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APPLICATION OF THE MINING INDUSTRY WASTES AS RAW MATERIAL FOR MELTING OF THE COMPLEX FESIAL FERROALLOYS

An economical alternative for the steel industry which uses a separate ferrosilicon and aluminum for the deoxidization of steel is a complex deoxidizer in the form of FeSiAl alloys. The effectiveness of complex deoxidizers is higher and they have a positive effect on quality improvement and also for mechanical properties of the finished steel. It is associated with a smaller number of non-metallic inclusions and a more favorable its distribution in the structure of steel. Noteworthy are the waste from the mining industry simultaneously contains SiO_2 and Al_2O_3 oxides with a few of dopants in the form of CaO, MgO, FeO, TiO_2 oxides. These wastes are present in large quantities and can be a cheap raw material for obtaining complex FeSiAl ferroalloys by an electrothermal method. "Poor" hard coal grades which so far did not apply as a reducing agent in the ferroalloy industry because of the high ash content can also be a raw material for the electrothermal FeSiAl process. The electrothermal FeSiAl melting process is similar to the ferrosilicon process in the submerged arc furnace. For this reason, a model based on Gibbs' free enthalpy minimization algorithm was used to analyze the simultaneous reduction of SiO_2 and Al_2O_3 oxides, which was originally elaborated for the ferrosilicon smelting process. This is a system of two closed reactors: the upper one with the lower temperature and the lower one with the higher temperature. Between the reaction system and the environment, and between the reactors inside the system, there is a cyclical mass transfer in moments when the state of equilibrium is reached in the reactors. Based on the model, the basic parameters of the electrothermal reduction process of SiO_2 and Al_2O_3 oxides were determined and a comparative analysis was made towards the ferrosilicon process.

Keywords: FeSiAl, FeSi75, model, submerged arc furnace, Gibbs energy minimization method

1. Introduction

The FeSiAl alloys could be melted by the carbothermal process of simultaneous reduction SiO_2 and Al_2O_3 oxides in the submerged arc furnace [1,2]. In nature, there are large quantities of minerals that could be the good raw materials for the production of FeSiAl alloys due to a simultaneous content of silica and aluminum oxides with a few impurities such as iron, calcium, magnesium and titanium oxides. Large resources of cheap raw materials for the FeSiAl production is a selected waste from hard coal mines (Table 1). Also, the "poor" hard coals, which so far have not found any application in the ferroalloys industry due to their high ash content (Table 2) are also worth mentioning. The FeSiAl process in the submerged arc furnace is very similar to the carbo-thermic reduction of silica in the ferrosilicon process. With regard to the unique properties of complex FeSiAl deoxidizers in comparison to traditional de-oxidizers [3,4], and to the economic considerations at the Re Alloys LLC ferroalloys has been started a pilot installation for the FeSiAl melting in the 2017 year. The basic element of the installation is the submerged arc furnace with two transformers of 7.75 MVA. It is the six-electrode furnace with the rectangular furnace body. Two three-phase transformers independently supply 3 electrodes with a diameter of $d = 0.9$ m, arranged linearly in two rows separated by a partition through the middle of the bath. The basic raw material for FeSiAl production is a selected waste from hard coal mines and also "poor" hard coal with high ash content. It was assumed that FeSiAl alloy will be a substitute for FeSi65 and FeSi75 ferrosilicon produced in a furnace with six electrodes previously in which 10% Si will be replaced by 10% Al, These alloys are analogous to FS55A10 and FS65A10 alloys produced in Kazakhstan [1].

