if you notify me about them so I can gradually correct them. You can notify me either directly during classwork or by email to karel.michalek@vsb.cz

I wish all of you who will use this study support, a lot of strength in your study!
THEMATIC BLOCK 1

The present state and perspectives of steel production in electric furnaces

- Approximately 40% of the total amount of steel is produced in electrical furnaces (USA, Canada more than 45 %)
- Czech Republic – long term 7 – 10 % from the total production of app. 7 million tons
- Positive effect on ecology (reduction of the number of coking plants and agglomerations)
- The possibility of processing a high proportion of steel scrap
- The development of DC EAF, the introduction of new processes – the use of fuel gasses, flexible (hybrid) processes, intensified processes.
- Parameter of current EAF: melting approximately 100 tons, power consumption of 300 to 450 kWh.t\(^{-1}\), electrode consumption of 1.9 to 2.9 kg.t\(^{-1}\), melting time of approximately 70 minutes

Division of electric furnaces

- Electric arc furnaces (EAF) – the batch is melted by the emerging electric arc
- Induction furnaces (IF) – the batch is heated and melted by eddy currents, the emergence of which is related to the electromagnetic induction.
- Electric resistance furnaces – the heat is created by the flow of electric current through the resistive elements
The scheme of electric resistance furnace

- The heat is created by the flow of electric current through the resistive elements (silites – sintered silicon carbides SiC, molybdenum disilicid MoSi₂, Tungsten heating elements, graphite heating segments, etc.

- These furnaces are used most often to heat the metal before its heat processing or they are used as drying or baking furnaces, but also for melting color metals and alloys as well as for research purposes in laboratory conditions (Tammann’s furnace), etc.
The division of electric arc furnaces (EAF)
a) Powered by alternate current (AC)
   - With a directly functioning arc
     - Arc furnaces with non-conducting bottom
     - Arc furnaces with conducting bottom
   - With indirectly functioning arc

b) Powered by direct current (DC)
   - with a bottom electrode or electrodes
   - arc furnaces with non-conducting bottom

The original Héroult’s arc furnace

Studying of Appendix on final pages of didactic text is also a part of this thematic block.
Questions

1. The present share of steel production in EAF, the state in EU, in the whole world, in CR, current technical parameters of EAF.
2. The division of electric furnaces.
4. Fundamentals of high power alternating current – circuit with an ohmic resistance, with inductance, with capacity (see Appendix).
5. Fundamentals of high power electrotechnics of alternating current – series and parallel resonance, resonant frequency (see Appendix).
6. Fundamentals of high power electrotechnics of alternating current – the power of alternating current (see Appendix).
THEMATIC BLOCK 2

The principle of formation and composition of electric arc

- Thermic emission of electrons from the cathode (increases with temperature)
- Collisions of electrons with the molecules and atoms of gasses →
  - Dissociation of the gas molecules into atoms,
  - Ionization of atoms into ions and electrons (or also the backward recombination)
- The space between electrodes is ionized and is a „conductive path“
- Electric arc is formed subsequently – a special state of matter – plasma – created between electrodes. The plasma can be simply regarded as a mixture of neutral particles, electrons and ions of gas with a very high temperature – reaching 5000 to 15000 K. Fully ionized plasma is very stable at temperatures up to $10^5$ K, when the collisions between particles are so intensive that the neutral particles cannot hold in the plasma anymore.

![Diagram of electric arc]

The composition of the arc:

- Cathode area of conductive discharge – length of $10^{-4}$ mm, adjacent to the cathode, ionization processes take place in it, it contains a cathode stain with high current densities (up to 3000 A.mm$^{-2}$).
- Ionized arc column – conversion of electrical energy into thermal
- Anode area of conductive discharge – length of $10^{-4}$ mm, adjacent to the anode, anodic stain in the area of impact of electrons and ions on the anode (up to 300 A.mm$^{-2}$)
Conditions of electric arc burning

For the flow of the current through the arc (so-called arc burning), it is necessary that the voltage between the ends of the electrodes $U_o$ was higher or equal to the so-called ignition voltage $U_i$

$$U_o \geq U_i$$

$$U_i = \alpha + \frac{\rho_{s,0}}{k} \cdot l_o = \alpha + \beta \cdot l_o$$

$\alpha$ - the voltage drop upon the flow of the current through the cathode and anode area of conductive discharge (between the cathode and the columns of the arc and the column of the arc and the anode)

The values of $\alpha$ for different environments:

- graphite – molten steel: 22 V
- graphite – alkaline slag: 9 V (Ca is easily ionisable)
- graphite – acid slag: 30 V

$\rho_{s,0}$ - resistivity of the arc column; $\Omega \cdot m$

$k$ - constant of proportionality; $m^2 A^{-1}$

$\beta$ - gradient of the electrical potential in the arc column; $V \cdot m^{-1}$ of the arc

The degree of ionization of the mixture of vapors and gasses forming the arc column has a strong influence over the value of $\beta$. The higher this degree of ionization, the lower the value of $\beta$. The degree of ionization increases with the temperature.

The values of $\beta$ during the individual phases of melting:

- melting: 10000 – 12000 V/m of the arc (10 - 12 V/mm)
- oxidation phase: 3500 – 4000 V/m of the arc (3.5 – 4 V/mm)
- reduction phase: 1000 – 1200 V/m of the arc (1.0 – 1.2 V/mm)

$l_o$ - length of the arc

The influence of the shape of the electrode end on the length of the arc – only in short arcs it is the distance electrode-pool
Necessary arc voltage $U_0$ for its burning will be the lower,

- The lower the ionization potential of the vapors and gasses of the arc - $\alpha$,
- The shorter the length of the arc - $l_0$
- The lower the value of electric potential gradient in the column of the arc - $\beta$ (meaning the lower the resistance of the column arc $\rho_{s,0}$).

**Volt-ampere characteristics of the electric arc of two different lengths**

- When evaluating the behavior of only the arc itself, we come to the conclusion that the current of the arc does not practically depend on the voltage on the arc. When the current rises, there is even some decrease in necessary voltage on the arc, due to the rise in temperature of the working space of the furnace and therefore the rise of average degree of ionization and therefore the decrease of $\rho_{s,0}$ and therefore also $\beta$.

![Diagram showing volt-ampere characteristics of the direct current electric arc of two different lengths](image)

Volt-ampere characteristics of the direct current electric arc of two different lengths $l$

- At very high current intensities, the voltage on the arc may decrease under the value of $U_i$, and the arc then becomes unstable leading to its extinction – that is why the stabilization is necessary.
Stabilization of a direct current arc

Stabilization is done by including a resistor (resistance) in the electrical circuit of the arc – the included resistor limits the maximum current of the arc. When the current on the arc increases, the decay of voltage on this resistor also decreases and therefore the voltage on the arc decreases. The arc in the circuit may only exist in the case that the sum of voltages on the arc and on the resistor is equal to the voltage of the source, in other words the voltage on the arc must be equal to the difference between the voltage of the source and the voltage on the resistor.

Therefore, the following applies:

\[ U_{\text{source}} = U_O + U_R = U_O + R \cdot I \]

In other words:

\[ U_O = U_{\text{source}} - U_R = U_{\text{source}} - R \cdot I \]

The equation can be solved visually by drawing the arc characteristics and the so-called difference line \( U_{\text{source}} - U_R \). The intersections of difference lines with the arc characteristic determine the current-voltage ratios at which the arc can exist. If the intersection does not exist, the arc cannot burn in a stable way.

At points A and B, the conditions for arc burning are met. Stable arc burning is possible only at point B. The burning at point A is unstable and the arc moves towards the point B, towards higher current intensities at lower voltage.
The arc burning at point C occurs on the boundary of stability – for example when the value of \( R \) is high and there is a big decay of voltage on the arc, meaning that the voltage on the arc is not very different from the initial voltage. With further increase of \( R \) – the voltage on the electrodes after igniting the arc decreases under the initial voltage – the arc goes out or it is not even created, meaning that

\[ U_0 > U_{\text{source}} - U_R \]

On the other hand, at low values of \( R \) (the difference line crosses the x axis at higher values of current) the arc burning is moved towards the extreme currents, which can lead to the destruction of electrodes if the source is “hard” enough.

If the current changes depending on the time, the arc voltage does not follow the static characteristic, but it moves along the dynamic characteristic.

In order for the direct current arc to burn in a stable way, there must be an intersection of the difference line with the arc characteristic. This can be achieved by the following methods:
• Moving the arc characteristic towards the lower voltages – shortening it
• Lowering the value of resistance – R
• Increasing the voltage of the source
Current-voltage ratios in alternate current electric arc

- When using the alternate electric current, there are some necessary breaks during the arc burning in the periods when the voltage on the transformer $U_{tr}$ decreases under the value of extinction voltage $U_{zh}$.

- The consequence of intermittent arc burning – reducing the average active power released by the arc.

- The alternating of the function of cathode and anode – impairment of thermal emission of electrons from the cold batch at the beginning of the melting, there is an asymmetry in the current load, which leads to instability in arc burning and its extinction.
Current-voltage ratios in alternate electric arc stabilized by a suppression coil

- In order to stabilize, we use for example the inclusion of a suppression coil in series in the circuit with the primary winding of the transformer – a phase shift is created between the current and the voltage.
- An alternating electromagnetic field is created around the suppression coil.
- When the voltage $U_{2,p}$ decreases under $U_q$, the arc will not extinguish (the field reversely induces the current of the original direction and the suppression coil acts as an “accumulator” of energy, which tries to hold the current of the arc at the original size).
- The conditions of arc burning improve in this way – the time periods $\tau$, in which the arc is not burning.
- When including a value of $X_L$, which leads to reaching the effect of $\cos \varphi$ approximately 0.85, the time periods $\tau$, when the arcs are not burning are almost non-existent and the electric power introduced in the EAF is maximal.
- In large furnace the suppression coils are not necessary because of the substantial own inductive resistance of the transformer winding.
1. The division of electric arc furnaces.
2. The fundamentals of creation of the electric arc, the composition of ionized column of the arc.
3. The conditions of the arc burning, the definition of ignition voltage, the analysis of individual factors affecting the ignition voltage.
4. Volt-ampere characteristic of the direct current arc.
5. The point of stable arc burning, its definition and the possibilities of stabilization of direct current arc.
6. Current-voltage ratios on an alternate current electric arc without a suppression coil.
7. Current-voltage ratios on an alternate current electric arc with a suppression coil – stabilization of the alternate current arc burning.
THEMATIC BLOCK 3

Electric and thermal mode of EAF

The character of the melting speed of the batch and the speed of temperature change of the pool after the melting in the EAF as well, is controlled by the value of useful power, which is the power used to heat the batch and for the melting.

\[ P_{\text{useful}} = P_{\text{input}} - P_{\text{output}} \]

where: 
\( P_{\text{input}} \) – power fed into the working area of the furnace
\( P_{\text{output}} \) – power off from the working area of the furnace

\[ P_{\text{input}} = P_{\text{el}} + P_{\text{ex}} \]

where: 
\( P_{\text{el}} \) – active input by the electric energy (especially arcs)
\( P_{\text{ex}} \) – the power of exothermic reactions

\[ P_{\text{output}} = P_{\text{los}} + P_{\text{lining}} \]

where: 
\( P_{\text{los}} \) – direct thermal losses (combustion gasses, radiation, cooling water)
\( P_{\text{lining}} \) – power transmitted from the working area of the furnace to the lining (accumulation)

\[ P_{\text{el}} = P_{\text{total,el}} - P_{\text{los,el}} \]

where: 
\( P_{\text{total,el}} \) – total active power supplied from the network
\( P_{\text{los,el}} \) – power of electrical losses

The mentioned relations show that the increase of the values of \( P_{\text{useful}} \) can be achieved by increasing \( P_{\text{el}} \) a \( P_{\text{ex}} \) and by decreasing \( P_{\text{los}} \) a \( P_{\text{lining}} \).
Schematic representation of the flow of individual powers in the electrical arc furnace

For the rational energy management regime, it is neccessary to reach the optimum value of power brought to the working area of the furnace.
Simplified equivalent scheme of the arc furnace

The solution is based on so-called simplified transformer equivalent scheme of the arc furnace, in which the three-phase wiring is replaced by an equivalent scheme of circuit with one phase.

\[ U_{2,p} \ldots \text{secondary phase voltage} \]
\[ R, X_L \ldots \text{the sum of the respective resistors in the secondary part of the circuit and the transformed resistors from the primary part} \]
Electric and thermal mode of EAF

The value of $P_{el}$ is given by the difference between the total input electric power and the power of electric losses

$$P_{el} = P_{total,el} - P_{los,el}$$

$$P_{total,el} = P_{apparent} \cdot \cos \varphi = 3 \cdot U_{2,p} \cdot I_2 \cdot \cos \varphi$$

$$P_{los,el} = 3 \cdot R \cdot I_2^2$$

$$P_{el} = 3 \cdot U_{2,p} \cdot I_2 \cdot \cos \varphi - 3 \cdot R \cdot I_2^2$$

The $I_2$ current can be determined using the relation including the impedance of the circuit $Z$

$$I_2 = \frac{U_{2,p}}{Z} = \frac{U_{2,p}}{\sqrt{(R + R_0)^2 + X_L^2}}$$

The power factor $\cos \varphi$ can be determined using the ratio of the resistance and impedance of the circuit

$$\cos \varphi = \frac{R + R_0}{Z} = \frac{R + R_0}{\sqrt{(R + R_0)^2 + X_L^2}}$$

The decisive part of the value of $P_{el}$ is formed by the power input, which is released by the arcs themselves:

$$P_o \equiv P_{el}$$

The resulting relation for the power released on the arcs is:

$$P_o \approx P_{el} = \left(3 \cdot I_2 \cdot \sqrt{U_{2,p}^2 - (\omega \cdot L)^2 \cdot I_2^2} - 3 \cdot R \cdot I_2^2\right)$$
**Electric and thermal mode of EAF**

The change of power brought to the working area of the furnace by the electric energy (in other words the power released on the arcs) can be performed by:

1. **Changing the secondary voltage of the transformer** $U_{2,p}$
   
   This is performed by changing the wiring of the individual phases on the primary part of the transformer to a „star connection“ or to a „delta connection“ and by switching the taps on the primary wiring of the transformer.

2. **Changing the current of the $I_2$ arc at the given $U_{2,p}$**.
   
   The value of current going through the arc depends on the arc resistance $R_0$.

   $$I_2 = \frac{U_{2,p}}{Z} = \frac{U_{2,p}}{\sqrt{(R + R_0)^2 + X_l^2}}$$

   The arc resistance can be determined from the following relation:

   $$R_0 = \frac{U_0}{I_2} = \frac{\alpha}{I_2} + \frac{\rho_{S,0} \cdot l_0}{k \cdot l_2}$$

   - $\alpha$ - ionization potential of the vapors and gasses in the arc
   - $\rho_{S,0}$ - resistivity of the arc
   - $k$ - constant of proportionality
   - $l_0$ - length of the arc
   - $l_2$ - current of the arc

   The expression shows that the arc resistance can be controlled by its length.

   *Increasing the length of the arc increases the voltage on the arc and by that the resistance increases, current decreases and finally the thermal power of the arc also decreases.*
Electric characteristics of an arc furnace (associated work characteristics of EAF)

- These characteristics are most frequently compiled from the results of measurements on a real arc furnace. The measured values are used for further calculation of individual powers. From the characteristics, it is possible to determine the operating mode of the arc furnace.
- When measuring, we change the current of the arc by changing the length of the arc (or the voltage on the arc) at the given voltage degree.
- The order of writing $I_2, U_0, \cos \phi, P_{\text{apparent}}, P_{\text{total,el}}, P_{\text{loss,el}}, P_o, P_{\text{heat los}}, P_{\text{useful}}$.

During a short-circuit the $R_0$ is zero, but the ohmic resistance $R$ remains. That is why $P_{\text{total,el}}$ does not decrease under zero, but to a certain real value (the electrode is heated by ohmic heat). $P_o$ is zero, however, because the arc does not burn.
The dependence of the furnace productivity ($G$) and the specific consumption of electrical energy ($W$) on the arc current

The optimum range of currents is limited by the maximum productivity $G$ (the maximum power of the arc $P_0$) and the minimum specific consumption of electrical energy $W$.

The minimum specific consumption of electrical energy $W$ occurs at the maximum electrical efficiency $\eta_e$ which is determined by the following relation:

$$\eta_e = \frac{P_0}{P_{total,el}}$$

Operating the EAF on the ascending part of the performance curve of the arc – longer arcs, lower currents, higher power factor, greater stress of the lining.

Operating the EAF on the descending part of the performance curve of the arc – shorter arc, higher currents, lower power factor, lesser stress of the lining, higher requirements on the transformer.
Dynamic effects of arcs in EAF

The electric arc can be considered as conductor, whose shape is greatly influenced by the complex surrounding electromagnetic field, created not only by the action of the given arc, but also by the neighbouring arcs. The shape of the arc is also influenced by the surrounding metal construction of the furnace.

Consequence:

- Bulging of the arcs towards the walls of the furnace – increasing the thermal stress on the furnace walls
- Existence of axial forces in the arc – recess of the arc, creating a „wall“
- Mixing of the pool under the arcs

Physical and chemical effects of arc in EAF
Physical and chemical effects:

- Transition of hydrogen and nitrogen to the molten pool – with the condition of dissociation of gas molecules to atoms (arc)
- Formation of calcium carbide – carbide slag
  \[(\text{CaO}) + 3 \text{C} \rightarrow (\text{CaC}_2) + \text{CO}_2\] strongly endothermic reaction
- Carburizing of the pool – from the electrodes (electrode breaking, improper regulation of the electrodes etc.)
- Evaporation of the pool ingredients – Ni, Mn (due to the high vapor pressure of metals)
Ultra High Productivity furnaces
The division of EAF according to electrical power inputs:

- regular productivity RP
- high productivity HP
- ultra high productivity UHP
- super ultra high productivity SUHP

Criteria of UHP:

1. The maximum value of specific active electrical power input \( P_{\text{total,el}} \) during the period of melting \( (P_{\text{total,el}} = P_{\text{apparent}} \cdot \cos \phi) \) must reach 300-600 kW/t of the liquid metal (in other words \( P_{\text{apparent}} \) of the transformer of app. 500-1000 kVA/t).

