MATERIAL BALANCE MODEL FOR STEEL PRODUCTION IN ELECTRIC ARC FURNACE - MELTING PERIOD

Petar B. Petrov

University of Chemical Technology and Metallurgy
Department of Metallurgical Technologies, Electrical Engineering and Electronics
8 Kliment Ohridski blvd., 1756 Sofia, Bulgaria
E-mail: pbpetrov@uctm.edu

ABSTRACT

The material balance modeling during the melting period is considered in the development, as an initial period in obtaining a type of tool steel, such as bearing steel. The method used for the production of bearing steel is electric arc, with the possibility to be realized in an electric arc furnace. Based on the real chemical composition of the charge materials presented in the introduction, a model for calculation of the charge was created, consistent with the technological conduct of the process. The presented values in the experimental part and the results as well as the analysis are based on the modeling of the process made in the development during the melting period.

Keywords: electric arc process, melting period, material balance model, steel production.

INTRODUCTION

The main requirement for bearing steel is the low content of non-metallic inclusions. In order to obtain steel with a low content of oxide inclusions, it is necessary to use a charge with a low silicon content, increased manganese content (most often by using ferromanganese as part of the charge) during the melting period and to import limestone during melting [1].

After melting, oxidation and reduction periods, in order to meet the relevant standards for bearing steel, the metal must have a chemical composition in the following ranges: C - 0.95 % - 1.11 %; Si - 0.15 % - 0.35 %; Mn - 0.20 % - 0.40 %; Cr - 1.30 % - 1.65 %; S - ≤ 0.02 %; P - 0.027 % [1].

The chemical composition of charge and slag-forming materials is shown in Table 1 and Table 2, respectively.

The calculations in development are based on 100 kg of charge. Where necessary, acceptances made by metallurgical practice have been made [1 - 3]. The electrode waste is calculated so that the total carbon content reaches 1.20 %. It is assumed that the absorption of electrode waste is 60 % (% E.W. assimilation) and 40 % (% E.W. burn) of it is burned [4]. The ferromanganese is calculated so that its total content in the charge reaches about 0.70 %. All calculations made in the development are consistent with the technology of the main electrical steelmaking process [2 - 6].

Data on the weight amount of the elements imported from the charge components are presented in Table 3.

EXPERIMENTAL

Formation of metal and slag during the melting period [1]

The elements imported from the charge materials are partially oxidized during the melting period and pass into the slag. It is assumed that the elements are oxidized as follows: C - it is assumed that the oxidation of carbon is compensated by carbon from the electrodes and electrode waste; Fe - from 1 % to 3 % (average 2 %); Si - from 60 % to 80 % (average 70 %); Mn - from 40 % to 60 % (average 50 %); S - it is assumed that during this period sulfur is not oxidized; P - from 10 % to 30 % (average 20 %). It is assumed that from 2 % (or

Table 1. Chemical composition of charge materials, %.

Charge component	C	Si	Mn	Cr	Al	P	S	ash	Fe
Carbon steel - large	0.60	0.30	0.30	-	-	0.04	0.02	-	to 100
Carbon steel - medium and small	0.20	0.30	0.30	-	-	0.04	0.02	-	to 100
FeMn	6.00	2.00	80.0	-	-	0.30	0.03	-	to 100
Electrode waste and electrodes	99.00	-	-	-	-	-	-	1.00	-
FeSi	0.12	72.0	0.40	-	2.50	0.04	0.03	-	to 100
FeCr	4.00	2.00	0.40	70.00	-	0.05	0.03	-	to 100
Al	-	-	-	-	98,00	-	-	-	2.00
SiMn	1.0	18.0	67.0	-	-	0.08	0.05	-	to 100

Note: Some of the presented charge materials are technologically added after the melting period considered in the development

Table 2. Chemical composition of slag-forming materials, %.