2. Model of the FeSiAl melting process

It has been assumed that the electro-thermal melting process of the FeSi65Al10 and FeSi55Al10 alloys in the submerged arc furnace is close to the ferrosilicon FeSi75 and FeSi65 melting in which part of the silica in charge is replaced by sillimanite ($Al_2O_3*SiO_2$) so that in the final alloy about 10% of Si will be replaced with Al. Therefore, in the model, the total content of Si + Al in the FeSiAl alloys should be 75% and 65%

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Chemical composition of waste rocks from different coal mines in Poland

Mine	Component, wt. %				Ash chemical composition, wt. %					
	A^r	V^r	W^r	C_{fix}	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	SO_3	P_2O_5
Bogdanka	84,62	11,95	0,79	2,64	57,11	23,51	12,46	1,14	1,45	0,14
Boleslaw Śmiały	85,4	9,37	0,81	4,42	60,44	25,74	5,15	1,07	1,93	0,08
Pniowek	84,92	9,67	1,12	4,29	53,64	27,56	6,29	1,08	0,35	0,36
Staszic	87,99	9,17	0,61	2,23	64,22	22,25	5,01	1,04	0,31	0,06

Chemical composition of hard coal grades with high ash content which so far have not found any use in the ferroalloys industry as reducing agents

Mine	Component, wt. %				Ash chemical composition, wt. %					
	A^r	V^r	W^r	C_{fix}	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	SO_3	P_2O_5
Marcel	21,5	24	8,5	46	52,67	25,28	5,65	1,03	3,67	0,27
Piast-Ziemowit	22,50	39,75	6,50	31,25	49,03	24,48	9,66	1,04	4,20	0,13
Powstancków Śląskich	21	30,5	3,8	44,7	38,1	21,43	5,24	1,59	5,36	0,08

respectively, similar to Si content in ferrosilicon. To simulate a continuous process of simultaneous reduction SiO_2 and Al_2O_3 oxides in submerged arc furnace the model was used that had been firstly developed for the ferrosilicon melting process. It is a system of two closed isothermal reactors: an upper one with a lower temperature T_1, and a lower one with a higher temperature T_2. Between the reactors and the environment, as well as between the reactors inside the system, a periodical exchange of mass occurs at the time when the equilibrium state is reached in the reactors. In each cycle, a reaction mixture with the molar composition corresponding approximately to the batch mixture of raw materials for the process is fed into the upper reactor [5]. At the same time, the condensed products of chemical reactions move from the top to the bottom, and the gas phase components move in the opposite direction. The gas flow problems in a lump deposit are presented in the publication [6,7]. Simulation of the continuous process is implemented recursively. In Cycle 1, a portion of the reaction mixture is fed into the upper reactor where the reactions take place until the equilibrium state at the temperature T_1 is reached. Then, the gas-phase products leave the Reactor 1 and after cooling to the temperature $T_w = 850°C$, they do not participate in the further process. Simultaneously, the products of condensed phases of the Reactor 1 flow down and are introduced into the Reactor 2 where they react with each other until the equilibrium at the temperature T_2 is reached. Then, the condensed phase products leave the Reactor 2 and, after cooling to the temperature T_1, they form metallic and slag phases and do not participate in the further process. The gaseous products with the equilibrium composition leave the Reactor 2 and, after cooling to temperature T_1, they are introduced back into the Reactor 1 where they react to reach the equilibrium state again at temperature T_1 in the next cycle. Cycle 2 and each next cycle of the reaction system starts with an introduction of a new portion of the reactants to the Reactor 1. They react together with the gaseous products of the previous cycle until the equilibrium is reached

at the temperature T_1. In the subsequent cycles, the process is the same as in Cycle 2. In a real process, temperature T_w corresponds to the temperature of gases that are by-products of the reduction process, measured immediately after leaving the furnace charge surface. It can be assumed in the model that Reactor 1 corresponds to the charge zone of submerged arc furnace where heat is released as a result of resistive heating and Reactor 2 corresponds to the zones of the furnace where heat is produced by the electric arc. For a fixed composition of the initial reaction mixture and for set conditions of temperature and pressure (T_1, T_2, $P = 1$ bar), the equilibrium composition of the Reactors 1, and 2 was determined by a non-stoichiometric algorithm of the Gibbs Free Energy Minimization using the HSC 7.1 thermochemical software. It allows for the use a thermochemical database and solution of the Gibbs Minimization problems directly in the Excel spreadsheet [8]. The non-stoichiometric algorithm of the Gibbs Free Energy Minimization arrives at solving the non-linear optimization problem with limitations resulting from the mass balances of individual elements [9]:

$$\left. \begin{array}{c} \min_{n} \dfrac{G(T_i, P, \boldsymbol{n}_i)}{RT_i} \\ \boldsymbol{A} \cdot \boldsymbol{n}_i = \boldsymbol{B} \\ \boldsymbol{n} \geq \boldsymbol{0} \end{array} \right\} \qquad (1)$$

where:

$G(T_i, P, \boldsymbol{n}_i)$ – Gibbs free enthalpy function for the reactor i, $i = 1,2$ MJ/kmol,

$\boldsymbol{n}_i = (\boldsymbol{n}_i^1, \boldsymbol{n}_i^2, ..., \boldsymbol{n}_i^f)^T, \boldsymbol{n}_i^r = (n_{1,i}^r, n_{2,i}^r, ..., n_{k^r,i}^r)^T,$

$\boldsymbol{n}_i^r$ – vectors which elements are numbers of kmol of the various phase r components, $r = 1,2,...,f$,

$\boldsymbol{A}$ – atomic matrix with dimensions $N \times n$, which elements are number of particular atoms in phase components (Table 3),

TABLE 3

The components of specific phases of the Fe-Si-Al,-O-C system
$(N = 5, f = 5, n = 84, k^1 = 28, k^2 = 25, k^3 = 1, k^4 = 1, k^5 = 13)$

§ PHASE 1:	C5(g)	C6(g)	C7(g)	C8(g)	C60(g)	C70(g)	CO(g)	CO2(g)
	C2O(g)	C3O2(g)	Fe(g)	Fe2(g)	Fe(CO)5(g)	FeO(g)	FeO2(g)	O(g)
	O2(g)	O3(g)	Si(g)	Si2(g)	Si3(g)	Si4(g)	SiC(g)	SiC2(g)
	Si2C(g)	SiO(g)	SiO2(g)	Si2O2(g)				
§ PHASE 2:	Al4CO4	AlO	Al2O3	Al2O3*SiO2	Al2O3*2SiO	*3Al2O3*2Si	Al2SiO5(A)	FeAl2O4
	Fe2Al4Si5O1	Fe3Al2Si3O1	FeCO3	Fe(CO)5	Fe2(CO)9	Fe3(CO)12	Fe0.945O	Fe0.947O
	FeO	FeO1.056	Fe2O3	Fe3O4	FeO*SiO2	*2FeO*SiO2	FeSiO3	Fe2SiO4(B)
	SiO2							
§ PHASE 3:	C							
§ PHASE 4:	SiC							
§ PHASE 5:	Al4C3	Al4SiC4	Fe2C	Fe3C	Al	Fe	FeSi	FeSi2
	Fe3Si	Fe5Si3	Si	FeSi2.33	FeSi2.43			

$n = k^1 + k^2 + ... + k^f$, number of components in the reaction system,

B – vector $N \times 1$, $B = (e_1, e_2, ..., e_N)^T$,

e_i – mass of the element type i in the system, kmol,

$i = 1, 2, ..., N$,

f – number of phases in the system,

N – the number of elements in the system,

R – gas constant, kJ/(kmol · K).

First, a model was developed for the Fe-Si-O-C-Al system [6]. However, in addition to SiO_2 and Al_2O_3 oxides, the chemical composition of mining waste includes minerals containing small amounts of oxides: CaO, MgO, TiO_2. Therefore, in this publication, the model has been extended to the Fe-Si-O-C-Al-Ca-Mg-Ti system. Based on the HSC 7.1 database, it was determined that there may be $n = 150$ components in this system and $f = 5$ phases. The phase selection method is shown in Table 3, but due to a large number of components, it is limited to the Fe-Si-O-C-Al system only.