<table>
<thead>
<tr>
<th>Up to 35 t</th>
<th>40 – 90 t</th>
<th>&gt; 100 t</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP furnaces</td>
<td>200 – 350</td>
<td>150 – 300</td>
</tr>
<tr>
<td>UHP furnaces</td>
<td>450 – 550</td>
<td>400 – 500</td>
</tr>
<tr>
<td>SUHP furnaces</td>
<td>600 – 700</td>
<td>550 – 600</td>
</tr>
</tbody>
</table>

2. The ratio of average power input of the operating furnace to the maximum electrical power input during the melting must be ≥ 0.7

3. The ration of arc burning period to the total length of the melting has to be ≥ 0.7

4. High durability of the lining

5. Uniform distribution of the received energy between individual phases

„Ultra High Chemical Power“ furnaces
In recent year, the so-called UHCP – Ultra High Chemical Power furnaces are being constructed and pushed forward. They are furnaces with very high productivity with
Development and technical parameters of newly constructed EAF

Questions
1. Electrical and thermal working mode of the electric arc furnace – how to influence the useful power put into the EAF.
2. A substitute diagram of one phase EAF.
3. How is it possible to perform the change of power released on the arcs.
4. The combined working characteristic of the EAF - construction.
5. The work of EAF on the increasing and decreasing branch of the characteristic, advantages and disadvantages.
6. Specific consumption of electric energy during the melting in EAF.
7. Dynamic, physical and chemical effects of arcs in the EAF.
8. UHP and SUHP furnace, conditions of including EAF among the UHP furnaces and UHCP furnaces.
THEMATIC BLOCK 4

Development of technology to produce steel in arc furnaces - intensification of melting

- theoretical consumption of electrical energy to melt 1t of steel - 380 kWh/t
- real consumption - cca. 450 to 600 kWh/t (overheating to 1600 °C, steel refinement)
- operation consumptions for these values indicate the usage of other energy (besides electrical) to heat and melt the batch.

Other sources of heat in an EAF

Thermal effect of exothermic reactions
- reactions between individual components of the pool
- reactions between components and refinement medium (gaseous oxygen)
- reactions during oxidation of auxiliary fuels

Use of gaseous oxygen in the conditions of EAF

1. Pre-melting nozzles – „cutting“ bigger chunks of batch

2. Refining oxygen nozzles – oxidation of accompanying elements and oxidation of C over the scope of carbon reaction (carbonification of the pool), transfer of heat into the pool (almost 100 %), creation of CO (post combustion treatment)

   Thermal effect in oxidation of the pool elements (1 kWh = 3600 kJ)
### Electrometallurgy and Ferroalloys Production

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$-\Delta H$; kWh/kg Me</th>
<th>$-\Delta H$; kWh/m³ O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\text{ Al} + 1,5\text{ O}_2 = \text{Al}_2\text{O}_3$</td>
<td>8,61</td>
<td>13,86</td>
</tr>
<tr>
<td>Si + O₂ = SiO₂</td>
<td>8,70</td>
<td>10,92</td>
</tr>
<tr>
<td>$\text{Mn} + 0,5\text{ O}_2 = \text{MnO}$</td>
<td>1,95</td>
<td>9,56</td>
</tr>
<tr>
<td>$2\text{ Cr} + 1,5\text{ O}_2 = \text{Cr}_2\text{O}_3$</td>
<td>3,05</td>
<td>9,44</td>
</tr>
<tr>
<td>$\text{Fe} + 0,5\text{ O}_2 = \text{FeO}$</td>
<td>1,32</td>
<td>6,58</td>
</tr>
<tr>
<td>C + 0,5 O₂ = CO</td>
<td>2,55</td>
<td>2,73</td>
</tr>
<tr>
<td>C + O₂ = CO₂</td>
<td>9,10</td>
<td>4,88</td>
</tr>
<tr>
<td>CO + 0,5 O₂ = CO₂</td>
<td>2,81</td>
<td>7,02</td>
</tr>
</tbody>
</table>

Real values of the thermal effect achieved in melting in EAF are between 2 and 4,5 kWh/1 m³ of O₂.

Advantages of the occurrence of exothermic reactions in the melt:

- the forming heat completely *moves into* the batch (melt)
- large amount of CO forms, which represents additional - and in terms of potential thermal effect even more significant - source of energy (thermal effect of the carbon oxidation reaction until the formation of CO₂ is triple compared to the oxidation into CO only).
The use of gaseous oxygen in EAF conditions

3. Oxygen-powered burners - natural gas + oxygen (1:2), temperature of the flame exceeds 2800 °C, power 2 to 4 MW (10 MW), use of heat during the melting decreases from 80 down to approx. 30 %. The manufacturers of burners: e.g. Air Products, Linde.

Implementation: mobile door burners, wall burners (usually 3 of them)
Electrometallurgy and Ferroalloys Production

Oxygen-powered burner JetBOx (Air Products) with the influx of powdered carbide substances

Oxygen-powered burner JetBOx (Air Products) with the influx of powdered carbide substances
Use of gaseous oxygen in EAF conditions

4. Post combustion nozzles – post combustion treatment of CO, which is formed during the carbon reaction and burning the additional or fossil fuels

- Theoretical limit of the thermal effect in afterburning CO into CO₂ is 7.02 kWh/Nm³ of oxygen (at 1600 °C).
- Electrical energy savings can achieve up to 72 kWh/t of steel.

Technical data of the use of oxygen and fuels in the conditions of intensified EAFs

Consumption of oxygen: 5 to 30 m³/t (possibly 60 m³/t), where 1 m³ of oxygen/1t of steel replaces 5 kWh of electrical energy /1t of steel.
Consumption of natural gas: 4 to 8 m³/t, where 1 m³ of gas /1t steel is replaced by approx. 8 kWh of electrical energy /1t of steel.
Consumption of carbonizing agent: 0–14 kg/t.

Energy balance of a modern arc furnace
(calculated for 1t of liquid steel):

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical energy</td>
<td>Liquid steel</td>
<td>380 kWh (60%)</td>
</tr>
<tr>
<td>Chemical energy-burners</td>
<td>Gas exhausts</td>
<td>125 kWh (20%)</td>
</tr>
<tr>
<td>Other chemical energy</td>
<td>Cooling water</td>
<td>60 kWh (9%)</td>
</tr>
<tr>
<td></td>
<td>Slag</td>
<td>60 kWh (9%)</td>
</tr>
<tr>
<td></td>
<td>Additional losses</td>
<td>15 kWh (3%)</td>
</tr>
<tr>
<td>Total</td>
<td>Total</td>
<td>640 kWh (100%)</td>
</tr>
</tbody>
</table>

The problem of purity with the gaseous oxygen used in EAFs

- The aim during steel production is primarily to prevent the potential „influx“ of nitrogen (and also hydrogen) to the metallic pool in the entire course of the technological cycle.
"Air-tight" EAFs ensure certain tightness of the entire construction and prevention of outside atmosphere penetrating in (high partial pressure of nitrogen with not insignificant content of air humidity). Using this technology and other measures, and EAF can produce "primary" steel with the content of nitrogen being less than 40 ppm.

- An important source of nitrogen may also be the purity of the used gaseous oxygen. In past or even present workshops (constructed earlier) the EAF uses oxygen which is approx. 90% pure.

- During the blowing of oxygen into this purity, the workspace of the furnace experiences and inflow of a sizeable amount of nitrogen which leads to an increase of its partial pressure in the workspace of the furnace and also in the formed slag emulsion and thus also the conditions for its transition into the steel.

- The existence of high-temperature sources in the shape of electrical arcs - dissociation and ionization of molecules and atoms occurs easily. A potentially higher danger can be expected of its transition into the metallic pool and thus increase of its amounts in the liquid steel despite the EAF conditions having a relatively effective way for nitrogen removal from the steel due to the course of the carbon reaction.

- Current and especially future conditions in the purity of gaseous oxygen used for being blown into the EAF are nearing or are almost the same as the conditions for purity of the oxygen blown into the oxygen converter. A range of intensified processes uses oxygen of 98 % to 99.5 % purity.

- Detailed tests have shown that a certain mild "pick-up" of nitrogen (cca 3 ppm) from the blown oxygen can be expected in 2000 ppm (0.2 %) of gaseous oxygen. At higher volumes, this pick-up will be much more pronounced.

- The second aspect which supports the necessity for using highly pure gaseous oxygen for melting intensification in UHP EAF is the ecological aspect. With the increasing amounts of nitrogen in the gaseous oxygen, the potential amount of very damaging oxides creation (of NOx type) intensifies.
Foaming nozzles

Blowing oxygen + ground carbide substances (coke, coal) into the slag
Reaction of carbon and blown oxygen in the slag with the creation of CO bubbles causing the slag foam. Possible course of the reaction of carbon with iron oxides in the slag.
Formation of CO bubbles, formation of foaming slag – shielding of long arcs.

Advantages to using a foaming slag:
- decreases the use of lining and electrodes
- decreases thermal loses through the furnace walls
- better transfer of heat from the arc into the pool
- decreases the furnace noise - the arc is shielded

The foamability of slag is positively affected by
- its increased viscosity (lower fluidity) – stabilizes the foam
- lowered surface tension – decreases the energy necessary for bubble formation
- higher basicity of the slag - higher than 2.5
- FeO content within 15 to 20 %, which we keep through the reaction of C with FeO

Disadvantage - formation of high amounts of CO within the furnace (heat losses)

EAF Bottom Stirring with Inert Gas

Melting intensification - thermal and concentration homogenization of the pool, better course of physical-chemical reactions
Basic methods of placing the stirring blocks in the bottom of the EAF
Basic implementation of blowing blocks in the EAF’s bottom

- **single-opening nozzle** – the disadvantage is „leakage“ of liquid metal, the nozzles must always be overpressured by gas
- **multi-opening block** – directional porosity plug
- **porosity of the block** – non-directed porosity, possibility of disrupting the blowing

Volumetric flow: 50 to 80 l.min⁻¹ (per 1 blowing block)
Metallurgical and economic effects of using blowing blocks at the bottom of EAF

1. decrease in iron content in the slag on average by 4 %
2. pool is closer to C-O equilibrium; no penetrations are observed
3. low content of carbon at the end of refinement phase (oxidation) – 0.02 %
4. lower losses of manganese in the slag (due to lower content of iron in slag), higher yield of alloying elements
5. achieving lower phosphorus, sulfur and nitrogen content in the steel (by 20 ppm N)
6. increase of thermal homogeneity of the pool
7. lower consumption of electrical energy by 10-20 kWh.t\(^{-1}\) due to faster melting of the waste and lower radiation losses
8. shortening of the melting period on average by 2.5 to 5 minutes
EAF productibility

EAF productibility is usually given in tons of produced steel in 24 hours and is one of the main parameters of an EAF.

EAF productibility is determined by this equation:

\[
G = g_0 \cdot n = g_o \cdot \frac{24}{t_{celk}} = \frac{24 \cdot g_o}{\tau_1 + \tau_2 + \tau_3}
\]

where:
- \( G \) - furnace productibility; \( t/24 \) h
- \( g_0 \) - mass of the melting; \( t \)
- \( n \) - number of meltings performed in 24 hours
- \( t_{celk} \) - overall time of melting; \( h \)
- \( \tau_1 \) - length of the time interval since turning off the furnace during tapping until turning on the furnace for the next melting; \( h \)
- \( \tau_2 \) - length of the melting period

where \( \tau_2 = \tau'_2 + \tau''_2 \)
- \( \tau'_2 \) - the sum of period when the arc is interrupted
- \( \tau''_2 \) - the sum of periods when the arc is ignited
- \( \tau_3 \) - the time of the period of finishing a heat
Distribution of power in individual phases during an EAF melting

$\tau_1$

In period $\tau_1$, the transformer is not under load - it is turned off. This interval’s length depends on the work organization, difficulty and scale (or length) of inter-melting repairs, development of contracts, etc.

$\tau_2'$

 Interruption of the arc during the melting period is always undesirable and is caused by various factors. Most often is it wrongly assembled batch that can disintegrate onto the electrodes causing short circuits, etc. To prevent the arc being switched off, it is necessary to include choke into the circuit (lowering the $\cos \phi$). Interruption of the arc burning is related to the possibilities of the transformer, which does not allow for switching to other voltage level under load. The value of $\tau_2'$ is influenced by the perfection of electrical and mechanical equipment of the furnace (parameters of electrode regulation, etc.).

$\tau_2''$

Shortening the period when the arc is ignited can be done only under the assumption of further intensification of the melting - is the funcion of $P_{useful}$, which is dependent on the power lead into the EAF (UHP furnace, oxygen-powered burners, etc.) and on the power lead out (especially thermal losses - perfect isolation of the furnace coating). Some furnace constructions utilize water-cooling with large-area coolers (i.e. higher outflow of heat - losses). In such case, assumptions must be made to increase $P_{el}$ (active power of electrical energies) or $P_{ex}$ (power by exothermic reactions), so that the shortening of $\tau_2''$ occurs.

$\tau_3$

During the finishing period, the transformer is not under full load. The length of this period is determined primarily by the technology used - production program, furnace equipment, scale of the out-of-furnace processing of steel in the steel-mill, etc.
1. Other sources of heat during the melting in an EAF, melting intensification.
2. Development and innovation tendencies in EAF melting.
5. Thermal effect of exothermic reactions of dissolved elements with gaseous oxygen.
7. Blowing inert gas through the bottom of the EAF - significance, construction implementation, metallurgical effects.
8. Productibility of EAF – equation definition, options to increase productibility.
A schematic of an electrical arc furnace

Electrical arc furnace is a relatively complex metallurgical aggregate and the most complicated part is related to the character of heat input - i.e. to the electrical energy, its distribution, transformation into the required voltage and upkeep of the electrical parameters of the arc, i.e. with the regulation of electrodes. Apart from the electrical section, each EAP is equipped with a mechanical part that ensured the movement of electrodes, shift of the lid, tilting the furnace, setting the furnace, etc. and also equipped for cooling the furnace and sucking out and purifying the furnace gases.

1 – high voltage supply 6 – electrode arms
2 – main switch 7 – electrodes
3 – choke 8 – electrode holders
4 – furnace transformer 9 – cooling rings
5 – belt Cu 10 – copper flexible cables
Electrical schematic of an alternating EAF

1 - isolator HV
2 - main switch HV
3 - choke
4 - switch choke
5 - furnace transformer
6 - switch connecting the transformer
7 - electrodes EAF
Arrangement of a classical AC EAF

1 - EAF shell
2 - water-cooled EAF roof
3 - slag door
4 - tapping
5 - furnace tilt
6 - tilting hydraulics
7 - stand of the rotary lid
8 - support
9 - lid lifting mechanism
10 - electrode arms
11 - electrodes
12 - electrode holder mechanisms
13 - conductors
14 - secondary power cables
15 - transformer exit
16 - transformer
17 - suction out of the EAF
View of a hall with an EAF installed
View of a 180t EAF by VAI company
**EAF furnace transformer**

The furnace transformer lowers the high voltage from the supply grid (6 ÷ 30 kV) to the voltage suitable for powering the EAF (100 ÷ 1000 V)

**Furnace transformer requirements:**
- optimal dimensions based on the tonnage of the furnace (apparent power 0.5 to 1 MVA/t, up to 120 kA on the secondary side)
- sufficient number of voltage levels (branching, switches Y-Δ)
- option to switch under load (800 switches per day)
- resistance against short circuiting currents and overstrain
- resistance of construction to mechanical and thermal effects
- inductance of all three phases must be the same

**Examples of EAF transformer connection**

- Switching the voltage levels is done on the primary side
- Melting of the batch occurs always at higher voltage (longer arc), load on the lining is then higher (the batch partially protects the lining. In the finishing period, it switches onto secondary voltage [shorter arcs - decrease of thermal load on the lining (but a worse cos φ)].
EAF furnace transformer by ABB

EAF choke
The choke balances (lowers, limits) sharp changes of the current in the electrical circuit of EAF, which form for example at turning the circuit on/off, short circuits, etc. Changes in the electrical circuit cause a change in the magnetic field around the coil and then electro-motoric voltage is induced in the coil, which acts always against changes that have caused it.

It is connected in a series to the primary side of the furnace transformer.

Functions during the melting in an EAF:
- *dampers the current bumps* during pre-melting of the solid metal batch
- protects the transformer from *short circuits*
- stabilizes *arc burning*
- *increases inductance* (inductive resistance) of the EAF electrical circuit

Construction - similar to the transformer, the choke has one coil; the magnetic circuit is not "closed" - increase of the magnetic flow deviation - increase of inductivity. It has minimal ohmic resistance.
Compensation of effects using the choke

Due to their inductive resistance, chokes reduce \( \cos \varphi \) of the grid - power factor. In UHP furnaces, during the period of non-covered burn of the arcs, \( \cos \varphi \) can decrease down to the values of 0.71-0.68, which decreases the active power released on the arcs and also decreases the power factor in the electrical distribution grid. That is why the power factor needs to be compensated using a method, where the phase shift caused by inductivity is compensated for by phase shift due to the input capacities of the condenser.

**Implementation:** use of condenser batteries, which are switched on when needed using thyristors to achieve the required \( \cos \varphi \).

Other tasks of compensation:

- balances out the asymmetrical load on the grid during the period when only two arcs burn short term, which usually occurs in case of the electrodes going down and touching the batch.
- ensures filtration of higher harmonic frequencies, which form due to the differences in voltages on the arc and powering voltage and which would input a reactive component into the power grid.
- dampers the imbalance in voltage in the power distribution grid, which is exhibited by unpleasant flickering light with a frequency of 3–7 (20) Hz. It is the so called flicker effect which is caused by imbalance of current input and short circuits during pre-melting the batch in an arc furnace.
**Nomogram for basic calculation of reactive power compensation**

**Melting the batch:** to increase the effect from 0.7 or 0.8 to 0.9, it is necessary to compensate reactive energy by 2.6 to 4.5 MVAr (A-A’, B-B’).

**Oxidation period of melting:** works with lower power in the transformer and with worse power factor (point C) for achieving cos φ=0.90 it is necessary to compensate by 4.5 MVAr (C-C’).

**Finishing the melting:** the transformer is under 25 % load (point D) with power factor of 0.65, therefore it is necessary to compensate by 1.2 MVAr (D-D’).
Secondary power cables

Electrical lead between the outputs on the secondary side of the transformer and the furnace workspace - copper flanges, flexible cables, conductors on the electrode holders, electrode holders, electrodes including the links.

- The line should be as short as possible – therefore „short grid“.
- Minimization of transfer resistance - extreme currents – \( n.10^4 \) A, loss of power \( P = R \cdot I^2 \)
- All three inputs should be the same in terms of electrical parameters.
- The formation of alternating magnetic field around the short grid - influence on inductance of individual phases (and subsequently on the reactance and the resulting impedance)
- Different reactance causes also a different transfer of energy through the individual phases - creation of wild and cold phases.
- With the arrangements of terminals on a plane - the middle phase has the highest power
- Symetrization of intakes - phases are arranged into a equilateral triangle.
- Bifilar lines from the transformer to the electrodes - reactance of the short grid in individual groups of conductors are compensated by conflicting segments of the current.
Different lines from the transformer to the electrodes

- a) linking the coils in transformers or on the transformer lid
- b) c) linking at the electrodes—bifilar lines
- d) linking beyond the flexible cables
EAF electrodes

Price of the electrodes - cca 40.000 CZK/1t for RP and HP, up to 100.000 CZK /1t for a UHP

Graphite electrodes are usually used in EAFs.