Slag-forming component	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	CaF_2	P_2O_5	CO_2	H_2O	S
Baked lime	92.00	3.30	2.50	1.00	0.60	-	0.10	0.20	0.20	0.10
Iron Ore	0.10	0.30	6.25	2.50	90.00	-	0.15	-	0.70	-
Fluxspat	0.40	-	3.10	0.20	0.80	95.00	-	0.30	-	0.20
Sand	-	-	97.00	1.00	2.00	-	-	-	-	-
Dinas	0.60	-	97.00	0.75	1.30	-	0.75	-	-	-
Magnesite	3.50	90.25	3.45	0.80	2.00	-	-	-	-	-
Ash - electrodes and elect. wastes	11.80	-	56.50	31.70	-	-	-	-	-	-

Note: Some of the presented slag-forming materials are technologically added after the melting period considered in the development.

Table 3. Quantity of the elements of the charge components, kg.

Name	Total weight	C	Si	Mn	P	S	Fe
Carbon steel - large	49.10	0.295	0.147	0.147	0.020	0.010	48.481
Carbon steel – medium and small	49.10	0.098	0.147	0.147	0.020	0.020	48.668
FeMn	0.49	0.029	0.010	0.392	0.001	0.00015	0.058
Electrode wastes	1.31	0.778	-	-	-	-	-
Total weight of the elements	100.00	1.200	0.304	0.686	0.041	0.030	97.207

2 kg) of iron oxidation, 12 % of it is oxidized to FeO, 3 % is oxidized to Fe_2O_3 and 85 % is evaporated (fallow) in the arc area.

Thus, the amount of the corresponding element in the slag from the charge materials ($m_R^{r.m.-slag}$) is calculated according to the following formula:

$$m_R^{r.m.-slag} = m_{R-total}^{r.m.} \frac{\%R^{oxidation}}{100} \quad , kg \quad (1)$$

where: $m_{R-total}^{r.m.}$ - total weight of the element of the charge component, kg;

$\% R^{oxidation}$ - percentage of oxidation of the element from the charge component, %.

The quantities of oxides of the elements of the charge materials passing into the slag ($m_{RxOy}^{r.m.-slag}$) are calculated by:

$$m_{RxOy}^{r.m.-slag} = m_R^{r.m.-slag} \frac{M_{RxOy}}{M_{Rx}^{RxOy}} \quad , kg \quad (2)$$

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where: M_{RxOy} - molecular mass of the corresponding oxide;

M is the molecular or atomic mass of the element Rx of the corresponding oxide.

After calculation, the transferred amounts of oxides from the charge components in the slag are shown in Table 5.

The quantities of non-oxidized elements of the charge materials ($m_R^{r.m.-metal}$) passed into the metal from the rest are calculated according to:

$$m_R^{r.m.-metal} = m_{R-total}^{r.m.} - m_R^{r.m.-slag}, \text{ kg.} \quad (3)$$

Thus, the metal content is calculated and presented in Table 4.

During melting, lime is applied in an amount of 1 % to 3 % of the weight of the charge (for the present calculation, 3 % (or 3 kg - ($m_{melt.}^{lime-slag}$) is assumed). The lime components introduce oxides ($m_{RxOy}^{lime-slag}$) into the slag according to the formula:

$$m_{RxOy}^{lime-slag} = m_{melt}^{lime-slag} \frac{\%RxOy^{lime}}{100}, \text{ kg} \quad (4)$$

where: $\%RxOy^{lime}$ - percentage of participation of the respective oxide in lime, %.

After calculation, the transferred amounts of oxides of lime in the slag are shown in Table 5.

During the melting, parts of the dinas vault of the furnace are broken off and enter the slag. It is assumed that a total of 12 kg or 1.2 kg per 100 kg of charge enters 1 ton of steel from the arch. This quantity is distributed as follows: in the melting period - $m_{melt.}^{dinas-slag} = 0.6$ kg; in the oxidation period - $m_{oxid.}^{dinas-slag} = 0.2$ kg; in the reduction period - $m_{red.}^{dinas-slag} = 0.4$ kg. The amount of oxides from the vault passing into the slag ($m_{RxOy}^{dinas-slag}$) during the melting period is calculated by:

$$m_{RxOy}^{dinas-slag} = m_{melt}^{dinas-slag} \frac{\%RxOy^{dinas}}{100}, \text{ kg} \quad (5)$$

where: $\%RxOy^{dinas}$ - percentage of participation of the respective oxide in the dinas vault, %.

After calculation, the transferred amounts of oxides from the dinas vault in the slag are shown in Table 5.