This approach does not specify the chemical reactions or stoichiometric equations. For each cycle, the equilibrium composition of the reaction system as well as the mass, and energy balances can be determined [10]. Based on the energy balance, the components Q_R, Q_{Arc} of the heat balance that characterize the distribution of heat in the reaction zones located around the electrodes of the submerged arc furnace were determined [6]. The component Q_R corresponds to the charge zones where heat is released as a result of resistive heating and the Q_{Arc} corresponds to gas chambers localized around the electrode tips where heat is released by radiation of arc. The distribution of heat in the process can be characterized by percentages Q_1, Q_2 related to Q_R and Q_{Arc} as follows:

$$Q_1 = 100 \cdot \frac{Q_w}{Q}, \quad Q_2 = 100 \cdot \frac{Q_{Arc}}{Q}, \% \qquad (2)$$

where:

h – factor related to the thermal efficiency of the furnace, $\eta \approx 0.88$,

Q – total energy demand in the process, MJ.

Fig. 1 presents a comparison of calculation results for models simulating FeSi75 and FeSi65Al10 melting processes. The ferrosilicon smelting process is well known and the calculations results for the FeSi75 model are in good agreement with industrial data. This applies not only to the Si yield and energy consumption index but also to the trace elements in the chemical composition (Al, Ca, Mg, Ti, C). It can, therefore, be assumed that the obtained results of calculations with the help of the model can provide some explanations which will be useful in the production of FeSiAl alloys under industrial conditions. The calculations show that the FeSiAl electrothermal melting process is more energy-consuming and requires much higher temperatures of reaction zones compared to the ferrosilicon process. This also shows that in industrial practice, the melting processes of FeSiAl alloys will be more difficult compared to the ferrosilicon process. It results not only from higher temperatures but also from the proportion of energy demand in the upper and lower zones of the furnace. Obtaining the suitable proportions in the energy distribution as a result of resistive heating and as a result of the arc radiation in the submerged arc furnace causes great difficulties and is one of the most common reasons for the disturbances in the ferrosilicon smelting process. In the melting of the FeSi65Al10 process, obtaining the correct heat distribution in the furnace working space will be even more difficult. This requires a deeper placement of the electrodes tips and the operation of the furnace with the higher current load of the electrodes compared to the ferrosilicon process.