Requirements for the graphite electrodes:

1. Low electrical resistivity $\rho$ - 8 to 12 $\Omega$.$\text{mm}^2$.m$^{-1}$, it is not constant throughout the cross-section of the electrode. The electrode’s core, which is not as well graphitized, has higher resistivity.

2. The corresponding thermal conductivity and thermal expansion

3. High capacity of the electrode - $\nu$ A.cm$^2$; decreases with increasing diameter of the electrode, for electrodes of $\varnothing$ 355 mm the capacity is 21 A.cm$^2$ for UHP up to 35 A.cm$^2$
4. Low specific consumption of electrodes - moves within a wide range – between 2 to 6 kg/t of produced steel and depends on various factors including:

- the steel production technology (double-slag, single-slag, with oxidation by gasous oxygen, using oxygen-powered burners, etc.),
- the method of production (from solid batch, from liquid batch, ..),
- the furnace tonnage,
- the time of melting - shortening the melting period by 10 minutes brings a decrease in electrode consumption by approx 0.3 kg.t⁻¹
- the quality of the electrodes themselves and others

The electrode consumption/1 t of produced steel is an important technical-economical factor of EAF operation.
Consumption of EAF electrodes

Electrode consumption is the result of several processes happening at the same time:

- **Frontal burn** - increases with the increasing value of current, form a hot anode and cathode stain on the electrode, forms tension and release of graphite particles, dissolution of graphite in drops of steel.

- **Side burn** - rises with the oxidation ability of the surrounding gaseous phase and speed of its flow, forms a cone-shape electrodes in the EAF workspace.

  Decrease of side-burn intensity – phosphorus varnish (protection only up to 800 °C) or saturation of electrodes - putting a special coating based on Al and SiC onto the electrode surface about 0.5 to 0.8 mm thick (decrease of electrode consumption by 8-15 %).

- **Electrode fracture** - batch slide + unsatisfactory electrode regulation

Other requirements on electrodes:

- electrodes must not contain additives that pollute the steel
- sufficient strength at low and high temperatures (fractures during furnace tilting)
- smooth surface – low transfer resistances, higher resistance against oxidation
- ability to connect electrodes – using junctions - which are screwed into the threads on the from side of the electrode. The junctions usually have trapezoid shape, the connection must be firm, various binders are used.
Graphite electrode production

Energy consumption to produce 1t electrode is approx. 10x higher than the energy needed to produce 1 t of steel (up to 8000 kWh/t of electrodes).

**Graphite electrode production process:**

- **raw materials:**
  - base - anthracite, coke, petroleum coke, natural graphite (seldom used– has low strength),
  - binder - coal tar, tar products
- **calcination** – roasting in order to remove water and volatile substances (1400°C - in an electrical furnace)
- treatment of the basic raw materials – *grinding, sorting* to the 2-10 mm size
- **preparation of the mixture** with the binder
- **sintering** under the pressure of 30 - 50 MPa
- **impregnation** (filling the pores and holes by substances based on coal pitch)
- **graphitization** – at temperatures of 2500 to 3000 °C (conversion of amorphous carbon into grains of graphite with hexagonal grid; begins at 2200 °C) the process takes 2-3 weeks
- **processing by working** it into the required shape, including links

Graphite electrodes are stronger than carbon electrodes and have 4-5 times lower electrical resistivity (graphite is more conductive than amorphous carbon)
Questions

1. Basic equipment of electrical arc furnace - electrical and mechanical part.
2. Requirements put on the furnace transformer, wiring of transformers.
3. Significance of the choke in the EAF circuit, construction of the choke.
4. Power factor compensation, flicker effect
5. Short EAF grid, reactance of individual phases, wild and cold phase, types of bifilar lines.
6. EAF electrodes – requirements on the thermo-physical properties, electrical properties, capacity of electrodes, electrode consumption.
7. Electrode burn - side, frontal, electrode fracture.
8. The technology of producing graphite electrodes - main component, the basics of graphitization.
Regulation of movement of EAF electrodes

- The task of automatic electrode regulation:
  - to preserve the set **active power** brought in by electrical arcs into the furnace workspace
  - to ensure the **setting of the working point** on the associated characteristics for each voltage used

Apart from this, other requirements are put on the automatic regulation

- ensure conditions for the arc ignition
- exiting of electrodes or unplugging the furnace from the grid in case of the batch sliding and short circuit occurrence
- to prevent carbonization of the pool from electrodes during the reduction period
- systems of regulation of each electrode cannot be mutually influenced
- it must react even to non-standard working conditions, such as presence of non-conductive material in the batch
- it must allow for manual control over electrodes - especially their exit from the furnace

Power of the arc can be regulated by changing its length - shortening will increase its power (increasing branch characteristic).

The working point cannot be determined by power because the same power can be achieved at two different values of voltage - the power cannot be used as a regulated quantity.

Choice of regulable quantities in theory is:
- **arc voltage** – is not changed much, not used for regulation
- **arc current** – unable to ignite the arc during an interruption
- **arc voltage and current ratio** – voltage-current (impedance, differential).
Static characteristics of electrode regulator in EAF

Dependence of electrode movement speed in \((m/min^{-1})\) on the size of deviation of the regulated quantity (e.g. arc impedance - \(Z_2\))

Division of regulation:
- non-proportional – speed of electrode movement in not dependent on the size of regulated quantity deviation (e.g. contact regulation)
- proportional – speed of electrode movement in dependent on the size of regulated quantity deviation (e.g. hydraulic regulator)

Insensitivity range - electrode does not react to the change of regulated quantity deviation
Transition characteristic of EAF electrode regulator

Time progress of electrode speed from since the start of the given regulatory deviation until its removal

The regulator will have faster feedback if the overall delay $t_z$ is lower and if the time constants $\tau_n$ and $\tau_d$ are lower. The size of the time constant is positively influenced by the speed of electrode movement.
A schematic of automatic regulation of electrode in an arc furnace

- The measuring element of the regulator performs measurements of quantities, their comparison and control of the core element and contains:
  - the control element which inputs the required value of the measured quantity $w$ into the comparison element
  - comparison element, which compares the measured value $U_0/I_2 = x$ with the value of the control quantity, the deviation $w-x$ is then input into the core element
- Core element amplifies the deviation $w-x$ so that it can directly control the active element (such as the power amplifier, magnetic amplifier, thyristor or hydraulic amplifiers)

- Active element performs the electrode movement directly through
  - electromotor, cable or chain gears
  - hydraulic elements – the electrode column is part of the hydraulic cylinder
A schematic of electromechanical electrode regulation in EAF using a differential relay

It basically is an impedance regulator and its control element is a differential relay (balance relay) which ma two coils wired by

- the voltage of the electrode against ground
- and the voltage of the measurement transformer, which is proportional to the passing current to the electrode.

Both coils affect the rocker system of the relay. If the current of the arc increases, the rocker falls out of balance and switches a set of contacts of the electromotor, which lifts the electrode through a pulley system. If the current in the electrode decreases, the balance relay switches the contacts to move the electrode downward.
A schematic of an electrohydraulic regulation of EAF electrodes using Ferraris engine

The core element of this type of regulation is the so called Ferraris engine, its rotor is in the shape of aluminum drum and the stator has two-phase coils - excitation coil and regulatory coil.

The excitation coil is powered by the voltage from other two phases other than the regulated phase. The regulation coil is differentially connected to two sources of alternating voltage. One of them is the voltage proportional to the voltage between the electrode and the batch. The other source is the voltage which is excited by the flow of regulated phase in the measuring transformer. If these two voltages are of same amplitudes, no current flows through the regulatory coil, because both sources have opposite effect (phase shift is 180°). If a difference is formed - such as during the increase of the arc current related to the decrease of voltage on the electrode - some current flows through the regulatory coil which creates rotary electromagnetic field; its effect speeds up the rotor. The torque is proportional to the current flowing through the regulatory coil, the direction of rotation is dependent on if the balance is disrupted by overflow of voltage which is proportional to the arc current over the voltage measured from the electrode or vice-versa. It is clear that the regulated quantity is the arc impedance. The rotor here acts as the core element of the regulator. Rotation of the rotor is transferred through the gear segment and an arm onto the rod of the regulatory hydraulic valve damper, which controls the hydraulic piston with the arm of the electrode.
A schematic of a hydraulic arc furnace electrode regulator
New views on the properties of regulated EAF system

Complications and problems of a regulated EAF system:

Gradient of voltage on the arc (V.mm⁻¹) changes depending on the batch composition and temperature during the technological process more than by an order, i.e.

➢ to a certain value of a regulation deviation (w-x) the regulator should react by a different value of action quantity (i.e. the ratio of electrode moment) depending on if the gradient of voltage on the arc is low or high.

Electrical parameters of individual arcs are mutually bound because the electrical circuit for the current of the given arc must necessarily close through arcs of the remaining electrodes, which means that in the situation of a given electrode, the arc length corresponds to the required state and it is not suitable to move the electrode, especially the change of current in a different electrode (albeit short-term) will be seen as a change of current. It is evident that if the change is short term, it would be best not to react to it at all.
Induction mixing of the pool in an EAF

- electromagnetic coil for induction mixing is placed under the bottom of the arc furnace (analogy to the expanded stator of an asynchronous engine)
- rotor (with the „short-term anchor”) is the pool itself
- the coil is wired by current of lower frequency (up to 1 Hz).
- the coating on the furnace floor must be made from non-magnetic steel
- the source of the connecting current are rotation or thyristor converters

If a current of low frequency passes through the coil, it causes movement of the melt as shown on the figure below.

Advantages of induction mixing:
- the homogeneity is increased for alloying, especially by heavy elements such as wolfram or vanadium
- the thermal homogeneity of the pool is increased
- it speeds up the occurring diffusion processes between slag and metal, such as the diffusion deoxidation and desulfurization
- facilitates the removal of inclusions
- facilitates withdrawal of slag
- used during the reduction period of the melting
EAF linings

Furnace floor - hearth

Tightness against penetration of steel and resistance to bubbling up is a requirement in furnace floor. The floor takes part in physical-chemical reactions, it is heavily strained both thermally and mechanically (during setting of the steel waste).

The required properties of the floor are achieved by a suitable combination of thickness and execution of the isolation layer, magnesite bricks and work layer.

The work layer is made from dense, volumetrically stable and well sintered monolith. It is made from finely ground magnesite (or magnesite-dolomite) clinker.

The floor monolith may be produced by several methods:

- by stomping of the grainy material with the addition of tar
- by stomping of the grainy material wetted by water solutions: MgSO₄, MgCl₂
- by stomping of the grainy material wetter by water-glass
- by stamping dry grainy material in layers
- by densening dry grainy material through deep vibration using needle vibrators

Dry floors provide several advantages - they do not have to be dried, they exhibit higher density and volumetric stability. Before the first melting, the floor is covered by pieces of sheet metal and lighter waste is set. The first melting is performed intermittently at lower degrees of voltage.

In the production of stainless steels through oxidation remelting, the floors are strained by significantly high temperatures. Suitable lifetime of floors has been achieved through several preventive measures that result in formation of a chromium gathering at the place where hearth meets the pool.

The gathering is formed during the processes between the original magnesite or dolomite hearth and the elements of chromium slag, components of highly-alloyed pool and the used reparatory material. The main components of this gathering are complex spinels of MgO.Cr₂O₃, FeO.Cr₂O₃.

Furnace walls

The furnace wall lining is also strained by temperature changes due to arc burning, mechanical tension during the tilting of the furnace and other factors.

The finish of the EAF walls and their lining can be divided into 2 groups based on the method of heat transfer from the workspace of the furnace:

- outflow of the heat through the furnace coating into its surrounding where the magnesite lining itself is isolated from the coating to varying degree
- The use of water coolers (for large areas) which remove the heat from larger part of the furnace workspace, which is made up by a thin lining or coating of ceramic
matter or gatherings on the colder ones. The use of coolers allows for full use of the UHP furnaces and thus higher productivity, lower consumption of heat-resistant material.

- Water cooled panels are constructed as tubular (the radius of the tubes is 70-90 mm), the thickness of the wall is 8-10mm and it must be sufficiently resistant to mechanical influences on the other hand it must ensure fast transfer of heat into the cooling water. They are made from steel with good thermal conductivity ($50 \text{ Wm}^{-1}\text{K}^{-1}$) or for especially strained areas even from copper ($383 \text{ Wm}^{-1}\text{K}^{-1}$) such as for the zone near to the slag line or oxygen-burning burners, etc. The panels do not come into long term direct contact with liquid metal or slag. They are placed above the slag line.

**A segment of water-cooled EAF wall panel**
Water-cooled EAF roofs

The roofs used to be lined by silica, because it has suitable properties - low weight, not too expensive. But if the temperature only slightly exceeds 1670°C, it lead to a significant wear.

Modern EAFs use aluminum rich roofs, basic roofs or water cooled lids.

- Aluminum-rich - based on Al₂O₃, 75-80 % Al₂O₃
- Basic - magnesite-chromium
- Water-cooled - the coolers are in the peripheral part, the middle part around the electrode is built using masonry methods.

Coolers are built using a pipe-space-pipe system, the cooling is divided into several cooling circuits. On the inside (furnace) side, the tube constructions are melted by thorns, which act as holders of the refractory concrete that is put onto the entire surface before the furnace is used. The weight of the water-cooled lid is small than the brick one. The amount of flowing water must ensure sufficient cooling without the formation of vapor - up to 200 m³/hour for a lid that is 6 m in diameter.
Suction of the furnace gases from an EAF

During the melting, especially with oxygen-intensified technologies, a high amount of furnace gases form within the furnace as products of the oxidation reactions. These gases contain an amount of dust, which can be 14 to 20 kg/t of steel during the production of carbon or low-alloyed steel and 6-15 kg/t of steel in case of highly-alloyed steel production.

The forming furnace gases must be sucked out from the furnace area during the melting. For the suction, several technological principles are used

- suction by the so called fourth hole in the lid (arch) of the furnace or the second hole in case of a DC furnace
- using suction lid over the arc furnace
- using the dog-house cover, in which the whole EAF is placed and which opens only during the setting and certain manipulations (such as sampling); a positive effect of this principle is also shielding of the noise and lowering its amount during the melting by 10 to 20 dB
- suction of the entire steel mill

The stated procedures may be combined to achieve the maximum effect and thus reducing secondary emissions from the operation of arc furnaces.
### Chemical composition of dust in furnace gases

<table>
<thead>
<tr>
<th>Component</th>
<th>Dust from carbon and low-alloy steel production, %</th>
<th>Dust from high-alloy and stainless steel production, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe total</td>
<td>25-50</td>
<td>30-40</td>
</tr>
<tr>
<td>SiO₂</td>
<td>1,5-5</td>
<td>7-10</td>
</tr>
<tr>
<td>CaO</td>
<td>4 –15</td>
<td>5-17</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0,3-0,7</td>
<td>1-4</td>
</tr>
<tr>
<td>MgO</td>
<td>1-5</td>
<td>2-5</td>
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<tr>
<td>P₂O₅</td>
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<tr>
<td>Cr₂O₃</td>
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Adjustment of furnace gases suction consists primarily in their clean-up using bag filters (90 % of devices) or using electrostatic separators or water filters. 2/3 of the separated dust is dumped in the EU, the rest is recycled (dust from the production of stainless steel) or is further utilized externally.
Data on the input and output of carbon steel production in an electric arc furnace taken from various references

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<td>noise</td>
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Questions

1. Main task of electrode regulation.
2. Requirements of electrode regulation.
3. Advantages and disadvantages of voltage, current and voltage/current regulation.
4. Statistic and transfer characteristics of EAF electrode regulator.
5. A block scheme of EAF electrode regulation.
7. Complicated states in electrode regulation.
8. The significance and the implementation of induction mixing of the pool in EAF.
9. EAF lining – classification, gathering, lid implementation, water-cooled panels.
10. Suction of furnace gases from the EAF, gas purification.
Steel production in an electrical arc furnace is characteristic for certain specific options which result from the existence of high-temperature concentrated heat source (electrical arc) which is not dependent on the progress of oxidation (or combustion) reactions.

In the workspace of the furnace, both oxidation and reduction conditions can be created.

a) **double-slag technology** - melting is comprised of the period of batch melting, oxidation period and reduction period

   This technology had two sub-variants:
   - with the withdrawal of oxidation slag at the end of oxidation period
   - without the withdrawal of oxidation slag at the end of oxidation period

b) **single-slag technology** - the melding has a period of melting, oxidation and finish - the melting occurs without reduction period

c) **remelting** - right after the melting goes the reduction period, there is no oxidation period

   There is a great number of modifications of these technologies - production of carbon steel, alloyed, highly alloyed, tool steel, steel for casts, etc.
Double-slag technology

Before the rise of secondary metallurgy, it was the most used one. It is currently used in smaller units for creation of special steels.

Preparatory work before starting the melting:

- repair of the lining between meltings
- batch preparation – especially sorting in terms of chemical composition
- setting the batch into the furnace - using setting baskets or setting machines, light waste to the bottom (absorbs impacts of heavy waste) and then heavy waste and light waste again

The most often used types of setting baskets:

Two-jaws peel scrape
1 - furnace; 2 - jaws; 3 - scrape frame;
4 - drapes gaping jaws

Segmented peel scrape
1 - furnace; 2 - closed elements;
3 - open elements; 4 - closing rope
Setting the batch using a setting basket
Melting period

It is the time period from ignition of the arc until the withdrawal of the first sample after melting. Maximum value of secondary voltage is used for melting (longer arcs are shielded by batch), which shortens the melting period.

**Intensification of melting:**
- Blowing of gaseous oxygen - aids the melting of unmelted chunks of batch outside of the electrode area
- Use of oxygen-powered burners - usually for methane and oxygen, batch can be preheated outside the furnace in setting baskets, shafts etc.
- Rotary hearth - hearth will rotate by 30-40°

**Metallurgical reactions in the melting period:**
- Oxidation reaction – on smaller scale - dephosphorization and oxidation of Si, Mn; related to the formation of reactive calcium-iron slag
- Intentional carbonization of the pool - adding coke, fractions of electrodes or raw iron. Carbonization is necessary for the occurrence of carbon reaction which controls a significant part of thermodynamic and kinetic conditions of processes during oxidation refinement (such as dephosphorization, removal of gases, etc.)