During the melting, parts of the magnesite walls and the floor of the furnace are broken off and enter the slag. It is assumed that, on 1 ton of steel, from the walls and floor receives a total of 25 kg or 2.5 kg per 100 kg of charge. This quantity is distributed as follows: during the

Table 4. Content of elements in the liquid metal.

elements	kg	%
C	1.200	1.237
Fe	95.263	98.250
Si	0.091	0.094
Mn	0.343	0.354
S	0.030	0.031
P	0.033	0.034
total	96.960	100.00

melting period - $m_{melt.}^{magnesite-slag} = 1.0$ kg; in the oxidation period - $m_{oxid.}^{magnesite-slag} = 1.0$ kg; in the reduction period - $m_{red.}^{magnesite-slag} = 0.5$ kg. The amount of oxides from the walls and floor passing into the slag ($m_{RxOy}^{magnesite-slag}$) during the melting period is calculated by:

$$m_{RxOy}^{magnesite-slag} =$$
$$= m_{melt}^{magnesite-slag} \frac{\%RxOy^{magnesite}}{100}, \text{ kg} \quad (6)$$

where: $\%RxOy^{magnesite}$ - percentage of participation of the corresponding oxide in the walls and floor, %.

After calculation, the quantities of oxides passed from the walls and the floor in the slag are shown in Table 5.

During the melting, the ash from the electrode waste enters into the slag. According to Table 3, the amount of electrode waste is $m_{melt.}^{electrodewaste} = 1.31$ kg. Then, the amount of ash from the electrode waste passing into the slag ($m_{electrodewaste}^{ash-slag}$), according to Table 1, will be:

$$m_{electrodewaste}^{ash-slag} =$$
$$= m_{melt}^{electrodewaste} \frac{\%electrodewaste^{ash}}{100}, \text{ kg} \quad (7)$$

where: $\%electrodewaste^{ash}$ - percentage of ash participation in electrode waste, %.

After calculation, the amount of ash from the electrode waste going to the slag is $m_{electrodewaste}^{ash-slag} = 0.013$ kg.

The amounts of oxides from the ash of the electrode waste passing into the slag ($m_{RxOy(electrodewaste)}^{ash-slag}$) during the melting period are calculated by:

$$m_{RxOy(electrodewaste)}^{ash-slag} =$$
$$= m_{electrodewaste}^{ash-slag} \frac{\%RxOy(electrodewaste)^{ash}}{100}, \text{kg} \quad (8)$$

where: $\%RxOy(electrodewaste)^{ash}$ - percentage of

participation of the respective oxide in the ash from the electrode waste, %.

After calculation, the transferred quantities of oxides from the ash from the electrode waste in the slag are shown in Table 5, together with the quantities of ash oxides passed from the electrodes in the slag.

During the arc process, it is assumed that the electrodes are consumed in the amount of $m_{EAP}^{electrodes} =$ 7 kg/t of steel or 0.7 kg/100 kg of charge. By periods this cost represents: $m_{melt.}^{electrodes} = 0.42$ kg/100 kg charge; $m_{oxid.}^{electrodes} = 0.14$ kg/100 kg charge; $m_{red.}^{electrodes} = 0.14$ kg/100 kg charge.

During melting, as in other periods, the ash from the electrodes enters the slag. The quantity of electrodes is $m_{melt.}^{electrodes} = 0.42$ kg/100 kg charge. Then, the amount of ash from the electrodes passing into the slag ($m_{electrodes}^{ash-slag}$), according to Table 1, will be:

$$m_{electrodes}^{ash-slag} = m_{melt}^{electrodes} \frac{\%electrodes^{ash}}{100} \text{, kg}$$

(9)

where: $\%electrodes^{ash}$ - percentage of ash participation in the electrodes, %.

After calculation, the amount of ash from the electrodes going to the slag is $m_{electrodes}^{ash-slag} = 0.004$ kg.

The amounts of oxides from the ash of the electrodes passing into the slag ($m_{RxOy(electrodes)}^{ash-slag}$) during the melting period are calculated by:

$$m_{RxOy(electrodes)}^{ash-slag} =$$
$$= m_{electrodes}^{ash-slag} \frac{\%RxOy(electrodes)^{ash}}{100} \text{, kg}$$

(10)

where: $\%RxOy(electrodes)^{ash}$ - percentage of participation of respectively oxide in the ash from the electrodes, %.