Below on Figs. 2-4 the most interesting dependencies regarding the FeSi65Al10 process obtained using the model has been presented. This applies to the influence of the coal reducer contribution in the reaction mixture and the temperature conditions of the reaction zones on the FeSiAl melting process.
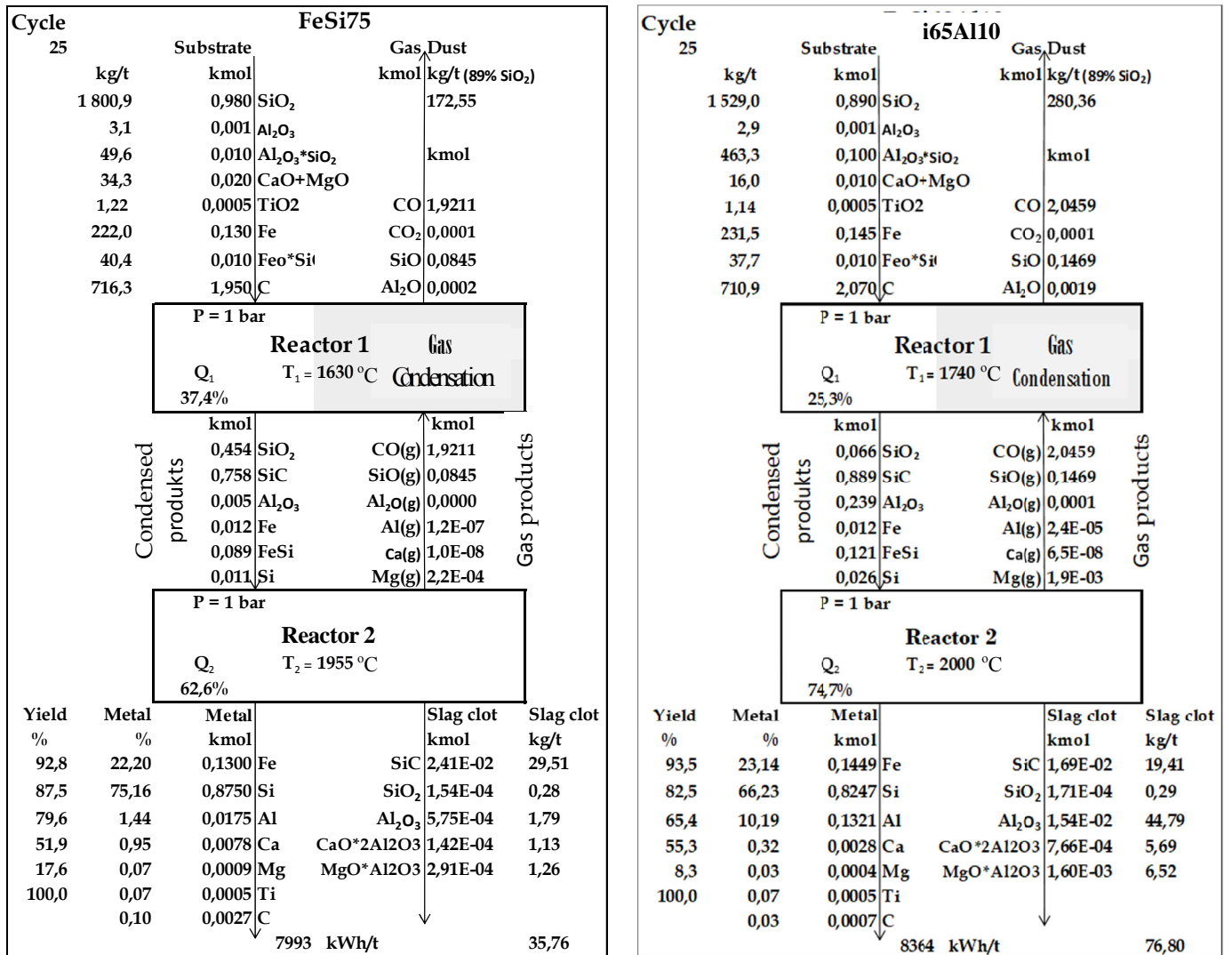
FeSi75

Cycle 25	Substrate			Gas Dust
kg/t	kmol			kmol kg/t (89% SiO₂)
1 800,9	0,980	SiO₂		172,55
3,1	0,001	Al₂O₃		
49,6	0,010	Al₂O₃*SiO₂		kmol
34,3	0,020	CaO+MgO		
1,22	0,0005	TiO2	CO	1,9211
222,0	0,130	Fe	CO₂	0,0001
40,4	0,010	Feo*Si	SiO	0,0845
716,3	1,950	C	Al₂O	0,0002

P = 1 bar

Reactor 1 — Gas Condensation
Q_1 $T_1 = 1630\ ^{\circ}C$ 37,4%

Condensed produkts / Gas products

kmol				kmol
0,454	SiO₂	CO(g)		1,9211
0,758	SiC	SiO(g)		0,0845
0,005	Al₂O₃	Al₂O(g)		0,0000
0,012	Fe	Al(g)		1,2E-07
0,089	FeSi	Ca(g)		1,0E-08
0,011	Si	Mg(g)		2,2E-04