The melting period ends with the complete melting of batch, the transformer is switch to a lower level of secondary voltage (shorter arcs).
Oxidation period of melting

Time period from the first sampling since the batch melting until the removal of oxidation slag.

Tasks of the oxidation period:

1. Oxidation of phosphorus (dephosphorization)
2. Oxidation of other accompanying elements (Si and Mn, Cr)
3. Oxidation of carbon (decarbonization)
4. Lowering the content of gases (N₂, H₂)
5. Partial decrease in the content of sulfur
6. Decrease of the amount of non-metal inclusions
Dephosphorization of steel in EAF

**Molecular theory:**

\[
2 [P] + 5 \text{(FeO)} = (P_2O_5) + 5 \text{Fe} \\
(P_2O_5) + 4 \text{(CaO)} = \text{(Ca}_4\text{P}_2\text{O}_9) \\
2 [P] + 5 \text{(FeO)} + 4 \text{(CaO)} = (\text{Ca}_4\text{P}_2\text{O}_9) + 5 \text{Fe}
\]

**Conditions for achieving low content of phosphorus in metal:**
- relatively low temperature (exothermic reaction) – at high temperature, reverse reduction of phosphorus from the slag into the metal may occur
- low activity of the reaction product in slag - \text{Ca}_4\text{P}_2\text{O}_9
- high activity of CaO and FeO in slag – for the optimal ratio of CaO and FeO in slag

**Influence of CaO/FeO ratio on the division of P between metal and slag**

![Graph showing the influence of CaO/FeO ratio on the division of P between metal and slag.]

**Ionic theory:**

\[
[\text{P}] + 4 (\text{O}^{2-}) + 2.5 (\text{Fe}^{2+}) = (\text{PO}_4^{3-}) + 2.5 \text{Fe}
\]

**Conditions for achieving low amounts of phosphorus in the metal:**
- high activity of \text{O}^{2-} and \text{Fe}^{2+} ions - influence of ionic potentials
- low value of \text{PO}_4^{3-} anion activity coefficient
Oxidation of carbon in EAF

Homogeneous carbon reaction can be described as

\[ [C] + [O] = \text{CO}_g \]

Equilibrium constant

\[ K_{C,O} = \frac{p_{\text{CO}}}{f_c \cdot [C] \cdot f_O \cdot [O]} \]

\[ \log K_{C,O} = \frac{1168}{T} + 2.07 \]

\[ \Delta G = -5343 - 9.47 \cdot T \]

Oxidation of iron in the primary zone

\[ [\text{Fe}] + \frac{1}{2} \text{O}_2 = (\text{FeO}) \quad \text{exo} \]

Transfer of oxygen from the slag phase into the metal can be described as:

\[ (\text{FeO}) = [\text{Fe}] + [\text{O}] \quad \text{endo} \]

Homogeneous carbon reaction then occurs in the melt

\[ [C] + [O] = \text{CO}_g \quad \text{exo} \]

The overall thermal effect of the carbon oxidation reaction in iron melt is formally equal to the progress of the summary reaction

\[ [C] + \frac{1}{2} \text{O}_2 = \text{CO}_g \]

The progress of carbon reaction is possible only after fulfilling all other conditions (physical ones) - partial pressure of \( p_{\text{CO}} \) in the forming bubble must be greater than the sum of \( p_{\text{atm}}, p_{\text{fer}} \) and \( p_{\text{kap}} \).

\[ p_{\text{CO}} > p_{\text{atm}} + p_{\text{fer}} + p_{\text{kap}} \]

\[ p_{\text{CO}} > p_{\text{atm}} + h \cdot \rho \cdot g + \frac{2 \sigma}{r} \]

where: \( \sigma \) - interphase pressure between the forming CO bubble and melt

\( r \) - CO bubble radius
Decreasing the content of dissolved gases (N₂, H₂)

Sieverts law (\( \frac{\%N}{N} = k \cdot p_{N^2}^{1/2} \)).

During the progress of carbon reaction, CO bubbles form, in which the partial pressure of nitrogen and hydrogen is zero. Atomically dissolved nitrogen and hydrogen diffuses in the pool into these CO bubbles and is brought to the surface.

Partial decrease of sulfur content

The thermodynamic conditions are unfavorable - high content of FeO in slag (12 – 15 %). Good kinetic conditions of the process (mixing) allow for partial decrease of sulfur content.

Decrease of the amount of non-metal inclusion

Through mixing (carbon reaction) occurs an increase of the amount of collisions and thus also the increase of coagulation and coalescence of inclusions and their quicker separation into the slag.

Flotation effect of CO bubbles - raises the inclusions into the slag. Basis of this flotation is lowering of the overall surface energy of the pool-inclusion-CO bubble system (see Secondary metallurgy).

Reduction period of the melting
The time period since deoxidation of the pool until the tapping.

Tasks of the reduction period:

1. Deoxidation of steel
2. Desulfurization of steel
3. Alloying of the pool and final adjustment of the chemical composition
4. Adjustment of pool temperature to the tapping temperature
5. Final deoxidation of steel and formation of optimal slag composition

**Deoxidation of steel**

*Preemptive collision deoxidation* – performed after withdrawing the oxidation slag using SiMn or FeMn+FeSi or aluminum weighing 0.5 to 2 kg Al.t⁻¹; the aim is to create conditions for the formation of reduction slag.

**Diffusion deoxidation**

Basis:

- *lowering the activity (FeO) in slag* - by adding C, FeSi, FeMn
- resulting in violating the equilibrium between the amount of oxygen in the pool and slag and beginning the process of the *extraction process*

\[
[\text{FeO}] \rightarrow (\text{FeO})
\]

equilibrium of this reaction is set by *Nernst division coefficient* dependent on temperature and composition of both phases in contact:

\[
L_O = \frac{a_{(\text{FeO})}}{a_{[O]}} \approx \frac{(\text{FeO})}{[\text{FeO}]}
\]

resp.

\[
L_O = \frac{(O^{2-})}{[O]}
\]

With lowering of (FeO) or \(a_{(\text{FeO})}\) the violation of equilibrium occurs and also subsequent transfer of oxygen from metal into slag until a new equilibrium is set:

\[
(\text{FeO}) = L_O \cdot [\text{FeO}]
\]
Advantage of diffusion deoxidation - products of deoxidation are formed in the slag
Disadvantage - slow (diffusion process).

**Diffusion deoxidation may be performed under white or carbide slag.**

**a) White slag**

White slag – a mixture of lime and fluorspar (cca 4:1), after forming the liquid slag, powdered coke or ground electrodes (sources of carbon are added).

A reaction occurs

\[(\text{FeO}) + C = \text{[Fe]} + \text{CO}_g\]  

(1)

CO is formed, which fills workspace with smoke which creates a reduction atmosphere.

Further deoxidation can be performed using reduction mixture containing FeSi (i.e. lime + CaF$_2$ + FeSi). Content of (FeO) is lowered to **0,5 to 1%**.

White slag disintegrates after cooling into a white powder (formation of 2CaO.SiO$_2$, change of modification at decrease of temperature)

Composition of white slag:

- $\sim 50 \% \text{ CaO}$,
- $\sim 6 \% \text{ CaF}_2$,
- $\sim 13 \% \text{ SiO}_2$,
- $\sim 6-10 \% \text{ MgO}$,
- $\sim 0,5-1 \% \text{ FeO}$,
- $<0,5 \% \text{ CaC}_2$

(2)

Usage of white slags:

- during production of low-carbon and mid-carbon steels.
b) Carbide slag

Ration of coke in the reduction mixture is higher, in one dose contains only CaF₂ and CaO without FeSi. In high temperatures under the arcs, the following reaction occurs:

\[ 3\, C + (\text{CaO}) = (\text{CaC}_2) + \text{CO}_g \quad \Delta H \text{ strongly endo} \]

carbide of lime reacts with (FeO):

\[ (\text{CaC}_2) + 3(\text{FeO}) \rightarrow (\text{CaO}) + 2\text{CO}_g + 3[\text{Fe}] \]

two elements take part in slag deoxidation (Ca, C), which positively affects on greater decrease of (FeO) content in the slag - down to 0,3-0,5 %. Content of CaC₂ in carbide slag is higher - 1 to 2,5 %.

Advantage of using carbide slag:
- higher deoxidation abilities

Disadvantage
- possibility of carbonizing the pool
- higher density
- lower fluidity (higher viscosity)
- lower interphase tension between slag and steel (high wettability)

Due to the stated disadvantageous physical properties, carbide slag has difficulties being released from the metal during tapping and may be the cause of a great amount of non-metal inclusions in the steel. For these reasons, carbide slag is transformed into white slag before tapping by ventilating the furnace (raising the lid), surplus CaC₂ undergoes oxidation and we put ground FeSi onto the slag.

By the end of the reduction period, we achieve content of oxygen in steel between 0,0400 to 0,0800 %.
Desulfurization of steel in EAF

Molecular theory:

\[
(CaO) + [FeS] = (CaS) + (FeO) \\
(CaO) + [S] + Fe = (CaS) + (FeO)
\]

Ionic theory:

\[
[S] + 2 \text{ e} = (S^{2-}) \\
(O^{2-}) - 2 \text{ e} = [O] \\
[S] + (O^{2-}) = [O] + (S^{2-})
\]

From the value of equilibrium constant \(K_S\) we can create equation for \(\%S\)

\[
\%S = \frac{f_o \cdot [%O] \cdot a_{(S^{2-})}}{K_S \cdot a_{(O^{2-})} \cdot f_s}
\]

In order to achieve low content of sulfur in metal, it is necessary to achieve

- low activity of oxygen \(a_o\) in steel (low content of dissolved oxygen and low value of activity coefficient \(f_o\))
- low activity of sulfur anions \(a_{S^{2-}}\) in slag
- high values of \(K_S\) - reaction is weakly exothermic, the influence of the process’ kinetics is more important
- high values of oxygen anion activities \(a_{O^{2-}}\) in slag (high basicity, i.e. high content of (CaO), low of (FeO))
- high values of activity coefficient \(f_s\) in steel (activity of sulfur is increased by C, Si; oxygen decreases it significantly)
Influence of C, Si, O on sulfur activity coefficient

![Graph showing the influence of C, Si, O on sulfur activity coefficient](image)

Influence of slag basicity and (FeO) content on the sulfur division coefficient

![Graph showing the influence of slag basicity and (FeO) content on the sulfur division coefficient](image)
Behavior of sulfur during the reduction period of an EAF melting

Alloying the pool and adjusting the chemical composition

The main rule of alloying:

- elements with high oxygen affinity (Al, Si, V, Ti) have to be added at the end of the melting; on the other hand, low oxygen affinity elements (such as Ni, Mo) can be added into the batch or at the start of the oxidation period.

It is also necessary to consider:

- the needed level of pool alloying
- melting temperatures of additives
- effective density of additives
- content of gases in additives
- content of unwanted inclusions

In order to remove possible non-homogeneity of the pool’s chemical composition, several methods may be used, such as

- induction mixing of the pool using an induction mixed
- mechanized mixing of the pool using a currycomb
- mixing the pool by blowing inert gas through the porous blocks in the hearth of the furnace or through the top of the submerged nozzle
Influence of placing the blowing block in the bottom of the pan and volume flow of argon on homogenization times

The basic solution lies in moving the alloying into a device of pan metallurgy

Production of alloyed steel by reduction remelting

Basic timeline:

Production of alloyed steel by reduction remelting with short oxidation refinement by gaseous oxygen after the melting period

Basic timeline:
Tapping the steel from EAF

After alloying, adjustment of temperature and slag composition, tapping of steel is performed - the classical method is through a tapping trough at an angle or using a damper tap – such as the EBT (Eccentric bottom Tap-hole) method.

Single slag technology for steel production in EAF

The effort for increased productivity of EAF and decreased specific consumption of electricity lead to shortening the reduction period or its total removal.

A whole range of different technologies was created, which are differentiated primarily by the performance of collision deoxidation at the end of oxidation refinement. After this deoxidation, no usual reduction period happens. These technologies can be labeled as single-slag.

The basic variant of a single-slag technology is characterized by relatively high additions of aluminum at the end of oxidation refinement (2-3 kg Al/t of steel). Next is the mixing of pool, addition of lime, alloying and tapping.

Single-slag technologies are not usable in all cases of steel production. Since this technology lacks a reduction period, intense desulfurization of steel cannot occur within the furnace. If the steel mill is not equipped with a device for out-of-furnace desulfurization, this technology cannot be used. It is more suitable to use intensified double-slag technologies.

A certain problem of this technology can also be the reversed transfer of phosphorus from the slag into the metal after performing deoxidation by silicon (the forming product of reaction - SiO₂ - pushes out the P₂O₅ from the bond with CaO, (Si)/[Si] balance is damaged and silicon transfers back into the metal).
Questions

1. Basic division of melting technologies in EAF.
2. Double-slag technology - characteristics.
3. Adjustments between meltings, setting of the batch, periods of melting, metallurgical processes in the melting periods, electrical mode.
4. Tasks of oxidation period.
5. Dephosphorization, molecular and ionic theory, analysis of conditions for dephosphorization.
6. Decarbonization, homogeneous carbon reaction, resulting thermal effect, physical conditions for the progress of carbon reaction.
7. The basis and mechanisms of lowering the content of gases (hydrogen, nitrogen) and non-metal inclusions in the oxidation period.
8. Tasks of the reduction period.
10. White and carbide slag, chemical composition, advantages and disadvantages.
The thermodynamics of metallurgical processes in oxidation refinement of chrome-rich iron melt

During the oxidation of chrome-rich iron melt by gaseous oxygen, the carbon oxidized into CO and chrome in the melt into \(Cr_3O_4\) (or to \(Cr_2O_3\)) based on reactions:

\[
[C] + [O] = CO_g \quad \Delta G^{\circ}_{1873} = -5343 - 9.47T
\]

\[
\frac{3}{4}[Cr] + [O] = \frac{1}{4}(Cr_3O_4) \quad \Delta G = -58047 + 25.48T
\]

Both partial reactions (oxidation of carbon and chrome) are exothermic reaction. They differ by thermal dependence of Gibbs energy change (free enthalpy). Change in \(\Delta G\) of the \(C\rightarrow CO\) reaction with increasing temperature becomes more negative (affinity increases); in \(Cr\rightarrow Cr_3O_4\) reaction, the \(\Delta G\) becomes positive with temperature (affinity decreases).

At certain temperature, the oxidation of Carbon into CO occurs primarily, Carbon may also reduce into oxides \(Cr_3O_4\) according to the reaction:

\[
\frac{1}{4}(Cr_3O_4) + [C] = \frac{3}{4}[Cr] + CO_g \quad +52704 - 34.90T
\]

The equilibrium constant of this reaction can be expressed as:

\[
K_{C, Cr} = \frac{a_{[Cr]}^{3/4} \cdot a_{CO}}{a_{(Cr_3O_4)}^{1/4} \cdot a_{[C]}}
\]

If \(a_{Cr_3O_4} = 1\), then by further adjustment, we get

\[
K_{C, Cr} = f_{Cr}^{3/4} \cdot \left[\% Cr\right]^{3/4} \cdot P_{CO} \cdot f_C \cdot \left[\% C\right]
\]
From the given equilibrium constant, the relation for carbon content in the melt can be expressed:

\[
\left[\% C\right] = \frac{f_{Cr}^{3/4} \cdot \left[\% Cr\right]^{3/4} \cdot P_{CO}}{f_{C} \cdot K_{C, Cr}}
\]

From this relation we can perform a simplified analysis of the main thermodynamic factors that influence the resulting carbon content in the melt at certain Cr content in the melt.

The carbon content after oxidation refinement will be lowered by:

- low coefficient of chrome activity \( f_{Cr} \) - chrome activity is lowered by e.g. Si, C; increased by e.g. Ni (\( e_{Cr}^{Si} = -0.0043; e_{Cr}^{C} = -0.12; e_{Cr}^{Ni} = +0.0002 \))
- lower amount of chrome in the resulting melt
- lower partial pressure of CO in the gas atmosphere
- higher carbon activity coefficient in the pool - activity of carbon is increased by Ni, Si, oxygen decreases activity (\( e_{C}^{Ni} = +0.012; e_{C}^{Si} = +0.08; e_{C}^{O} = -0.34 \))
- higher value of equilibrium constant - this is a strongly endothermic reaction, i.e. its higher value will be achieved at higher temperatures.

**Influence of temperature, nickel content and \( p_{CO} \) on equilibrium contents of C and Cr during highly-alloyed steel production**

The rules stemming from equilibrium constant may be visualized using the so called Hilty-Chipman diagrams:
Electrometallurgy and Ferroalloys Production

Influence of temperature

Influence of nickel content

Influence of pressure
Dephosphorization during highly-alloyed steel production

EAFs do not provide suitable conditions for dephosphorization of chrome-rich melts.

Causes:
- high temperature during oxidation refinement – acts negatively on dephosphorization (reversible reduction)
- formation of very viscous chrome slag - worsening of the process’ kinetics
- negative effect of chrome on the activity of phosphorus ($e^{Cr_p} = -0.044$)

Dephosphorization of chrome-rich melts on the principle of phosphorus oxidation is limited in EAFs. It is therefore necessary to pay increased attention to the choice of batch raw materials.

Reduction of alloying elements’ oxides from slag into the pool

Reduction of $Cr_2O_3$ (or $Cr_3O_4$) bound in the heavily meltable spinels of chrome slags using silicon can be expressed in an equation:

$$2(Cr_2O_3) + 3[Si] \rightarrow 4[Cr] + 3(SiO_2) \quad \Delta H = -$$

Relation for the $Cr_2O_3$ content in slag can be expressed from equilibrium constant by reaction:

$$\left(\%Cr_2O_3\right) = \left(\frac{a_{SiO_2}^3 \cdot a_{[Cr]}^4}{\gamma_{Cr_2O_3}^2 \cdot a_{[Si]}^3 \cdot K}\right)^{\frac{1}{2}}$$

$Cr_2O_3$ content in slag after performing reduction will be lowered by
- lower activity of $SiO_2$ in slag
- lower activity of chrome in the metal pool
- higher value of $\gamma_{Cr_2O_3}$
- higher activity of silicon in the pool
- lower temperature of the system
The additive of the reducing agents leads to decrease in \( \text{Cr}_2\text{O}_3 \) content but also increase of \( \text{CrO} \). The reason is gradual reduction of certain amounts of \( \text{Cr}_2\text{O}_3 \) into \( \text{CrO} \). At the same time, a bond of \( \text{CrO} \cdot \text{SiO}_2 \) is formed, which is difficult to reduce:

\[
x \text{(CrO)} + (\text{SiO}_2) \rightarrow (x\text{CrO} \cdot \text{SiO}_2)
\]

Early addition of an optimal amount of quicklime not only limits the production of \( (x\text{CrO} \cdot \text{SiO}_2) \), but also decreases the value of \( a_{\text{SiO}_2} \), which leads to lower amounts of \( \text{CrO} \) in the slags.