After calculation, the transferred amounts of ash oxides from the electrodes in the slag are shown in Table 5, together with the quantities of oxides from the ash from the electrode waste in the slag.
The composition and amount of slag from the melting period is shown in Table 5.

During melting, FeO formed during the oxidation of iron from charge components passes into the slag, but part of it is returned and dissolved in the metal ([% FeO]). This part is determined by the formula:

$$[\% \text{ C}] \cdot [\% \text{ FeO}] = 0.0124 - k \cdot [\% \text{ C}], \% \quad (11)$$

from which it follows that: $[\% \text{ FeO}] = 0.0124 + \dfrac{k. [\%C]}{[\%C]}$, where: [% C] - percentage of carbon content in the metal bath during melting, according to Table 4 - is accepted for 1.24 %; k - coefficient of FeO content in the slag during melting, according to Table 5 - 0.05 is taken. Thus, [% FeO] = 0.060 %.

Formation of gas phase [1]

a) As mentioned, the electrodes during the melting period are consumed in the amount of: $m_{melt.}^{electrodes}$, kg.

b) In addition, part of the electrode waste is burned in the amount of:

$$m_{electrodewaste}^{burn} = m_{melt.}^{electrodewaste} \frac{\%E. W.^{burn}}{100} \text{,}$$
kg

(12)

It is assumed that the carbon from the electrodes and the electrode waste is oxidized by air oxygen in the ratio: 70 % to CO ($\%E.W.-C{\rightarrow}CO^{burn}$) and 30 % to CO_2 ($\%E.W.-C{\rightarrow}CO_2^{burn}$).

Thus, with the formation of CO burns carbon in an

Table 5. Structure of slag in the melting period.

Sources	CaO	MgO	SiO_2	Al_2O_3	FeO	Fe_2O_3	MnO	P_2O_5	total
Metal	-	-	0.456	-	0.299	0.083	0.444	0.018	1.302
Lime	2.760	0.099	0.075	0.030	-	0.018	-	0.003	2.985
Vault	0.004	-	0.582	0.005	-	0.008	-	0.005	0.600
Floor and walls	0.035	0.903	0.035	0.008	-	0.020	-	-	1.000
Ash - electrodes and electr. waste	0.002	-	0.007	0.005	-	-	-	-	0.017
Total, kg	2.801	1.002	1.155	0.048	0.299	0.229	0.444	0.026	5.904
Total, %	47.47	16.97	19.53	0.81	5.07	2.19	7.52	0.44	100.00

Note: After a melting period, 70 % of the slag with a calculated mass of 5.904 kg ($m_{melt.}^{slag}$) is removed

amount:

$$m_{e.+e.w.}^{C \to CO} = m_{melt.}^{electrodes} +$$

$$+ m_{electrodewaste}^{burn} \frac{\%E.\,W. - C \to CO^{burn}.\,\%C_{e.+e.w.}}{100}$$

, kg   (13)

where: $\%C_{e.+e.w.}$ - percentage of carbon in electrodes and electrode waste, %.

The amount of carbon monoxide formed is:

$$m_{e.+e.w.}^{CO} = m_{e.+e.w.}^{C \to CO} \frac{M_{CO}}{A_C}$$, kg.   (14)

Respectively, with the formation of CO_2 burns carbon in the amount of:

$$m_{e.+e.w.}^{C \to CO_2} = m_{melt.}^{electrodes} +$$

$$+ m_{electrodewaste}^{burn} \frac{\%E.\,W. - C \to CO_2^{burn}.\,\%C_{e.+e.w.}}{100}$$

,kg   (15)

The amount of carbon dioxide formed is:

$$m_{e.+e.w.}^{CO_2} = m_{e.+e.w.}^{C \to CO_2} \frac{M_{CO_2}}{A_C}$$, kg   (16)

where: M_{CO_2} - molecular mass of carbon dioxide.

