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TECHNICAL AND TECHNOLOGICAL SOLUTIONS IN DEVELOPMENT OF FeSiAl ALLOYS PRODUCTION FROM INDUSTRIAL WASTES IN SUBMERGED ARC FURNACE (SAF)

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This article presents a description of the carbothermic process concerning production of iron-silicon-aluminum alloys with 55 to 75 wt. % of silicon and 4 to 20 wt. % of aluminum in industrial conditions. For the process, mining waste resulted from mechanical processing of coal being the source of silicon and aluminum compounds as well as high-ash fine coal as a reducer was used. A modern technological line for FeSiAl smelting was described, consisting of a SAF (fitted with two 7,75 MVA three-phase transformers and six self-baking electrodes) to ensure optimum power distribution in the furnace. In addition, technical and technological parameters of the process were presented with a particular emphasis placed on Al and Si yields.

Keywords: FeSiAl alloys, ferroalloys production, SAF, waste

INTRODUCTION

Until middle 1950s, the scale of FeSiAl alloy production used to be minor due to a small market demand. The main reason was granulometric instability of the stocked alloy and reluctance of technologists to use a new steel deoxidizer. Ferroalloy-related literature from the first half of the 20th century also neglected problems with FeSiAl production or it was very scarce [1]. Methodical research, carried out in the Soviet Union in 1950s and further in Russia and the former republics, resulted in a description of the ferrosilicon-aluminum production technology using various raw materials, including industrial waste [2-6]. In Poland, the interest in application of complex FeSiAl ferroalloys dates back to 1980s [7]. A potential for industrial waste utilization in the process of their production was also considered [8]. Further research was continued in late 2010s and resulted in development of the FeSiAl production technology using industrial waste [9]. Ferrosilicon-aluminum manufacturing in a submerged arc furnace is based on Al_20_3 and SiO_2 reduction with carbon [10].

Utilization of industrial waste in the process of ferroalloy production demonstrates multidimensional ecological effects. This type of waste serves as a source of chemical elements that are desired for the process: silicon and aluminum. Coal gangue provides the material containing necessary components of the alloy (silicon and aluminum) and a part of the required carbon reducer to the furnace reaction zone. The use of waste raw materials with low-carbon gangue improves economic efficiency of the enterprise and restricts the amount of waste that must be stored. Waste processing to yield a full-value product requires an advanced technology and compliance with more exact technological restrictions despite apparent simplicity of the process. An additional problem is coexistence of chemical, physical and electrical processes in the furnace reaction zone that are related to the way of energy delivery for reactions. The materials mentioned above must be applied in lumped forms of selected sizes.

The aim of the article is to provide results of experiments performed during tests of the innovative ferrosilicon-aluminum production technology based on the industrial waste, particularly from coal mines.

DESCRIPTION OF THE NEW TECHNOLOGICAL LINE

A six-electrode submerged arc furnace was selected for production of the FeSiAl alloys. Critical components of the technological line, responsible for the physicochemical processes of simultaneous reduction of silicon and aluminum oxides, are the parameters of the submerged arc furnace: geometry of the furnace bath, types of refractory materials used for the refractory lining purposes, the furnace hood with the off-gas removal system. Another, equally important issue is location of the electrodes and their geometry with the fitted electrode columns as well as the devices that control the electrode loads through the change of the autotransformer taps and location of the electrode tips inside the charge material. The process is controlled by means of the control and measuring equipment that ensures cur-

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Table 1 **Technical parameters of the selected raw materials for FeSiAl production**

	Technical analysis			C_{fix}	Component contents in the ash / wt. %										
	A^a	V^a	W^a												
	/ wt. %				SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	P_2O_5	SO_3	K_2O	Na_2O	FeO
Quartzite	-	-	1,70	-	98,51	0,44	0,28	0,01	0,04	0,085	0,005	-	0,088	-	-
Coal	4,41	30,50	1,68	63,41	34,15	23,94	13,91	8,92	4,89	0,92	0,58	8,99	1,9	1,58	-
Fine coal	22,50	39,75	6,50	31,25	49,01	24,48	9,66	3,52	2,81	1,04	0,13	4,2	2,14	2,25	-
Aggregate	87,99	9,17	0,61	2,23	64,22	22,25	5,01	1,43	1,90	1,04	0,08	0,66	3,1	-	-
Electrode mass	3,3	12,6	0	84,10	30,61	9	33,03	1,52	1,27	0,16	0,28	2,25	-	-	-
Wood chips	0,2	37,2	53,6	9,00	8,7	1,76	2,7	59,75	7,17	0,01	4,35	0,61	4,3	5,9	-
Iron oxides	-	-	4,40	-	0,31	-	-	-	-	-	0,002	-	-	-	99,45

where: A^a - ash in analytical state, V^a - volatile matter in analytical state, W^a - moisture in the analytical state

rent control of the physicochemical processes inside the furnace operating zone and maintenance of the technology-related parameters.