**Influence of slag basicity on the chrome content in slag**

![Graph showing the influence of slag basicity on chrome content in slag](image)

**Alloying stainless steels by titanium**

„Stabilized“ stainless steels – addition of Ti to the content of \( T_{\text{min}} = 4 \div 5 \times [\%\text{C}] \)

**Effects of Ti:**

In stainless steels without Ti, formation of \( \text{Cr}_{23}\text{C}_6 \) type carbides occurs on the edges of the grains. Formation of these carbides is accompanied by decreasing amount of chrome near the grain boundaries (by diffusion), which leads to lowered resistance of these boundaries against *intercrystalline corrosion*. Addition of titanium leads to formation of TiC titanium carbides, which remain equally dispersed in the matrix during solidification and thus limit the formation of damaging chrome carbides.

Inclusion of titanium is performed at the end of the reduction timeline (26 % FeTi) or into the pan during tapping (70 % FeTi, with regards to the thermal balance).

CrNi stainless steel stabilized by titanium is prone to formation of defects caused primarily by clusters (lines after reshaping) of non-metal inclusions consisting not only of oxides but primarily of carbonitrates \( \text{Ti}(\text{C}_x\text{N}_y) \), which are heterogeneously expelled on Al oxides.
Solution:

- production of steel with significantly lower amounts of carbon and nitrogen (AOD, VOD).
- stabilization by Nb
- modification of forming non-metal inclusions by adding calcium - calcium modifies Al oxides into calcium-aluminum globular inclusions, where heterogeneous nucleation of titanium carbonitrates occurs with more difficulty.
Steel production in acid arc furnaces

Acid EAFs in foundries are further divided in the USA especially in smaller furnace units of 7-8 t. There is no acid furnace in the Czech Republic.

Lining of acid furnace may be comprised of silica pre-forms. Often, instead of silica lining, the furnace walls are stomped as a template by silica sand bound by water-glass, or creep-resistant clay may be added into the stomping mixture. The furnace is repaired by the same mixture.

The lids are lined by silica by the same method as in base furnaces. Lifetime of a silica lid on acid furnaces is longer.

Linings based on silica react with elements with higher affinity to oxygen than silicon (Al, Ti and at higher temperatures, carbon). In acid furnaces, after lowering the activity of oxygen below the value which usually corresponds with the equilibrium with silicon, oxygen may transfer from the lining into the steel. In acid furnaces, lowered activity of oxygen cannot be achieved to the same value as in base furnaces. This fact has influence on mechanical properties of the produced steel.

Advantages of acid arc furnaces compared to base furnaces

- steel produced in acid arc furnace contains less gases (especially hydrogen)
- amount of defects on the casts caused by bubbles and spines is usually higher,
- lower processing costs - by 20 % - caused by:
  - lower costs on creep-resistant material (lining and material for lining reparation),
  - lower consumption of electricity which is caused by lower thermal conductivity of acid lining and shorter time of melting,
  - lower consumption of graphite electrodes due to shorter time of melting,
  - lower costs of non-metal inclusions,
  - lower costs on transit and storage of slag, of which there is less in acid arc furnaces.

Disadvantages of acid arc furnaces

- necessity to process batch with guaranteed and suitable content of phosphorus and sulfur.
- production range of steels for acid arc furnaces is limited to non-alloyed steel and low-alloyed steel brands - highly alloyed chrome- or manganese-rich steels cannot be produced in them.
Questions about the presented material

1. Thermodynamics of metallurgical processes during oxidation refinement of the pool with high amounts of Cr, analysis of oxidation refinement conditions.
2. Hilty and Chipman diagrams, use in practice.
3. Dephosphorization during the production of highly-alloyed steel.
4. Reduction of alloying elements' oxides from slag into the pool.
5. Alloing by titanium, stabilized steels, basics of intercrystalline corrosion formation.
6. Production of steel in acid arc furnaces, advantages, disadvantages.
7. Combines processes: EOP-DH(RH)–(LF), EOP-AOD, EOP-VOD, EOP-OVD.
**THEMATICAL BLOCK 9**

**Behavior of hydrogen and nitrogen during the course of melting in an EAF**

Negative effect - flakes, bubbles, hydrogen-induced cracking (HIC), hydrogen embrittlement (HE), aging steel etc.
Alloying by nitrogen - increase of strength, creep resistance, substitute for Ni (austenite-forming)
Transition of hydrogen and nitrogen in the course of melting in an EAF - effect of the arc, dissociation of gas molecules into atoms of N and H, dissolution in the pool.

**Solubility of hydrogen in iron**

![Graph showing solubility of hydrogen in iron](image)

**Solubility of nitrogen in iron**

![Graph showing solubility of nitrogen in iron](image)
Electrometallurgy and Ferroalloys Production

Transfer of hydrogen into the steel through slag

A more significant mechanism than transfer of hydrogen into the pool under the arcs

Dissolution of hydrogen in slag:

\[
\{H_2O\} + (O^{2-}) = 2 (OH^-)
\]

Equilibrium constant of the reaction:

\[
K_{H,O} = \frac{a_{OH^-}^2}{a_{O^{2-}} \cdot p_{\{H_2O\}}}
\]

\[
a_{OH^-} = \sqrt{K_{H,O} \cdot a_{O^{2-}} \cdot p_{\{H_2O\}}}
\]

- Increase of oxygen anion activity in the slag leads to better solubility of hydrogen in the slag while forming complex hydroxyl anions OH\(^-\)

Diffusion of hydrogen from the slag into the metal pool

\[
2 (OH^-) - 2e = 2[O] + 2[H]
\]

\[
(Fe^{2+}) + 2e = [Fe]
\]

\[
2 (OH^-) + (Fe^{2+}) = 2[O] + 2[H] + [Fe]
\]

- Chemical composition of the slag has an undeniable effect on solubility of hydrogen and thus also on its amounts in the pool. Acid slags best protect the melt (low activity of O\(^{2-}\) due to formation of complex anions SiO\(_4^{4-}\)), the worst protection is offered by calcium rich slags with low contents of FeO (high activity of O\(^{2-}\)).

- Viscosity of the slag also has some influence on the hydrogen transfer - high viscosity worsens the course of the transfer.

- Sources of hydrogen - steel waste (moisture, rust), slag-forming additives, lime (hygroscopic properties)
Dissolution of nitrogen in the iron melt

\[ \text{N}_2 \rightarrow 2 \text{[N]} \]

\[ [\text{N}] = \sqrt{\frac{K \cdot p_{\text{N}_2}}{f_N^2}} \]

Process of nitrogen dissolution in iron melt will be more significant:

- at higher \( p_{\text{N}_2} \) values
- at higher values of the equilibrium constant \( K \) (i.e. higher temperature - the process of dissolving nitrogen is endothermic)
- at lower \( f_N \), values

Solubility of nitrogen in pure iron at 1600 °C is 0,0450 % (450 ppm). Chrome increases the solubility of nitrogen in iron \( (\varepsilon_{\text{N}}^{\text{Cr}} = 0,045) \), nickel decreases it \( (\varepsilon_{\text{N}}^{\text{Ni}} = 0,010) \). In 18/8 stainless steel, solubility of nitrogen is significantly higher (by cca 0,250 %).

The intensity of nitrogen transfer into the pool will also be influences by the value of nitrogen diffusion coefficient, thickness of the diffusion layer, constant area of the phases and composition of the metal pool. Overall in comparison with hydrogen, the transfer speed of nitrogen from the gaseous phase into the metal pool is 4-6 times slower which is related to lower values of the nitrogen diffusion coefficient in melted iron in comparison with hydrogen \( (D_{\text{N}} = 5,5 \cdot 10^{-9} \text{m}^2\cdot\text{s}^{-1}, D_{\text{H}} = 3,5 \cdot 10^{-7} \text{m}^2\cdot\text{s}^{-1}) \).

It is necessary to consider that this fact also make removing nitrogen from the pool more difficult during its vacuuming or decarbonization.
Influence of oxygen content in the pool on the „pick-up“ of nitrogen during tapping

![Graph showing the influence of oxygen content on nitrogen dissolution](image)

Oxygen and sulfur are (same as nitrogen) superficially active elements and their presence on the surface of the melt acts as a kinetic retardant during the dissolution of nitrogen because their atoms contain reaction places necessary for the dissociated nitrogen and thus they significantly lower the nitrogen dissolution in metal reaction speed.

The influence of sulfur content in the pool and volume of blown Ar during vacuuming RH on the decrease of nitrogen content in steel

![Graph showing the influence of sulfur content on nitrogen content](image)

At low content of sulfur (< 10 ppm) and consequent intense mixing of steel, the amount of nitrogen can decrease significantly during vacuuming (sulfur does not block transfer of nitrogen through the interphase metal-gas).
A schematic of a NITRIS devise for direct determination of nitrogen content in melted steel

- A carrier gas (helium) is blown into the pool via an auxiliary block, which captures certain amount of nitrogen dissolved in the pool just by passing through the melt.
- The blown helium with a certain amount of nitrogen is then collected by a special lid and lead into an evaluation unit, where its thermal conductivity is tested and the composition of the reference mixture N₂-He is calculated, which is in the next phase brought into the pool and also into the detector.
- At the end of this phase the measurement of nitrogen amount in the final gas is compared with the amount of nitrogen in the reference gas. If the difference is small, it determines the amount of nitrogen and the entire process is finished. If this is not so, it is necessary to perform an approximating calculation of reference gas composition for a new blowing.
Head of the HYDRIS probe (NITRIS) before the final installation into a cardboard pipe
Measurement of oxygen activity in melted steel

Direct measurement of oxygen activity in melted steel is based on the principle of electrochemical concentration cell which is comprised of 2 metal electrodes placed in two environments with different content of oxygen and divided by a solid electrolyte. The oxide electrolyte or the solid solution of oxides with high melting point must exhibit ionic conductivity (i.e. conductivity of oxygen anions) within the given concentration of oxygen. In these conditions and if the oxygen activity or partial pressure of oxygen in the reference source is known, the oxygen activity in the measured environment can be determined using Nernst equation.

\[
\log a_O = 4.51595 - \frac{13272.349 - 10079.906 \times E}{T}
\]
Rendering of the “CELOX” probe for measuring oxygen activity in melted steel
Automation of steel production control in EAF

Controlling the electric power and thermal mode

- creating the necessary thermal conditions in the pool for optimal course of metallurgical processes and for achieving required tapping temperature.
- controlling the energy mode during the melting (highest consumption of electricity) - static model x dynamic model
- The simplest (but also outdated) way is to control energy mode based on a pre-set timetable. Another group of an elaborate methods of control is based on consuming a predetermined amount of electrical energy. These methods do not guarantee optimal control of the EAF modes.

Control of metallurgical melting mode

- optimization of batch composition and determining additives for deoxidation and alloying using a system of balancing equations solved using a computer. The aim is to ensure the required composition of the produced steel at minimal cost of batch and alloying elements.
- automation of the melting mode is dependent on sufficiency of information about the chemical composition of the pool, its temperature, composition of the outgoing flue gas, CO/CO₂ ration in the flue gas, etc. Modern units have an in-built system of control, e.g. positioning of oxygen-powered burners which are used to speed up pre-melting the batch or directing the oxygen overflow in the post combustion nozzles depending on the composition of the flue gases. Some companies utilize control based on neuron networks, i.e. artificial intelligence, which have self-learning abilities (e.g. the Canadian EFSOP system – Expert Furnace System Optimization Process – utilizing control of burn optimization of additional fuels in real time. On the other hand a range of smaller and older units does not utilize such options and the main controlling factor is human.

Operative control of steel production in electric steel mill

- it is organization, control and coordination activities of all workstations in an electric steel mill with the aim to achieve maximum output in the required quality at minimal cost.
Questions

1. Hydrogen in iron melt, solubility of hydrogen, influence of hydrogen on steel properties
2. Thermodynamics of hydrogen transfer from furnace atmosphere through the slag into the metal, analysis of conditions
3. Sources of hydrogen and options of its removal from the liquid steel.
4. Nitrogen in iron melt, solubility of nitrogen, influence of nitrogen on steel properties
5. Transfer of nitrogen into the metal pool in EAF conditions
6. „Pick up“ of nitrogen during tapping, metallurgical options of its composition
7. Determining nitrogen amount in melted steel by „NITRIS“ probes, the principle of measurement, utilizing the measurement
8. Measurement of temperature by submerged thermo-cells and measurement of solidification temperature
9. The principle of oxygen activity measurement in liquid steel, types of oxygen probes
10. Automation of steel production control in an EAF, controlling the electrical power and thermal mode, control of metallurgical melting mode, operative control of steel production in an electric steel mill
Direct Current Arc Furnaces

Currently there are EAF powered by alternating current as well as younger (construction-wise) EAFs powered by direct current. Their development and installation started in the 70s and 80s of last century and are characterized by a whole range of original construction elements.

The development of DC furnaces utilizes knowledge especially:
- from the observation of UHP and SUHP furnaces
- from the energy semiconductor technology necessary for construction of robust rectifiers of AC into DC
- from the development of new electricity-conducting creep resistant materials bound by carbon for production of bottom electrodes

Equipment of electrical section of a DC arc furnace:
- furnace transformer
- diode or thyristor rectifier on the secondary side of the transformer
- suppression coil - on the primary and secondary side of transformer
- graphite electrode (cathode - connected to the negative pole of the rectifier)
- bottom electrode (anode - connected to the positive pole of the rectifier)
- electrode regulation
DC arc furnace with one electrode
**Furnace transformer**

Is constructed similarly to the AC furnaces. Its purpose is to lower the voltage of the grid to the operational voltage of the arc furnace for the required current load.

**Suppression coils**

They are either on the
- primary (high-voltage) side of the transformer - limits the voltage impact on the grid.
- secondary side of the transformer (behind the rectifier, sometimes also called the DC suppression coil) - smooths out the DC voltage and protects the rectifier diodes (or thyristors) against excessive short-circuit current.

**AC rectifier**

Is formed by a block of tens or hundreds of cooled high-voltage diodes or thyristors, which are wired in series and in parallel with regards to the layout of the voltage load, which is 40-140 kA overall based on the size of the furnace. The positive pole of the rectifier is connected to the floor electrode (floor anode), the negative pole (cathode) of the rectifier is connected to the graphite electrode.

**A block schematic of wiring of an DC arc furnace with two electrodes**
A schematic representation of the individual types of floor anodes of DC arc furnaces. The positive pole of the rectifier is connected to the floor electrode (floor anode).

- **Electric conductive lining**
- **Pins bottom anode**
- **Billet bottom anode**
- **Fin bottom anode**
Electric conductive furnace of the bottom in a DC arc furnace

- Creep resistant materials containing carbon (graphite-magnesite, etc.)
- Sufficient dimensions of the area of the conductive lining
- With an under-dimensioned area, the transition resistance increases and this rises the overall electrical loss which transforms into the heating of the lining (based on the relation $P=I^2.R=U^2/R$) and damage of the lining
- Transition of electrical current from the lining - a copper floor contact panel
Billet bottom anode by CLECIM

- Compact steel billet 100-150 (250) mm in diameter which is placed in a water-cooled copper sheath (under the lining) which ensures effective cooling of the electrode similarly to a crystallizer in fluent steel casting.

- Part of the billet in the lining is placed in a specialized creep resistant material. The upper part of the billet is then pre-melted and ensures contact with the pool and conducts the current. Cooling must be done so that the entire billet is not melted inside the sheath.

- The stated type of floor anode has a lifetime of 1300 meltings and usually 1-4 floor electrodes are used for 1-3 graphite electrodes.
Billet bottom anode by Danieli
**Pins bottom anode**

- High number of steel pins (rods) - contact pins (e.g. 150 - 400 pins approx. 45 mm in diameter), which are laid out in a cylinder which passes through the bottom of the furnace.
- The gaps between these pins are filled with creep resistant, usually magnesite lining.
- The lower part of the pins is connected in the contact panel which is then connected to the anode side of the rectifier.
- The outflow of heat from the floor electrode is ensured by forced flow of cooling air between the lower ends of the uncovered steel rods. The upper part of the pins is in contact with the steel pool.
The wear of the pins is similar to the wear of creep resistant material. In combination with the swaged magnesite, the lifetime of this type of floor electrode is more than 800 meltings. During the changing of the anode, it is removed as a whole by a hydraulic cylinder under the furnace and changed for a new anode.

**Fin bottom anode by VOEST ALPINE**

- Thin (1.7mm) steel plates that are laid out in ring formation on the bottom of the furnace and are melted into a steel bus at their lower end which is placed on the lower base connected to the wiring from the rectifier.
- The area between the individual rings (7-10 cm) are filled by a monolithic electric non-conductive magnesite matter.
- Advantages: high active area of the plates, perfect cooling by a material from the lining, additional air or water cooling is not required as opposed to other types of floor anodes.
- Another advantage is the balanced division of the current on a huge area on the bottom of the hearth which allows for calm and uniform transit of current through the melt. The diagonal area of the plates is sufficiently large for the current.
- Wear of the plates is from 0.3 to 0.5 mm per 1 melting.
Behavior of the electric arc in DC EAFs

- less divergence of the arc towards the walls of the furnace - approx. 15 to 30°.
- change in the shape of the arc - direct, angular, diffusion, etc.
- higher stability - voltage within the arc does not pass null

The course of melting the batch is a DC arc furnace
After igniting the arc, a free space (called "a well") forms under the arc down to almost the bottom of the furnace. As a result of the burning of the arc, a circular space from the material melted away forms around the electrode.

Due to the central placement of the electrode and vertical direction of the arc, a single coaxial space of heat distribution forms. There are no "hot stains" formed on the walls, which are common in triple-electrode AC EAFs.

The period in which the arc is surrounded by unmeltable scrap is longer in DC furnaces than in AC ones, which leads to heat loss through the walls and lid and to lower wear. This creates conditions for melting with extremely long arc (with \( U = 650 \text{ V} \), \( l \) up to 700 mm), which significantly speeds up melting of the scrap.