P = 1 bar

Reactor 2
Q_2 $T_2 = 1955\ ^{\circ}C$ 62,6%

Yield %	Metal %	Metal kmol			Slag clot kmol	Slag clot kg/t
92,8	22,20	0,1300	Fe	SiC	2,41E-02	29,51
87,5	75,16	0,8750	Si	SiO₂	1,54E-04	0,28
79,6	1,44	0,0175	Al	Al₂O₃	5,75E-04	1,79
51,9	0,95	0,0078	Ca	CaO*2Al2O3	1,42E-04	1,13
17,6	0,07	0,0009	Mg	MgO*Al2O3	2,91E-04	1,26
100,0	0,07	0,0005	Ti			
	0,10	0,0027	C			
					7993 kWh/t	35,76

i65Al10

Cycle 25	Substrate			Gas Dust
kg/t	kmol			kmol kg/t (89% SiO₂)
1 529,0	0,890	SiO₂		280,36
2,9	0,001	Al₂O₃		
463,3	0,100	Al₂O₃*SiO₂		kmol
16,0	0,010	CaO+MgO		
1,14	0,0005	TiO2	CO	2,0459
231,5	0,145	Fe	CO₂	0,0001
37,7	0,010	Feo*Si	SiO	0,1469
710,9	2,070	C	Al₂O	0,0019

P = 1 bar

Reactor 1 — Gas Condensation
Q_1 $T_1 = 1740\ ^{\circ}C$ 25,3%

Condensed produkts / Gas products

kmol				kmol
0,066	SiO₂	CO(g)		2,0459
0,889	SiC	SiO(g)		0,1469
0,239	Al₂O₃	Al₂O(g)		0,0001
0,012	Fe	Al(g)		2,4E-05
0,121	FeSi	Ca(g)		6,5E-08
0,026	Si	Mg(g)		1,9E-03

P = 1 bar

Reactor 2
Q_2 $T_2 = 2000\ ^{\circ}C$ 74,7%

Yield %	Metal %	Metal kmol			Slag clot kmol	Slag clot kg/t
93,5	23,14	0,1449	Fe	SiC	1,69E-02	19,41
82,5	66,23	0,8247	Si	SiO₂	1,71E-04	0,29
65,4	10,19	0,1321	Al	Al₂O₃	1,54E-02	44,79
55,3	0,32	0,0028	Ca	CaO*2Al2O3	7,66E-04	5,69
8,3	0,03	0,0004	Mg	MgO*Al2O3	1,60E-03	6,52
100,0	0,07	0,0005	Ti			
	0,03	0,0007	C			
					8364 kWh/t	76,80

Fig. 1. Comparison of the results of calculations for the ferrosilicon FeSi75 and ferrosilicon-aluminum FeSi65Al10 process models. The main components of the Fe-Si-O-C-Al-Ca-Mg-Ti system and efficiency of the recurrent process for experimentally determined parameters: T_1, T_2 and composition of the reaction mixture after 25 cycles
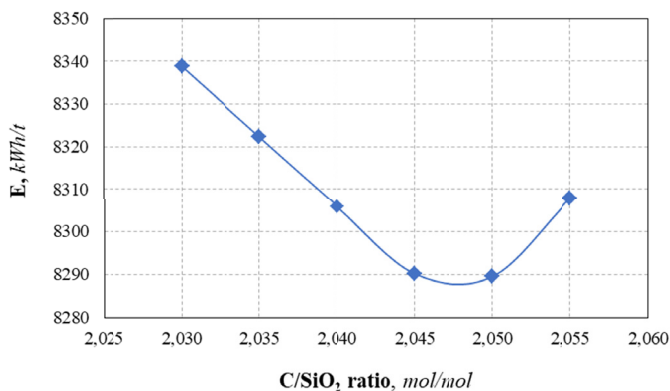