The furnace is fitted with an elliptic bath: 8 500 x 820 mm, 4 370 mm (height). The entire bath is located on a steel T-bar grid seated on a reinforced concrete foundation. The grid enables air flow and natural cooling of the bath bottom and it compensates for free movement due to thermal expansion. The bath has two tap holes placed on the opposite side walls intended for liquid smelting product tapping directly to the tap baths.

The furnace is equipped with an open hood intended to collect and deliver off-gases to the extraction system through vertical and horizontal channels and to reduce thermal emission to the environment. These gases feature a large amount of enthalpy in the physical meaning that can be used analogically to other processes of ferrosilicon production [11,12]. There are 6 holes in the hood for andalusite-sealed electrodes and a gas outlet with a flange for fixing the middle flue channel. The hood is fitted with a water cooling system. The lower edge of the hood has a ring with segmented screens hanging on it to reduce thermal emission from the upper charge material layer and burning off-gases to the outside of the furnace.

Six self-baking electrodes with diameters of 900 mm each (three electrodes for each side of the furnace, A and B) ensured optimum temperature distribution in the reaction zone and proper work of the furnace unit. In combination with two individual 7,75 MVA transformers and separation of the bath, this solution enables operation of only one side of the furnace without the need to shut down the whole furnace system.

For an appropriate assessment of the furnace operation, it is very important to measure electric current paths properly: single-phase active powers individually for each furnace electrode, phase and line-to-line voltages for each electrode, and the furnace phase currents.

TECHNOLOGICAL TESTING FOR FeSiAl PRODUCTION

This Based on results of laboratory analyses of the selected raw material samples as well as on the model calculations for the technological process, a decision was made to use specific materials for FeSiAl production. Their technical analyses, carbon contents C_{fix} and chemical compositions are presented in Table 1.

The parameters of the above raw materials (Table 1) were then used to calculate the final compositions of particular FeSiAl types. Results of the calculations for the final chemical compositions are presented in Table 2.

Technological experiments were performed in five cycles, gradually increasing the Al content in the alloy in each of them through the increase in the percentage content of the waste aggregate in the charge material. Durations of the particular experiment cycles varied from six weeks for the first cycle to two weeks for the fourth and fifth cycles.

Table 2 **Final chemical compositions of smelted FeSiAl types**

Type	Chemical element contents / wt. %				
	Si	Al	P	S	Fe
FeSi65Al5	65	4-6	< 0,03	< 0,01	the rest
FeSi65Al7	65	6-8	< 0,03	< 0,01	the rest
FeSi75Al7	75	6-8	< 0,03	< 0,01	the rest
FeSi55Al12	55	10-15	< 0,03	< 0,01	the rest
FeSi55Al16	55	15-20	< 0,03	< 0,01	the rest

Table 3 **Mean raw material consumption indicators for FeSiAl production**

Experiment cycle	Mean raw material consumption indicators						
	Aggregate	Quartzite	Hard coal	Fine coal	Wood chips	Iron oxides	Electrode weight
	kg / Mg	kg / Mg	kg / Mg	kg / Mg	kg / Mg	kg / Mg	kg / Mg
Cycle I	425,43	1 134,25	629,01	349,77	289,16	315,22	35,63
Cycle II	438,39	1 194,12	624,61	352,55	297,33	315,44	46,69
Cycle III	602,35	1 681,98	912,67	442,55	503,83	219,26	50,50
Cycle IV	1 501,04	532,60	259,17	1 041,89	683,89	326,72	43,81
Cycle V	1 540,17	382,64	136,29	1 270,08	755,11	260,89	43,25

Table 3 presents mean raw material consumption indicators for all experiment cycles. In Table 4, weighted average chemical compositions of the alloys resulted from the particular experiment cycles are listed.

The studies show that mining waste, as aggregate, is an effective aluminium-bearing material. Increasing the content of aggregate in the charge material instead of quartzite results in proportional increase in the Al content in the finished alloy. On the other hand, the aggregate can provide the alloy with chemical elements which, depending on the FeSiAl purpose, can be undesirable components (Ca or Ti) or impurities (e.g. P) like in other ferrosilicon alloys [13]. For example, phosphorus in FeSiAl leads to formation of compounds with calcium, aluminum and manganese that diffuse to grain boundaries where, due to the contact with moisture, they degrade and PH_3 is created.

One of important parameters enabling assessment of the ferroalloy production process is the yield of the main chemical element components of the alloy. In literature, a yield is defined as a ratio of an element mass content in the alloy to its mass content in raw materials within an analysed time unit. It is usually expressed as percentage. Yields of the basic chemical elements of the alloy, i.e. Si and Al, for the consecutive experiment cycles are shown in Figure 1. The silicon yield is above 85 % in further cycles except cycle III where its value slightly exceeds 77 %. The silicon yield near 85 % is typical of a classical proper process of FeSi alloy production. The yield values for Al vary. In the first three cycles, they were close to 60 %, while significant differences could be observed for the cycles IV and V: markedly lower and very high, respectively.