**Process of pre-melting the batch in a DC EAF by NKK**

- **Boring**
- **Stable Melting**
- **Scrap Fall**
- **Melt Down**
- **Refining**
Use of additional natural gas burners in AC and DC arc furnaces

The consumption of electrical energy can be lowered by using additional natural gas burners. These burners should be installed tangentially so that the flame does not interfere with the arc area and does not impede its burning.
The flow of steel pool in a DC arc furnace

Mixing of the pool in a DC furnace is from the metallurgical point of view very favorable for these reasons:

- it increases the speed and effectiveness of metallurgical reactions on the slag-metal interface
- it improves the control over the tapping temperature
- sampling during the melting is more representative

In large DC EAFs, it is necessary to ensure mixing by blowing inert gasses through the bottom of the hearth or using electromagnetic mixers.
Flow of steel pool and slag in a DC arc furnace

Consumption of graphite electrodes

The consumption of electrodes in DC furnaces is approximately 20 % lower than in high-impedance and 50 % lower than traditional AC furnaces. Usually, in DC furnaces achieves the electrode consumption of 1.1 to 1.3 kg.t⁻¹.

The causes for lower consumptions of electrodes can be summarized as follows:

- electrodes of higher quality (but also of higher price),
- electrode is always the cathode, there isn’t a hot anode stain formed on them (instead the impact of electrons is always in the metal),
- the side burn of electrode is smaller because the overall outer area of one electrode is smaller than the area of three electrodes in AC furnace,
- in AC furnaces, the inner area between electrodes is significantly overheated which also increases their wear by side burn.

An advantages of the electrode consumption in DC furnaces have to be considered in relation to the price of electrodes, which are generally higher in DC furnaces than in AC furnaces.
The consumption of electrical energy in DC furnaces

The consumption of electrical energy in DC furnaces is about 10-15 kWh/t lower than in AC furnaces, which represents 5-10 % of energy savings (average values without the use of burners are within 300-350 kWh/t, some sources say the consumption is up to 460 kWh/t). The main causes of lower consumption are:

- only one electrode
  - lower electrical losses - shorter grid, mounts, etc.
  - lower heat losses by radiation
  - lower heat losses through the opening around the electrode
- better transfer of heat during the pre-melting - the arc is surrounded for a longer time by steel waste (batch)
- transfer of energy from the electrodes at higher voltage, i.e. lower loss of $R.I^2$ in a short grid
- better transfer of heat into the pool (penetration of the arc, mixing of the pool)
- induction losses are lower compared to an AC furnace

Noise of DC furnace

- In the course of melting the scrap, the noise from the DC furnace is almost identical with the noise from AC furnaces and reaches - based on the furnace size - values of up to 110dB.
- With the increasing scope of pre-melting the liquid phase, noise of a DC furnace decreases and after pre-melting, it produces noise that is approx. 10 dB lower than AC furnaces (95 dB → 85 dB).
**Parameters of double electrode 170 t DC EAF in TRICO factory, Alabama, USA**

**yearly production** 1,25 mil. tons
**tap-to-tap time** 50 minutes
**charge-to-tap time** 40 minutes
**graphite electrodes** 2x610 mm
**transformer** 2x75 MVA (150MVA overall)
**sec. current** 85 kA / 1 electrode
**floor electrode** bar type (pin), 584 bars, ø 45 mm divided by refractory concrete
**burners** 6 oxygen-powered (natural gas), 1 door
**arc** water-cooled, tubular type, Al₂O₃ lining around electrodes
**hearth** 1010 mm, induction mixing, EBT, replaceable
**setting** by a setting basket (steel waste, raw iron)
**melting** el. arcs + burners, computer controlled
in partial melting, the blowing of coal powder with oxygen starts - foaming slag, changes the gas/oxygen ratio (afterburning function of the burners)
**floor tapping** EBT, diameter of the opening 165 mm, the tapping lasts 5 minutes, slag-less

**consumption of el. energy** 390 kWh/t
**oxygen consumption** 50 m³/t (1600 cu ft./ton)
**electrode consumption** 2,04 kg/t (target: 0,9 kg/t)
**floor anode lifetime** 500 melttings (target: 1500 melttings)
Summary of the main advantages and disadvantages of the DC EAFs compared to AC EAFs

- lower electrode consumption (by 40 - 60 %)
- lower electricity consumption (by 5 - 10 %)
- more stable burn of the arc
- lower „flicker effect“ value (50 %)
- lower noise level (95 → 85 dB)
- lower consumption of heat resistant material (by 5 - 10 %)
- more intense mixing in the furnace hearth
High-impedance AC EAFs

Use of higher voltage on the secondary side of the transformer.

- **Reason:** losses on the secondary side are a function of the reactivity of the secondary circuit but especially a function of the secondary current. If we increase secondary voltage, we may lower secondary currents for achieving the same effective power, but at lower overall losses.

- **The denomination of high-impedance** is a business name, because impedance is not changed in these furnaces (impedance of the secondary winding is 2.75 to 2.77 mΩ). Only the resistance of the primary circuit of the transformer is changed, into which additional resistivity of 2.5 - 3Ω is added in order to achieve stability of the long arc.

- **The increase of secondary voltage** is limited by the chosen transformer, the possibility of forming arcs between electrodes and the walls of the furnace, properties of the electrodes and also the foaming slag, which is very often used with the „long arc“ technology.

The use of lower secondary currents at higher voltage leads to

- lowering of electrode consumption by 10 %
- acceleration of the batch melting – the longer the arc, the greater portion of the batch is undergoing its effects
- lowering of electricity consumption by 10 to 20 kWh.t⁻¹
- lowering of the „flicker effect“ by 40 %
- improving the arc stability

High-impedance EADs are becoming the new standards in AC furnaces and a strong competitor to the DC furnaces.
Questions

1. DC arc furnaces, assumptions for their development
2. Electrical part of the DC furnace, differences from an AC furnace
3. The construction of the AC rectifier
4. Main types and construction of floor anodes, advantages and disadvantages
5. Requirements on the graphite electrodes of a DC furnace
6. Peculiarities and differences in melting in a DC furnace, behavior of the electrical arc, melting of waste, movement of the pool, flicker effect
7. Consumption of electrical energy and graphite electrodes in a DC EAD, causes of lower consumption in comparison with AC furnaces, melting noise
8. High-impedance AC EAFs, concept, advantages
THEMATIC BLOCK 11

New processes in production of EAF steel

The main aim of these new processes is:
- to increase flexibility in choice of energy and type of batch material
- to decrease production cost
- to decrease consumption of primary electric energy and electrodes
- to decrease emissions from steel production
- to increase quality of the steel produced
- to increase production

The main ideas which are used in these processes can be summarized into 3 main principles:

1. **Use of heat of the leaving furnace gasses for pre-heating of the metal batch**
2. **Post combustion treatment** of the forming CO within the furnace or in the pre-heating chamber
3. **Use of carbon and oxygen as sources of further energy** for melting

Principle of steel production in an EAF with pre-heated batch

Flue gasses from the workspace of the furnace are diverted into the pre-heating chamber where the steel waste is placed. By passing of the hot flue gas through the
layer of waste, about 35% of the flue gas heat is utilized with the waste being heated to 550-650 °C.

Advantages of steel waste preheating:
- increase of productivity by 10 to 20%
- decrease of electricity consumption by 70-80 kWh/t of liquid steel
- removal of moisture from the batch, which eliminates the possibility of explosion
- decrease in consumption of electrodes and lining
- decrease in dust development

Some of the disadvantages and shortcomings are:
- possibility of higher harmful substances emission from the contaminated waste
- bad control over temperature in the chamber that leads to a wide range of temperature of the pre-heated scrap
- at high temperatures (over 650°C) oxidation of the waste occurs, which leads to losses in yield

**Twin hearth DC EAD with batch pre-heating (UNARC, licenced by SMS GHH)**
A schematic of batch pre-heating in an EAF pre-heating chamber
Finger Shaft Furnace

The common principle of all modifications is the pre-heating shaft, which is placed over the EAF and which allows setting the pre-heated batch into the workspace of the furnace.

- Temperature of the preheated batch achieves 800 °C.
- Consumption of electricity - approx. 350 kWh/t of steel
- Consumption of electrodes - 1,8 kg/1t of steel
- Consumption of oxygen - 30 m³/1 t of steel
- Consumption of gas - 8,5 m³/ 1 t of steel
- Length of the melting - 40 to 60 minutes
- Yearly production - 0,8 to 1,25 mil. of tons
Comelt DC arc furnace

- four *skewed electrodes* entering from the side into the workspace of the furnace
- integrated *preheating shaft* for the batch is placed under the melting furnace.
ConSteel electrical arc furnace with batch pre-heating

Batch or the steel waste is continuously fed through the side entrance into the furnace using a vibration conveyor (width=1.2m, depth=0.3m), running through the heat-resistant material lined pre-heating tunnel 16m long which is heated by flue gas from the EAF and using combined natural gas burners up to 700 °C (usually only 550-600 °C).
Works with liquid residue (up to 15%), speed of the batch fed into the furnace is such that it is gradually melted by submerging; after achieving the nominal weight of the melting, the influx of waste is stopped (in a 70 t furnace for approx. 10 minutes), the tapping temperature is adjusted and tapping is performed. Wiring of EAF may be AC or DC. The arc is very stable because the process of melting always works a liquid pool.

Steel waste, raw iron, HBI or DRI is used as batch. 30-40% of liquid raw iron may also be used through a special through in the furnace casing. Shredded waste, reversible waste, light waste, etc. may be used for pre-heating.
Questions about the presented material

1. Main aims and course of the new processes in electric steel production
2. Pre-heating of steel waste, advantages and disadvantages
3. Fuchs Shaft Furnace, description, parameters
4. Verticon Process
5. COMELT VAI electric arc furnace
6. CONSTEEL process
7. ContiArc process of steel production
8. Twin-hearth EAF (Twin Shell EAF)
CONARC process

**Converter process** – One furnace is filled by liquid raw iron with a trough, then oxygen is blown in through the upper nozzle. In the second stage of blowing, DRI or steel waste is added which partially cools the pool and stops it from overheating. In the course of converter part of the process, the amounts of C, Si, Mn and P are lowered. Then the lid with the nozzle is moved to the second hearth (where the tapping of steel is occurring), steel waste and DRI are added to the furnace and a lid with electrodes is moved over the hearth.

**EAF process** – during which the melting of DRI and steel waste occurs as well as overheating the steel to the tapping temperature using the electric arc utilizing oxygen-burning burners and combustion of CO. At the same time, the converter process is occurring in the second furnace.
A Schematic blueprint view of the rotary lids of the ConArc furnace
DANARC PROCESS
- combustion of outgoing gasses
- synchronized blowing of oxygen through the floor lances,
- supersonic nozzles and blowing of carbide materials by side nozzles.

DANARC Plus PROCESS
- setting by one batch using a basket
- Better use of heat from the outgoing emissions - higher construction of the furnace, higher layer of batch, suction of emissions
- More effective combustion within the furnace - determined by higher construction of the furnace
- Higher effectiveness of the arc and burners - construction of the furnace and arrangement of the batch allows for increasing the power of the arc without increasing the load on the walls
- Utilizing the technology of foaming slag - increases the use of arc energy that transitions into the pool and lowers the load on the walls
- Electromagnetic mixing of the steel pool - optimized location of the floor anode in relation to the cathode
- Fully automatic control of the furnace - using an expert system which optimizes the working point of the furnace based on the given conditions

DANARC Plus M² PROCESS
- The furnace is equipped with an independent preheating chamber

Comparison of the individual DANARC processes

<table>
<thead>
<tr>
<th>Type of furnace</th>
<th>Power consumption</th>
<th>Oxygen consumption</th>
<th>Consumption of electrode AC</th>
<th>Consumption of electrode DC</th>
<th>Tap-to-tap time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kWh.t⁻¹</td>
<td>m³.t⁻¹</td>
<td>kg.t⁻¹</td>
<td>kg.t⁻¹</td>
<td>min</td>
</tr>
<tr>
<td>Standard EAF</td>
<td>410</td>
<td>30</td>
<td>1,9</td>
<td>1,4</td>
<td>60</td>
</tr>
<tr>
<td>DANARC</td>
<td>270-320</td>
<td>35-50</td>
<td>1,7</td>
<td>1,2</td>
<td>45-55</td>
</tr>
<tr>
<td>DANARC Plus</td>
<td>310-330</td>
<td>30</td>
<td>1,7</td>
<td>1,2</td>
<td>38-45</td>
</tr>
<tr>
<td>DANARC Plus M²</td>
<td>210-250</td>
<td>30</td>
<td>1,4-1,7</td>
<td>0,9-1,2</td>
<td>28-30</td>
</tr>
</tbody>
</table>

Note: Data are related to the batch without raw iron.
Main construction elements of the 90t DANARC furnace

- Oxygen-powered nozzles (i.e., combustion) – 6x3.4MW, oriented tangentially, put in through the side walls, at the height of the slag line
- Floor oxygen lances – 3x250m³/h, cambered 4° towards the center of the furnace
- Oxygen nozzles– 2x2300m³/h, positioned in the side walls
- Injection carbon nozzles – 2x19.5kg/t, positioned near the oxygen nozzles, they have foaming effect with the formation of CO for further combustion
1 - charging phase
2 - bucket positioning on preheating station
3 - starting melting
4 - melting and scrap preheating phase
5 - tapping phase
Questions

1. The ConArc process of steel production
2. The KES process of steel production
3. The DANARC process
4. The KorfArc process
5. Tendency for production and out-of-furnace processing of electric steel
Steel production in induction furnaces

- operating frequency – grid frequency 50 Hz, medium IP - 600 to 10000 Hz, high frequency (laboratory) IP - up to 500kHz
- power – 50 kVA to 5 MVA
- weight of the batch – 1 kg up to 10 t

The principle of heating and melting

Alternating current flowing through the inductor created alternating magnetic flow (field), which induces alternating electro-motoric current of opposing polarity within the batch. Induced current creates eddy currents in the batch which causes gradual heating of the metallic material to the required temperature and melting. Materials that conduct electricity can be heated by induction, however they do not have to be ferromagnetic.

Movement of the melt in electrical induction furnace

Electrodynamic movement of the pool is a characteristic feature of induction crucible furnace; this is caused by mutual electrical effects of the inductor current and current within the pool.

Mixing of the pool balances the chemical and thermal heterogeneity.

An accompanying phenomenon of this mixing is the characteristic and adverse bulging of the pool surface and its exposure because the slag flows to the walls of the crucible. This bulging can be suppressed by dividing the inductor into sections and disconnecting the upper section, or possible increasing the frequency or lowering performance.
Electrical wiring diagram of the induction furnace (principle)

Furnace inductor along with the batch represent a considerable inductivity (L), which delay the phase of the current against the voltage, which lowers the effect of $\cos \phi$ and the real power declines. A capacitor battery ($C_1$, $C_2$, $C_3$, ..., $C$) must be wired in parallel to the inductor, which compensates for the unproductive induction component of the current.

The value of added capacity would be high enough for the circuit to achieve parallel resonance, when the circuit behaves like an ohmic resistance.
Wiring of an electrical induction furnace

Mid-frequency induction furnaces used to be wired via a rotary converter, which is basically a mid-frequency alternator powered by asynchronous motor.

Currently, static thyristor alternators are used. In low-frequency and grid induction furnaces, regulatory transformers with a frequency multiplier are used - they are directly connected to the electrical grid.

Performance in mid-frequency furnaces can be regulated in two ways. In older furnaces with rotary converter by changing the current in excitation winding of the alternator, which changes its output. In newer thyristor alternators by changing the frequency. Thyristor alternators can set their optimal operating mode, so that they can always have full performance.

Wiring of a medium frequency induction furnace with rotary alternator

1 – furnace inductor
2 – capacitor battery
3 – breaker
4 – generator
5 – exciter
6 – shunt regulator
7 – asynchronous motor
8 – power switch
9 – trigger
10 – measurement devices
Wiring of a medium frequency induction furnace with a static thyristor alternator

1 – transformer  
2 – thyristor rectifier  
3 – smoothing choke  
4 – thyristor frequency alternator  
5 – capacitor battery  
6 – induction furnace inductor
The depth of induced current penetration into the batch

Due to the so-called „skin effect“ (compression of current on the surface of the conductor), the highest portion of the heat is induced in the surface layer of the heated and melted batch. The depth of induced current penetration into the batch can be determined from the empirical relation

$$\delta \approx 50,3 \cdot \frac{\rho}{\sqrt{f \cdot \mu}}$$

where: $\delta$ ... depth of the penetration of induced current into the batch; cm
$\rho$ ... batch resistivity; $\Omega \cdot cm$
f ... frequency of the current; Hz
$\mu$... relative permeability of the batch; H.m$^{-1}$ (for non-magnetic materials is $\mu \sim 1$, for magnetic materials is $\mu > 1$)

The current penetration depth is

- inversely proportional to frequency - the higher the frequency, the lower the induced current penetration depth. In mid-frequency furnaces, 86% of the electrical power consumption is changed into heat at penetration depth $\delta$.
- inversely proportional to relative permeability of the batch - at 768°C, permeability is decreased, the penetration depth increases

The bigger pieces of batch we use, the lower the frequency can be. In small pieces we must use higher frequency to achieve the required heating and melting.

Real power - $P_{el}$ - exerted by individual pieces of the batch or in the pool

$$P_{el} = b \cdot I^2 \cdot n^2 \cdot \sqrt{\rho \cdot \mu \cdot f} \cdot D \cdot K$$

where: $n$ ... number of threads in the inductor
$D$ ... median diameter of the batch:
- before melting: median diameter of the pieces
- after melting: median diameter of the pool (crucible)
$K$ ... correction coefficient, $K = f\left(\frac{D}{\delta}\right)$

The $P_{el}$ value is increased with $I$, $n$, $\mu$, $D$, $f$. The increase of $\rho$ has more complex effect on the changes in $P_{el}$. 

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The influence of $\chi=D/\delta$ on the value of correction coefficient $K$

Influence of temperature on the change of the batch resistivity ($\rho$), its relative permeability ($\mu$), current penetration depth ($\delta$) and the real power exerted by the batch ($P_{el}$)
A steep decline of permeability values of the batch $\mu$ and therefore also the decline of $P_{el}$ is related to the loss of magnetic properties of steel at heating (750 °C - Curie point). Gradual increase of $P_{el}$ is related to the permanent rise of $\rho$ and $D$ caused by filling the crucible with the melt. The (chemical) composition of the batch also has influence on $\mu$ and $\rho$ and the character of its change with temperature.
The technology of steel production in induction furnaces

In their character, most melting technologies are close to reduction re-melting in EAF (the occurrence of oxidation processes is limited).

Metallic batch is composed based on the character of the steel produced by waste, either alloyed or non-alloyed, and ferroalloys. Steel waste is often in the form of the crucible (e.g. in form of bars).

Slags which are formed during the melting fulfill the "covering" function and limit the penetration of nitrogen, hydrogen and oxygen into the forming pool.

After the batch is heated, the de-oxidation and alloying elements are inserted for composition correction, homogenizing the pool, to check the temperature and tapping.