For the formation of CO and CO_2 oxygen from the air is needed in the amount of:

$$m_{e.+e.w.}^{O_2 \to CO,CO_2} = \left(m_{e.+e.w.}^{CO} - m_{e.+e.w.}^{C \to CO} \right) +$$

$$+ \left(m_{e.+e.w.}^{CO_2} - m_{e.+e.w.}^{C \to CO_2} \right)$$,kg   (17)

The volume of oxygen from the air required for the formation of CO and CO_2

$$V_{e.+e.w.}^{O_2 \to CO,CO_2} = \{ \left(m_{e.+e.w.}^{CO} - m_{e.+e.w.}^{C \to CO} \right) +$$

$$+ \left(m_{e.+e.w.}^{CO_2} - m_{e.+e.w.}^{C \to CO_2} \right) \} \frac{1mol}{M_{O_2}}$$, m³   (18)

where: 1mol - one mole of oxygen gas - 22.4; M_{O_2} - molecular mass of oxygen.

Nitrogen is a part of the composition of the air. Its quantity is:

$$m_{e.+e.w.}^{N_2} = \{ \left(m_{e.+e.w.}^{CO} - m_{e.+e.w.}^{C \to CO} \right) +$$

$$+ \left(m_{e.+e.w.}^{CO_2} - m_{e.+e.w.}^{C \to CO_2} \right) \} \frac{77}{23}$$, kg   (19)

where: 77/23 - weight ratio $N_2:O_2$ in the air.

The volume of nitrogen from the air is:

$$V_{e.+e.w.}^{N_2} = V_{e.+e.w.}^{O_2 \to CO,CO_2} \frac{79}{21}$$, m³   (20)

where: 79/21 - volume ratio $N_2:O_2$ in the air.

Thus the volume of air is:

$$V_{e.+e.w.}^{air} = V_{e.+e.w.}^{O_2 \to CO,CO_2} + V_{e.+e.w.}^{N_2}$$,m³   (21)

The mass of the air is:

$$m_{e.+e.w.}^{air} = m_{e.+e.w.}^{O_2 \to CO,CO_2} + m_{e.+e.w.}^{N_2}$$,kg.   (22)

c) When heated, lime dissociates, releasing carbon dioxide and water. The amount of CO_2 emitted is:

$$m_{lime-melt.}^{CO_2-gas} = m_{melt.}^{lime-slag} \frac{\%CO_2^{lime}}{100}$$,kg   (23)

where: $\%CO_2^{lime}$ - percentage of CO_2 participation in lime.

Moisture is also released from the lime, the amount of which is calculated analogously to (23):

$$m_{lime}^{H_2O-gas} = m_{melt.}^{lime-slag} \frac{\%H_2O^{lime}}{100}$$, kg   (24)

where: $\%H_2O^{lime}$ - percentage of H_2O participation in lime.

d) To calculate the humidity introduced with the air, it is assumed that the temperature of the air (t_{air}) is 20°C, its pressure (p_{air}) is 760 mm Hg (mercury column), and its relative humidity (h_{air}) is 70 %. With the help of specialized guides it is found that the pressure of water vapor in the air (p_{air}^{H2O}) at t_{air} and h_{air} is 12.25 mm Hg. Then the volume of moist atmospheric air ($V_{air-melt.}$) will be calculated by the formula:

$$V_{air-melt.} = V_{e.+w.}^{air} \frac{\frac{273 + t_{air}}{p_{air}}}{p_{air} - p_{air}^{H_2O}}$$, m³   (25)

where: 273 - 273 K.

Considering that the temperature of moisture dew - t , for p_{air}^{H2O}, is about 14 °C, from specialized reference books it is found that the mass of water vapor ($m_{air-1m3}^{H2O}$) in 1 m³ of air is 0.012 kg.