Fig. 2. The impact of reducer participation in the reaction mixture on the energy consumption index E in the smelting process FeSi65Al10 for specified temperature conditions of the process: $T_1 = 1640\ ^{\circ}C$, $T_2 = 2000\ ^{\circ}C$
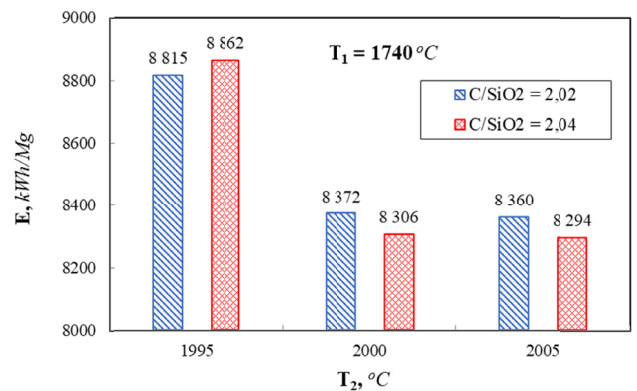

Fig. 3. Influence of the temperature T_2 and the contribution of the reducer in the reaction mixture to the energy consumption index E in the melting process FeSi65Al10 (other parameters as in Fig. 1)
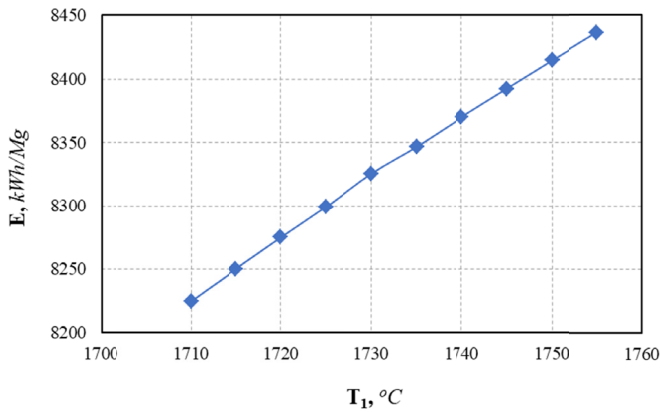
Fig. 4. Influence of temperature T_1 on energy consumption indicator. in the FeSi65Al10 melting process, for set temperature $T_2 = 2000°C$ (other parameters as in Fig. 1)
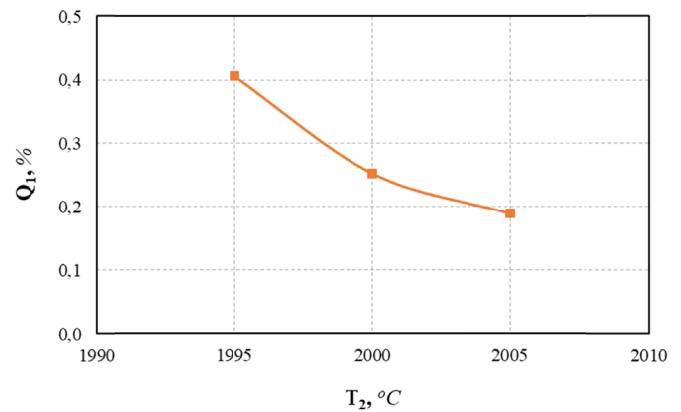

Fig. 5. The influence of temperature T_2 on the distribution of energy in the reaction system at a constant temperature $T_1 = 1740°C$ (other parameters as in Fig. 1)

3. Summary

The calculations show that the FeSiAl electrothermal melting process is more energy-consuming and requires much higher temperatures of reaction zones compared to the ferrosilicon process.

This also shows that in industrial practice, the FeSi65Al10 technological processes will be more difficult compared to ferrosilicon process. It results not only from higher temperatures but also from the proportion of energy demand in the upper and lower zones of the furnace.

Obtaining the suitable proportions in the energy distribution as a result of resistive heating and as a result of the arc radiation in the upper and lower zones of the furnace causes great difficulties and is one of the most common reasons for the disturbances in the technological process of smelting of FeSi.

In the melting process of the FeSi65Al10 alloy, obtaining the correct heat distribution in the furnace working space will be even more difficult.

This requires a deeper placement of the electrodes tips and the operation of the furnace at a higher current load of the electrodes compared to the ferrosilicon FeSi75 process.

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