Linings of induction furnaces

- acid – suracid – based on quartzite and binders – boric acid – they are more stable in dimension – smaller degree of lining fracturing
- base – 70 % Al₂O₃, 30 % MgO, formed by spinels of MgO. Al₂O₃ (over 1550 °C) – formation of monolithic layer at first melting – burning using a graphite thorn or steel pipe
Advantages of induction furnaces

- metal is not carburized during the melting, therefore the highly alloyed waste with low amounts of carbon and low amounts of gasses can be re-melted
- accurate regulation of the pool temperature
- low burn of the alloying elements
- intense mixing of the pool - advantageous for removing inclusions, thermal and chemical homogeneity
- possibility to perform the melting in an inert atmosphere or in vacuum

Disadvantages of induction furnaces

- low slag temperature (it is heated and melted by the metal)
- related worse process of reactions between metal and slag
- with acid lining (suracid based on quartzite and boric acid), is cannot be desulfurized or dephosphorized (acid slag)
Vacuum induction furnaces (VIF)

VIF work usually with residual pressure of 1 to 0.1 Pa.

Construction of the furnace allows

- to de-vacuum the workspace,
- to intake of an inert gas,
- to dispense ferroalloys,
- to measure temperature and casting of the melt in vacuum conditions.

Based on the type, these furnaces have either hinged inductor and crucible or the whole workspace.

The lining of the crucible is formed by MgO, ZrO₂ or Al₂O₃. They are rammed, formation of monolithic layer is achieved at first meltings.

The disadvantage of MgO crucibles is that at low pressures, MgO can be reduced by carbon from the pool

$$\text{MgO}(s) + [\text{C}] \rightarrow \text{Mg}(g) + \text{CO}(g)$$

(52)

Mg then evaporates from the pool. The use of Al₂O₃ leads to an unwanted rise in Al levels in the pool due to reduction processes.

Metallurgic processes occurring in VIF

Long-term retention and good mixing of the pool within the conditions of deep vacuum allows to perform these actions during the production of steel in VIFs

- lowering the amount of oxygen using homogeneous carbon reaction,
- effective degasification,
- lowering the amount of unwanted accompanying elements (Cu, Pb, Sn) and alloying without excessive burning of alloying elements.

Decarbonization and deoxidation

Decarbonization occurs due to homogeneous carbon reaction, which balance is moved towards CO at lowered pressure. Decline under 1000 Pa has no significant influence on the course of the carbon reaction - there is no proportional decline in $p_{\text{CO}}$ within the bubble

Deoxidation of the pool only by carbon in the conditions of VIF does not lead to a sufficient decrease of the amount of oxygen. It is necessary to perform reactionary deoxidation using metallic deoxidation agents - most often Al.
Degasification of the pool

Degasification i.e. the change of hydrogen and nitrogen from metallic into the gaseous phase with the absence of slag is characterized by well-known relations:

\[ \frac{2}{H/} \rightarrow H_2(g) \]
\[ \frac{2}{N/} \rightarrow N_2(g) \]

The transfer of hydrogen does not cause problems and the amount of hydrogen of \(1 \text{ cm}^3/100 \text{ g}\) can be achieved. In case of nitrogen, the process occurs much more slowly. This is due to lower values of diffusion coefficients of nitrogen in steel and more pronounced decrease of its activity coefficient by the components of melted steel. The oxygen and sulfur in the solution are significant superficially active elements, which prevent adsorption of nitrogen and thus slow down the process of its transfer from the melt into the gaseous phase.

Vaporization of the pool components

Lowering the pressure in VIFs is used to effective removal of unwanted inclusions, especially Cu, Pb, Sn, Sb, Bi, As. One of the basic factors that influence the speed of vaporization is partial pressure of the pool component - \(p_x\) - over the metal solution

\[ p_x = p_x^o \cdot a_x = p_x^o \cdot N_x \cdot \gamma_x \]

\(p_x^o\) ... part. pressure of pure substance \(x\) vapors

\(N_x\) ... molar fraction of substance \(x\) in the solution

\(\gamma_x\) ... coefficient of activity of substance \(x\) in the solution

Order of elements based on \(p_x^o\): W, Mo, Zr, B, V, Ti, Co, Te, Ni, Si, Cr, Cu, Al, Sn, Mn, Pb, Sb, Bi, Cd, Mg, Zn, S, P.
Examples of VIF usage

In VIFs, special types of steel are made, such as creep resistant, transformer, etc. In creep resistant steel, oxide net is formed during melting in regular conditions on the grain edges - this decreases the plastic properties of steel.

In vacuum, the net is disrupted due to the vacuum and the temperature.

Transformer steel (Si up to 6%) can be melted in vacuum without significantly lowering their formability due to formation of oxide inclusions.

Properties of steels melted in VIFs:

- lower amounts of NV – high micro-purity
- lower amounts of oxygen

Electro Slag Remelting of steel

The theory of the ESR process (*Electro Slag Remelting – ESR*) was patented in 1930 in USA, its practical realization and extension was done in the 60s.

The basics of ESR:

- remelting of metal electrode in copper, water-cooled crystallizer
- the electrode is evaporated in drops in the slag pool, the drops pass through a layer of slag and gather in the crystallizer, where the metal gradually solidifies
- the ingot is characteristic for directed structure, its grains are oriented in parallel to the longitudinal axis of the ingot.
- slag is heated resistively by so called *Joule* heat which forms during the pass of electrical current between the consumable electrode and the main board, then the forming ingot.
Ways of wiring the ESR device
ESR Electrodes

The electrode is made from a material that is remelted:
- rolled, forged or cast (i.e. ingot)
- diameter is greater than 300 mm (uncommonly from 150 to 250 mm)

Crystallizer
- made mostly out of copper in double-shell design
- the shape of crystallizer is most commonly circular, there are also cubic or slab crystallizers, or crystallizers of special cross-sections including crystallizers for production of hollow ingots.
- construction-wise, the crystallizer is usually immovable.
- in a different construction solution, only a short crystallizer is used, in which the melted slag and upper section of the ingot is where solidification occurs. The entire crystallizer is lifted based on the height of the ingot. Crystallizer can be also immovable and in that case, the main board descends with the ingot.

The parameters of remelting (voltage, current, power, stability of slag, slag surface height and the electrode-ingot diameter ratio) must be in line so that a constant melting and growth of the ingot is achieved with the same grain structure throughout.

The depth of submersion of the end of electrodes is kept to the optimum by automatic voltage or current control. A constant course of melting can be approximately kept using a smooth measurement of the weight of the electrode or its length and keeping the power in check.

The biggest ESR device is in SaarStahl GmbH in Voelklingen. It is able to create an ingot 2.1 m in diameter, up to 5m in length and weighing 160 tons. The process is done by multiple changes of the electrode. The Inteco company has an ESR with the crystallizer 1000mm in diameter and creates ingots weighing 14 tons.
Slags used in ESR

Slags used in ESR have to meet certain requirements:

- stability at operating temperatures - low tension of the slag components vapors
- lower melting temperatures - at certain measure of overheating the slag, melting of the metal is ensured
- Optimal electrical resistance (conductivity) - too high electrical conductivity leads to high currents, in extreme cases the melting of the electrode might not occur. At low conductivity, it is necessary to raise voltage (to achieve required current), which can form an unwanted arc
- metallurgic suitability for occurrence of certain reactions - the slag has different composition for desulfurization and different one for dephosphorization
- low viscosity
- low surface voltage
- high inter-phase voltage between the slag and the metal
- ability to absorb non-metal inclusions
- low content of unwanted elements

For ESR of lower diameter (< 500mm) slag in solid form is used, for higher diameters of ingots it is pre-melted away from the ESR and then put into the device from the top. If slag is used in solid form, an exothermic mixture has to be placed below the electrode at the outset of the process, which ensures formation of liquid slag upon its ignition.
**Desulfurization of metal in ESR**

Desulfurization occurs on 3 interfaces

- in the layer of liquid metal on the electrode,
- on the surface of drops of metal falling through the slag (1700-1900 °C) - large reaction interface
- on the surface of the liquid part of the ingot.

During ESR, high level of desulfurization can be achieved - between 20-80 % in fact. The level of desulfurization depends on:

- the amount of sulfur in the material being remelted,
- its overall composition,
- composition of the slag,
- composition of the atmosphere over the slag,
- on the energy mode during remelting etc.

For ESR, the most frequently used slags are based on CaF₂ (e.g. 70 % CaF₂ – 30 % Al₂O₃, 80 % CaF₂ – 20 % CaO, 60 % CaF₂ – 20 % CaO – 20 % Al₂O₃). These slags have relatively low dividing coefficient of sulfur \( L_S = 4 \div 30 \), with the rising content of CaO the \( L_S \) increases. A negative effect of SiO₂ was proved on the achieved values of \( L_S \).

High speed of desulfurization is not only a function of \( L_S \), but also of the kinetics of the process. Highly liquid slag allows for more expanded course of diffusion processes. Similarly, intense oxidation of sulfur may occur from the slag by the gas phase into SO₂.

\[
[S] + (O^{2-}) \rightarrow (S^{2-}) + [O] \quad (56)
\]

\[
(S^{2-}) + \frac{3}{2} O_{2(g)} \rightarrow SO_{2(g)} + (O^{2-}) \quad (57)
\]

The slag composition is determined based on the required metallurgical function:

- desulfurization – based on CaO-CaF₂
- dephosphorization – based on CaF₂-FeO

**Lowering the amount of oxygen and oxide inclusions during ESR**

The change in the overall amount of oxygen and oxides in the remelted steel is the function of several concurrently occurring processes:

- a portion of the inclusions is expelled directly from the steel during the formation of the liquid layer of melted steel on the electrode
Electrometallurgy and Ferroalloys Production

- during the melting of steel, conditions are created which are ideal for re-solution of a significant portion of inclusions, which were formed by homogeneous exothermal reactions during solidification of steel
- during crystallization, a directed front of solidification is slowly formed and thus conditions of rising of inclusions are created.

**Behavior of gases during ESR**

During ESR, an increase in the amount of hydrogen may occur during the process. The cause is the reaction of atmospheric air (containing $\text{H}_2\text{O}$) with base components of the slag and the transition of hydrogen from slag into the metal pool.

Prevention against the increase of hydrogen in steel during ESR:

- lowering the amount of $\text{H}_2$ in the steel undergoing the ESP
- using slags with lower amount of $\text{CaO}$, $\text{MgO}$, ideally then of the $\text{CaF}_2$-$\text{Al}_2\text{O}_3$ type without physically bound water
- use of protective atmosphere over the slag (dried air)

As far as nitrogen is concerned, its amount can be lowered by 15-30 %. The assumption is the use of slags able to dissolve nitrogen. Dissociation of TiN nitrides also has to occur based on reaction

\[
\text{TiN}_\text{(S)} \rightarrow /\text{Ti/} + /\text{N/} \quad (58)
\]

and part of the nitrogen may transition into a slag of suitable composition.

**Properties of steel remelted using ESR**

- suppression or complete elimination of segregation processes of accompanying elements - small volume of liquid metal
- directed solidification (from the underlay towards the top) - individual grains of the structure are oriented parallel to the longitudinal ingot axis - highly homogeneous steel is created
- high micro-purity of steel - division of the remaining non-metal inclusions evenly through the cross-section of the ingot
- high isotropy of the properties of the produced steel

ESR is used for remelting of not only classical steels, but also highly alloyed steels, superalloys and non-ferrous metals. Steels are utilized in electrical engineering industry, aviation, in production of complex ball bearings, etc. i.e. where there are increased requirements on homogeneity and micro-purity of steel.
New processes of electro-slag remelting

PESR – Pressurized Electro-slag Remelting
Uses remelting in a hermetically enclosed chamber with high pressure of nitrogen, which alloys the melted steel. With regards to the low transition of nitrogen from gaseous into solid phase (short-term exposure), nitrogen is added into the traction zone in form of alloying elements. It is used to prepare special steels and alloys.

VacESR – Vacuum Electro-slag Remelting
It is used to produce steels and alloys that are especially pure (e.g. for aviation industry), it is characterized by low mounts of hydrogen and oxide inclusions.

The Inteco company (Internationale Technische Beratung – Austria) developed two modifications of ESR with the aim to approach the advantages of fluent casting of steel. The two processes are the following

- **ESRR – Electro Slag Rapid Remelting**
- **ESCC - Electro Slag Continuous Remelting**

The basis of the ESRR process is in using crystallizer of so-called T-shape. Its lower, narrower part corresponds to the required diameter of the resulting remelted ingot. The upper part of the crystallizer is expanded and its diameter is defined based on the maximum diameter of the ingots used for remelting. By remelting the ingots (electrodes) of greater diameter into ingots of smaller diameters, the speed of their production is increased. Usually, diameters 2-3 times larger than the diameter of the resulting ingots are chosen (MPT International 5/96, p.48).
Questions on the presented study material

1. The principle of heating in induction furnaces
2. Electrical devices of induction furnaces, regulation of power in induction furnaces
3. Penetration depth of the induced current into the slag, analysis of the individual factors
4. Technology of steel production in induction furnaces, advantages and disadvantages of IC
5. Production of steel in vacuum induction furnace (VIF), metallurgic processes in VIF, de-carbonization, deoxidation, degassification, vaporization of pool components, examples of VIF use
6. Electro-slag remelting of steel (ESR), an ESR schematic, ESR wiring, slags used in ESR, desulfurization of metal in ESR, the basis of lowering the amounts of oxygen and oxide inclusions in ESR
7. Behavior of dissolved gasses in ESR, properties of ESR remelted steel
8. New processes of ESR - PESR, VaCESR, ESRR, ESCC
Ferroalloys production

Ferroalloys are alloys of iron and other metals and non-metals, e.g. FeMn, FeCr, FeP.

Ferroalloys contain:
- basic element - Fe, Si (basis)
- main element - Mn, Cr, V (the main reason for its production)
- unwanted inclusions - the content is not limited, ferroalloys also contain various unwanted inclusions
- harmful inclusions - their content is limited into a few 1/1000 %

For example, in a carbon-less FeCr there is:
- Fe - the basic element
- Cr - the main element
- Si - unwanted inclusion
- C,P,S - harmful inclusion

Ferroalloys are used for alloying, deoxidation and for steel and alloy modification, which is essential not only in steel production but also in production of non-ferrous metals.

Why ferroalloys are used instead of pure metals?
- ferroalloys are cheaper than pure metals
- lower burn of main element is achieved with ferroalloys as opposed to pure metals
- in some ferroalloys, (such as FeSi, FeTi), the density is increased which has positive effect on the dissolving process and therefore also on the burn
- lower melting temperature in some ferroalloys compared to pure metals (such as FeV, FeW, FeMo)
- ferroalloys may have other better physical properties - such as lumpiness (more easily dissolved in steel)

Industrial production of ferroalloys - 1960s
- reduction melting in crucible furnaces
- then production in blast furnace (blast furnace FeSi, FeMn - spiegeleisen)
- electro-thermic method in EAF - electric arc furnace, reduction environment
- aluminothermic method
Division of ferroalloys:

- based on the number of alloying elements:
  - simple ferroalloys - only one main element
  - complex ferroalloys - contain more main elements (in SiCr or FeSiCr they are Si and Cr)
- based on the amount of the main element
  - low-percentage (FeSi 15, 18, FeMn 25)
  - high-percentage
- based on the method of use
  - deoxidizing
  - alloying
- based on the method of production
  - blast-furnace - non-decarbonized ferroalloys
  - electro-thermal - carbo-thermal method
  - metalo-thermal - carbon-less ferroalloys

Thermodynamics, kinetics and mechanisms of the processes involved in ferroalloys production

There is a significant number of technologies for production of ferroalloys of the same or similar composition. In terms of the metallurgical basis - or rather the physico-chemical basis, these processes used for ferroalloy production can be divided into the following groups:

1. Carbo-thermal processes (reduction by carbon)
2. Refinement processes (refinement of products of carbo-thermal processes)
3. Metalo-thermal processes - silico-thermics, alumino-thermics
4. Remelting processes (for achieving some complex alloys)
5. Electrolytic processes
6. Other (e.g. nitrations)

Carbo-thermal processes

The principle of carbo-thermal processes is the reduction of metal oxides by carbon while creating stand-alone metals of these oxides (an analogy of BF processes).

Reduction reaction is conditioned primarily by stability of oxides at high temperatures. Stability of oxides is determined by the change in free enthalpy during the formation of oxides from basic elements.
The more negative the $\Delta G$ is, the more stable the oxide is. The least stable ones are MoO$_3$ and WO$_3$, the most stable ones are CaO, MgO, Al$_2$O$_3$ and this is why they are the most difficult ones to reduce.

- with the increasing temperature, the stability of oxides decreases ($\Delta G$ is less negative)
- exception: C $\rightarrow$ CO, with the increasing temperature, the stability of CO increases as well (affinity of C towards O increases)

**practical consequence:**
- at higher temperatures, some oxides can be reduced by carbon
- by increasing the temperature, more stable oxides can be reduced
- CO is gaseous, it leaks from the reaction area - $p_{CO}$ (advantageous)
- lower oxide (such as TiO) is more stable than a higher oxide (TiO$_2$).

Theoretically then, every element that forms a more stable oxide can become reducing agent of a less stable oxide. For practical realization of this reaction, it is necessary that the difference in $\Delta G$ is great enough (n.10$^4$ J). If this difference is not sufficient then the reduction does not occur completely and the resulting alloy contains increased amounts of the reducing element.

Usually this element is comprised of more oxides. Lower oxides are more stable then higher oxides. In some cases, lower oxide can be irreducible even if it is reducible as a higher oxide.
Reduction of oxides by carbon is an endothermic reaction, which excludes the option of these reactions occurring without an external heat source (such as heat of the electric arc, etc.)