Then, the air brings with it moisture ($m_{air-melt.}^{H2O-gas}$), the amount of which is:

$$m_{air-melt.}^{H_2O-gas} = m_{air-1m^3}^{H_2O}.\,V_{air-melt.}$$, kg   (26)

According to (24) and (26) the total amount of moisture ($m_{melt.}^{H2O}$) is:

$$m_{melt.}^{H_2O} = m_{lime-melt.}^{H_2O-gas} + m_{air-melt.}^{H_2O-gas}$$, kg   (27)

This amount of moisture will be reduced by CO by the reaction: $H_2O + CO = H_2 + CO_2$. This will form hydrogen with a mass of $m_{melt.-H2O}^{H2}$ according to the formula:

$$m_{melt.-H_2O}^{H_2} = m_{melt.}^{H_2O} \frac{M_{H_2}}{M_{H_2O}} \quad , kg \qquad (28)$$

where: M_{H2} - molecular mass of hydrogen; M_{H2O} - molecular mass of water.

The reduction will consume CO in the amount of $(m_{melt.-H2O}^{CO})$:

$$m_{melt.-H_2O}^{CO} = m_{melt.}^{H_2O} \frac{M_{CO}}{M_{H_2O}} \quad , kg \qquad (29)$$

where: M_{CO} - molecular mass of carbon monoxide.

After the reduction, CO_2 will be obtained in the amount of $(m_{melt.-H2O}^{CO2})$:

$$m_{melt.-H_2O}^{CO_2} = m_{melt.-H_2O}^{CO} \frac{M_{CO_2}}{M_{CO}} \quad , kg \qquad (30)$$

where: M_{CO2} - molecular mass of carbon dioxide.

The components of the gas phase from the melting period are presented in Table 6.

RESULTS AND DISCUSSION

After replacement with the known initial data and the data from the technological receptions, in the created optimized balance modeling of the melting period, the values of the components for the three phases - metal, slag, gas, are calculated. On this basis, the material balance of the melting period shown in Table 7 was calculated.

Table 6. Gas phase during the melting period.

Gas	kg	%
Carbon oxide	1.641	19.81
Carbon dioxide	1.214	14.65
Nitrogen	5.420	65.44
Hydrogen	0.008	0.10
Total	8.283	100

The results obtained for the revenue part during the melting period are optimal, given the chemical composition of the charge materials. All admissions are based on metallurgical practice. Iron scrap is considered to be free of impurities of oil and other components than those listed in Table 1. The dinas from the vault and the magnesite from the walls and floor of the furnace are taken on average. Electrode consumption data may also vary. The iron particles that go like fallow are actually part of the gas phase. Due to the accepted condition under Table 5, about 70 % of the amount of slag is poured between the melting and oxidation periods. Thus, for the next period - oxidation, about 30 % of the slag obtained during the melting period remains.

CONCLUSIONS

- A model has been created for calculating the income and expenses during the melting period, when receiving bearing steel by electric arc method.

Table 7. Material balance of the melting period.

EXPENDITURE	kg	INCOME	kg
Iron scrap	98.20	Metal	96.96
Ferromanganese	0.49	Slag	5.904
Electrode wastes	1.31	Gases	8.283
Lime	3.00	Fallow of iron (see p. II, p. 1)	1.652
Electrodes	0.42		
Magnesite	1.00		
Dinas	0.60		
Air ($O_2 + N_2$)	7.039		
unattached	0.740		
Total	112.799	Total	112.799

- Batch materials were used in accordance with the technological management of the process. Based on the created modeling, the metal, slag and gas phases are calculated.
- The melting period model allows, when changing the composition of one or more charge components, to calculate the final result for the three phases relatively quickly.

REFERENCE

1. F. Edneral, A. Filipov, Razcheti po electrometalurgii stali i ferosplavav, Moskva, GNTILChTsM, 1962, (in Russian).
2. D. Dyudkin, V. Kisilenko, Actual Technology of Steel Out of Furnace Treatment by Flux Cored Wire, Metallurgical and Mining Industry, 2, 2, 2010, 102-106.
3. A. Avramov, I. Ivanchev, Ts. Tsanev, Metalurgia na zheliazoto, Sofia, Technika, 1994, (in Bulgarian).
4. H. Erinin, Metalurgia na stomanata, Sofia, Technika, 1992, (in Bulgarian).
5. F. Edneral, Electrometallurgy of steel and ferro-alloys, Moscow, Mir, 1979.
6. M. Tunc, U. Camdali, G. Arasil, Mass Analysis of an Electric Arc Furnace (EAF) at a Steel Company in Turkey, Metallurgist, 56, 4, 2012, 52.