Reaction of some reductions (by carbon) represent a summary reaction of two partial reactions:

- indirect reduction of oxides by CO $\Delta H < 0$
- Boudoard reaction $\text{CO}_2 + \text{C} = 2\text{CO}$ $\Delta H > 0$ (171 880 cal.mol$^{-1}$)

Summary $\Delta H$ is always positive (endothermic reaction) as opposed to reduction by silicon or aluminum - both exothermic reactions!

for example:

\[
\begin{align*}
\text{MnO} + \text{CO} &= \text{Mn} + \text{CO}_2 \quad \text{endo or exo} \\
\text{CO}_2 + \text{C} &= 2\text{CO} \quad \text{endo} \\
\text{MnO} + \text{C} &= \text{Mn} + \text{CO} \quad \text{endo}
\end{align*}
\]

Diagram of $\Delta G$ change dependence on temperature during reduction of various oxides by carbon:

- reduction of $\text{MoO}_3$ by carbon will occur easily ($\Delta G$ is very negative)
- reduction of $\text{ZrO}_2$ by carbon will not occur ($\Delta G$ is positive)
- at higher temperatures, $\Delta G$ of metal creation is more negative, reactions will occur more fully - which means higher yield of metal

During reduction of oxides by carbon, not only pure metals are produced but also corresponding carbides of these metals (that's why the produced ferroalloys contain a certain amount of C). Carbides are formed because the $\Delta G$ of their formation is more negative than the $\Delta G$ of sole metal production (in reduction of
an metal oxide by carbon). The greater this difference is, the more difficult the production of a ferroalloy with low amount of carbon - the carbide is produced primarily, which predetermines the higher amount of carbon in the ferroalloy.

\[
\text{Cr}_2\text{O}_3 + C = \text{Cr} + CO \quad \Delta G = -126,000 \text{ J.mol}^{-1}
\]

\[
\text{Cr}_2\text{O}_3 + C = \text{Cr}_7\text{C}_3 + CO \quad \Delta G = -180,000 \text{ J.mol}^{-1}
\]

A low amount of carbon in the produced ferroalloy can be achieved only is the reaction occurs at high content of silicon in the ferroalloy. The change in free enthalpy of metal silicide formation (Me\text{\textsubscript{x}}Si\text{\textsubscript{y}} in general) is usually more negative than the change of free enthalpy of carbide formation. Silicon displaces carbon from the carbide bond (MeC) and silicides (MeSi) are formed, the surplus carbon is expelled from the metal in form of graphite (analogous to the raw iron - outflow of graphite, high content of Si in raw iron).

Reduction by carbon

\[
(\text{Me}_x\text{O}_y) + yC(s) \rightarrow x[\text{Me}] + y\text{CO(g)} \quad \text{metal} \quad \Delta H = +
\]

\[
(\text{Me}_x\text{O}_y) + (y+z)C(s) \rightarrow [\text{Me}_x\text{C}_z] + y\text{CO(g)} \quad \text{carbide} \quad \Delta H = +
\]

Reactions are endothermal and form gaseous product (CO), therefore they are accelerated by

- increased temperature (higher outflow of the reduced element, higher use of furnace lining, higher consumption of energy)
- decreased pressure

**Technological principles of carbo-thermal reduction**

Products of carbo-thermal reduction are solutions of the reduced Me component (basic element) in iron, the given solution also contains some amount of carbon. The ratio of its transition is given by the amount of silicon in the solution, which decreases the solubility of carbon (the more Si, the less C). It decreases it by primarily forming silicides with the basic element.

This if the melting is done only within a MeO-C-\text{\textsubscript{\textdegree}}Fe system, we obtain Fe-C-\text{\textsubscript{\textdegree}}Me solution as a product where Me and C make up - to a certain extent - the carbides dissolved in the resulting solution.

If we reduce Me\text{\textsubscript{x}}O\text{\textsubscript{y}} using the left C, but we also want to obtain a product with low amount of C, a precaution can to be done to increase Si in the product, such as concurrent reduction of MeO and SiO\text{\textsubscript{2}} into an Fe-Si-C-Me solution. With the increase of Si, C decreases. Another method is to reduce silicon into the already reduced Fe-Me-C system. Increase of Si in the solution leads to expulsion of carbon from the solution due to higher affinity of Si to Me, Fe (during formation of soluble silicides) than the affinity of C to Me, Fe. Therefore, this reaction occurs:

\[
[\text{Me}_x\text{C}_z] + n[\text{Si}] \rightarrow [\text{Me}_x\text{Si}_n] + z\ C(s)
\]

**Conclusion:**

Reduction by carbon results in us obtaining either
- carbonaceous Fe-Me-C solutions at relatively low amounts of Si,
- or low-carbon Fe-Me-Si solutions, with an increased content of silicon.

**Refinement processes of carbon reduction products**

The product of carbon reduction are solutions of Fe-Me-C↑-(Si↓), or Fe-Me-C↓-Si↑ type. These products can then be directly utilized (such as ↑C FeCr, ↓C FeSiCr), but more often serve for subsequent production of low-carbon or low-silicon ferroalloys by way of refinement processes.

The basic refinement processes are:
- de-carbonization using oxidation gasses
- de-siliconization using oxidation slag.

**Decarbonization of Fe-Me-C↑-Si↓ solution in a converter**

Is done using:
- gaseous oxygen
- mixture of O₂ + e.g. argon (analogous to AOD)
- gaseous oxide and using vacuum - analogy to the production of AK steels - lower burn of e.g. Cr during the oxidation of C (analogy to VOD)
- In solid state using oxides of MeₓOᵧ or SiO₂ type in the conditions of vacuum and increase temperatures following these reactions

\[
\begin{align*}
\gamma[C]_{\text{Fe-Mn-C}} + \text{Me}_x\text{O}_y & \rightarrow x[\text{Me}] + y\text{CO}_\text{(g)} \\
[C]_{\text{Fe-Mn-C}} + \text{SiO}_2 & \rightarrow \text{SiO}_2\text{(g)} + \text{CO}_\text{(g)}
\end{align*}
\]

**Desiliconization of Fe-Me-C↓-Si↑ solutions**

Is done using oxidation slag, such as periodic melting in hearth furnace. These are the occurring reactions (for the sake of simplicity, we consider MeO instead of MeₓOᵧ):

\[
\begin{align*}
[\text{Si}]_{\text{Fe-Me-Si↑-C↓}} + 2(\text{MeO}) & \rightarrow (\text{SiO}_2) + 2[\text{Me}] \\
(\text{SiO}_2) + 2(\text{CaO}) & \rightarrow 2\text{CaO.SiO}_2
\end{align*}
\]

the CaO binds SiO₂; CaO influences \(\gamma_{\text{MeO}}\) and \(\gamma_{\text{SiO}_2}\), which means a decrease in SiO₂.

Conditions demanded for the refining MeO:
- low affinity of Me to O - the higher the affinity, the more difficult the release of [O] meant for oxidation is
- low loss of \(\Delta H\)
- FeO - suitable - dilutes the ferroalloy
- MnO - suitable - main alloying element (such as MnO)
- (MeO)\(^-\) - only when we require Me\(^+\) in the alloy
Metalo-thermic processes

The principle of metalo-thermic processes is the reduction of oxides using metals with high oxygen affinity (such as Al, Si, Si alloys and others). This reduction releases high amounts of heat:

- without external influx of energy, very high temperatures are achieved
- products of the reduction (with high melting temperature) are formed in liquid state, thus the reduced metal is separated in form of drops. The reducing agent (metal) oxidizes into a corresponding oxide and almost fully moves into the slag.

The most common element for reduction is Al or Si - we then designate these processes aluminothermy or silicothermy. Reduction of MeO using Al is characterized by a more negative ΔH (the reaction is highly exothermic) than the Si reduction. Therefore, heating is essential during reduction by Si. (another reason for heating: formation of silicides - higher temperature is necessary for their dissolution).

Aluminothermy has the advantage of lower C content in the resulting ferroalloy (C is between 0.05-0.1 %). Products include: low-carbon FeW, FeMo, FeCr, FeMn, FeV, FeTi, FeNb, FeTa and ferroalloys TiAl, CrAl.

The initial material for aluminothermy requires refinement in terms of damaging inclusions (especially S, As, Sn, Pb, P < 0.05-0.1 %), because the slag that forms has relatively low refining effect.

The basics of metallurgy of metalo-thermic processes

Basic equation:

\[ \text{Me}_x\text{O}_y + z[R] \rightarrow x[\text{Me}] + R_z\text{O}_q \]

for example for reduction of TiO₂ using Al:

\[ (\text{TiO}_2) + 4/3[\text{Al}] \rightarrow [\text{Ti}] + 2/3(\text{Al}_2\text{O}_3) \quad \Delta H=-(\text{strongly exothermic}) \]

High temperature moves the balance of the metalo-thermic reaction to the left. During the design of reaction systems (what to reduce with, the melting agent, slag...) we consider:

- TD aspects: spontaneity of the considered reaction at various temperatures
- residual levels of reduction agents in the alloy (influence on quality)
- thermal dynamics - sufficiency for complete thermal balance (heat for melting, heat loss)
- TD and kinetic aspects: - influence of slag-forming melting agents
- economic aspects: - the price of reduction agents, yield from the concentrate, etc.

Thermodynamic aspects

For simplification, the reaction is presented by the example of TiO₂ reduction using Al.
The residual amount of TiO$_2$ in the slag (a criterion of yield from the reaction in case of balance) is determined by this relation:

$$X_{TiO_2} = \frac{1}{K_{Ti-Al}} \cdot \frac{[Ti]}{[Al]} \cdot \frac{f_{Ti} \cdot X_{Al_2O_3}}{f_{Al} \cdot X_{TiO_2}} \cdot \frac{\gamma_{Al_2O_3}}{\gamma_{TiO_2}}$$

The amount of TiO$_2$ in the slag will decrease with:

- lower temperature: exothermic reaction ($\uparrow t$, $\downarrow k$, $\uparrow X_{TiO_2}$)
- higher $f_{Al}$: presence of elements that increase Al activity
- lower $f_{Ti}$: presence of elements that decrease Ti activity
- lower $X_{Al_2O_3}$: addition of neutral MgO
- influence of basicity of the slag

**Thermal balance**

Thermal dynamics and the absolute value of $\Delta H$ are determining factors of thermal balance of a metalothermic reaction. It is also necessary to consider:

- $\Delta H$ of the formation of silicides or aluminates in metal
- $\Delta H$ of formation of silicates or aluminates in the slag
- $\Delta Q$ necessary for heating and melting of the initial substances and the products in $T$ of the reaction
Electrometallurgy and Ferroalloys Production

- ΔQ of thermal loss
- ΔH of the accompanying exoreactions, Q in heating (eventually), pre-heating of the batch

For example the reaction

\[(\text{Fe}_2\text{O}_3) + 2[\text{Al}] \rightarrow (\text{Al}_2\text{O}_3) + 2[\text{Fe}] \quad \Delta H^{0}_{298} = -854 \text{ kJ/mol} \]

- is strongly exothermic and ensures formation of products (Fe and Al\text{2O}_3) in liquid state.

However in the reaction:

\[3(\text{MnO}) + 2[\text{Al}] \rightarrow (\text{Al}_2\text{O}_3) + 3[\text{Mn}] \quad \Delta H^{0}_{298} = -519 \text{ kJ/mol} \]

- sufficient temperature is not present for melting of the aluminate slag. If we exchange MnO for Mn\text{3O}_4, the \(\Delta H^{0}_{298} = -2535\text{kJ/mol}\) and the thermal effect will be sufficient.

**Conclusion:**

- Enthalpy of the acquired slag, metal and thermal loss are approximately the same for the individual metals (assumption).
- A rule has been established:

  Aluminothermic process after ignition occurs *spontaneously* if the amount of developing heat corresponding to 1 g of the batch (this includes slag-forming additives) is greater than approx. 2300-2700 J.

  Sometimes this value is compared (not entirely correctly) to the specific *thermal effect* of an aluminothermic reaction

\[q = \frac{\Delta H^{0}_{298}}{n_{\text{MeO}} \cdot M_{\text{MeO}} + n_{\text{Al}} \cdot M_{\text{Al}}} \text{ cal/g of the batch (MeO+Al)}\]

The value of q does not consider the mass of the slag-forming additives and is valid for 298 K. However it is a suitable rule for judging (and comparing) the course. The values of q are tabulated.

The following is evident from these values:

- most metals for alloying steel can be acquired by Al reduction from their higher oxides
- when using Si, reduction is only possible for Mn, Mo, Cr (others only with provision of external heat)

Under „spontaneity“, we consider not only the condition of negative ΔG, but also

- sharp division of metal and slag
- optimal amount of Al and Si additives, so that liquid slag is obtained: MeO-Al\text{2O}_3, MeO-SiO_2 or MeO-SiO_2-Al\text{2O}_3
- amount of additives should not be lower than 200 kg (so that the heat loss is not too great)
Electrometallurgy and Ferroalloys Production

- particle size of MeO, Al, Si should not be greater than 0.3 mm
- purity of Al; content of [O] in it is not greater than 0.0500 %

Another way for increasing yield (and often also the option for performing aluminothermic reduction in terms of thermal balance) is utilizing collateral exothermic reactions. For this purpose, MeO oxides with low $\Delta H^0$ (of MeO formation) are suitable. In other words - with low affinity to oxygen such as FeO, Fe$_3$O$_4$, Fe$_2$O$_3$. Iron reduced from FeO or from Fe$_2$O$_3$, Fe$_3$O$_4$ acts favorably in the forming alloy on the yield with its diluting effect.

Options of the collateral exo reactions:
- use of higher Me oxide instead of or with the MnO (e.g. MnO$_2$+MnO, CrO$_3$+Cr$_2$O$_3$ etc.)
- use of Me salts that contain oxygen (e.g. KMnO$_4$); use of potassium salts (KClO$_3$)
- use of higher oxide, which reduces only to a lower one and does not enter the metal alloy, in form of a metal (e.g. CaO$_2$ -> CaO... , BaO$_2$ -> BaO+ ...)

The course of collateral reaction requires increase in consumption of Al or Si. The overall amount of slag is also increased.

*Additional heat* in reactions with insufficient $\Delta H$, can be acquired also by preheating the components before igniting the mixture.

The melting temperature of Al$_2$O$_3$ slag from aluminothermic reduction can be lowered by increasing the content of MeO, FeO, ZrO$_2$, TiO$_2$.

**Kinetics and mechanisms of metalothermic reactions**

These conditions should be ensured:

1. Low residual value of $X_{MeO}$ (maximum reduction of MeO)
   - thermodynamically:
     - high $\gamma_{MeO}$
     - low $\gamma_{RZOy}$
     - low temperature
   - kinetically: strong approximation of the system to the state of equilibrium, i.e. strong liquification of the forming slag containing primarily R$_2$O$_y$.

2. Sufficient reaction speed

3. Sufficiently fast removal of granules from the slag layer (before it solidifies)

   Note: This is an exothermic reaction, high temperature is necessary for points 2 and 3, but not suitable for point 1.

*Use of additives* lowering the temperature of melting slags is limited - high consumption of heat to melt them. It is possible to acquire it as a product of the collateral reactions.

The speed of the aluminothermic reaction must be controlled and directed (discharges, health hazards). Suitable grain dimensions must be used - bigger
chunks slow the process, slag and metal must be liquid for a longer period so that the reaction can finish. In first moments of the reduction, Me is depleded around Al and an Al-Me drops form, which moves downwards through the slag layer and is further refined from Al.

- Reaction temperatures - 2200-2400 °C
- In FeW production - 2500 °C

**Re-melting processes**

**Aim:**
To achieve a complex alloy

Multi-component alloys - remelting in an IF or VIF or EAF from pure components or alloys.

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**Questions on the presented study material**

1. Division of ferroalloys, basic element, main element, unwanted inclusion, harmful inclusion
2. Advantage of using ferroalloys instead of pure metal
3. Thermodynamics of carbothermic processes
4. Technological principles of carbothermic reduction
5. Refinement processes of carbon reduction products
6. Basics of metalurgy for metalothermic processes of ferroalloy productions
7. Thermal balance of metalothermic processes
8. Kinetics and mechanisms of metalothermic reactions
9. Characteristics of remelting processes
APPENDIX TO THE THEMATIC BLOCK 1

Courses of alternating voltage and current in circuits with ohmic, inductive and capacitive resistance

The circuit of alternating current with ohmic resistance $R$
phase shift between the current and voltage is null

Circuit of alternating current with inductivity $L$
- due to self-induction in coil, the current is delayed after voltage by $\varphi = \frac{\pi}{2} 90^0$

Circuit of alternating current with capacity $C$
- voltage is delayed after current by $\varphi = \frac{\pi}{2} 90^0$
Courses of alternating voltage and current in circuits with a combination of ohmic, inductive and capacitive resistance

The circuit of alternating current with $R$, $L$, $C$ series connection

\[ Z = \sqrt{R^2 + \left( \omega \cdot L - \frac{1}{\omega \cdot C} \right)^2} \]

$Z$ – impedance, apparent resistance

$X = X_L - X_C$ – reactance; \[ \text{tg} \phi = \frac{X_L - X_C}{R} \]

If $X_L = X_C$ then $Z=R$ which are conditions for creation of serial resonance of the circuit. In serial resonance, the circuit acts as if only a resistor was connected, i.e. the current is in phase with voltage. Resonance may occur at constant frequency if we change $L$ and $C$ or at constant $L$, $C$ if we change the $f_{rez}$ frequency. This frequency is then called resonance frequency

\[ f_{rez} = \frac{1}{2 \pi \sqrt{L \cdot C}} \]

Circuit of alternating current with $C$ and $L$ connected in parallel

\[ Z = \frac{1}{\omega \cdot C - \frac{1}{\omega \cdot L}} \]

If $X_L = X_C$ then parallel resonance occurs. Electrical field of the condenser is changed into a magnetic field of inductance and vice-versa.

$\omega$ - angular speed

$\omega = 2 \cdot \pi \cdot f = 6,28 \cdot 50 = 314 \text{ s}^{-1}$ (for 50 Hz)
Alternating current power

Apparent power: \[ P_{\text{apparent}} = U \cdot I \] [VA]
Real power: \[ P_{\text{real}} = U \cdot I \cdot \cos \varphi \] [W]
Reactive power: \[ P_{\text{reactive}} = U \cdot I \cdot \sin \varphi \] [Var]

where \( \varphi \) is the phase shift between voltage and current \( \varphi_{\text{teor.}} \) \( < -90; 90 > \) and \( \cos \varphi \) is the power factor.

Three-phase current

![Three-phase current diagram]

Basic connection of three-phase appliances

Star connection

\[ U_p = U_{L1-N} = U_{L2-N} = U_{L3-N} = 230 \text{ V} \]
\[ U_{\text{ptp}} = U_{L1-L2} = U_{L1-L2} = U_{L1-L2} = 400 \text{ V} \]
\[ U_{\text{ptp}} = \sqrt{3} \cdot U_p \]
\[ I_{\text{ptp}} = \sqrt{3} \cdot I_p \]
\[ P_{\text{real}} = 3 \cdot U_p \cdot I_p \cdot \cos \varphi \]

Delta connection

\[ P_{\text{real}} = 3 \cdot U_{\text{ptp}} \cdot I_{\text{ptp}} \cdot \cos \varphi \]
\[ P_{\text{real}} = 3 \cdot \sqrt{3} \cdot U_p \cdot I_p \cdot \cos \varphi \]

Power increases at switching \( Y - \Delta \)
\( \sqrt{3} \) times = 1,73-times