The analysis of experimental data showed that a change in the quartzite percentage content in the substrates during the experiment cycles only slightly affected the silicon yield, which is illustrated in Figure 2. Even a three-fold increase in the quartzite mass content in the charge material causes extremely small fluctuations of the silicon yield.

The influence of the percentage content of the aggregate waste in the substrates on the Al yield is not

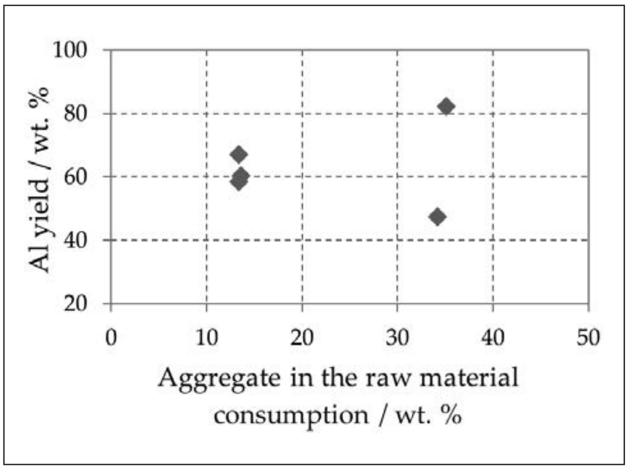

Figure 2 Silicon yield versus percentage content of quartzite in the substrates

strictly defined. It is shown in Figure 3. Determination of such a relationship requires collection of further data from next complex FeSiAl alloy production campaigns. For their processing, advanced mathematical algorithms are necessary.

The technological process resulted in trace amounts of slag relative to amounts of the alloy, which demonstrates a nearly complete reduction reactions of SiO_2, Al_2O_3 and FeO. The resulting liquid elements formed the FeSiAl alloy.

Mean electrical parameters of the furnace only slightly changed during the first four cycles of the experiment. The mean active power (cycles I to IV) for the A side of the furnace was 5,567 MW with the max deviation + 1,6 % for the cycle I and – 1,5 % for the cycle IV. Regarding the B side of the furnace, fluctuations of the mean parameters were slightly higher: the mean active power (cycles I to IV) was 5,472 MW with the max deviation + 3,5 % for the cycle I and – 6,5 % for the cycle IV. The mean cosine φ value during cycles I÷IV of the experiment for the sides A and B of the furnace was 0,771 ± 0,005. For the cycle V, due to a change in the power supply parameters, the values of cos φ were 0,734 and 0,744 for the sides A and B, respectively. In

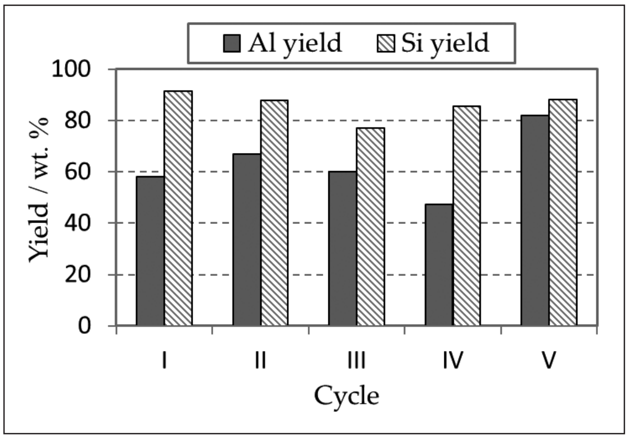

Figure 1 Si and Al yields in the consecutive cycles of the experiment

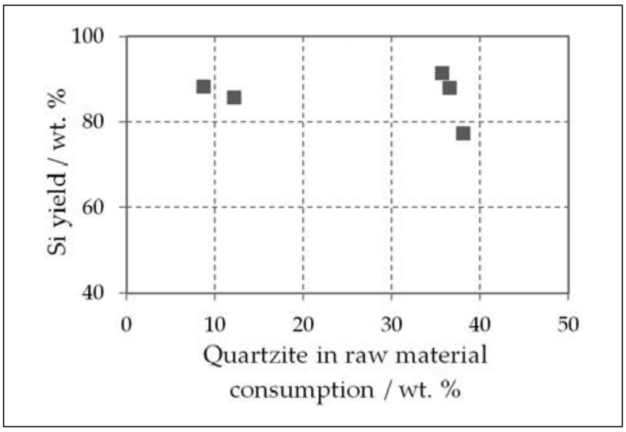

Figure 3 Al yield versus the percentage content of aggregate waste in the substrates

the cycle V, compared to the previous cycles, the active power values decreased to 4,676 MW and 4,688 MW for the sides A and B of the furnace, respectively. The reason was a reduction of the transformer taps from the phase voltage of 136 V to 121 V in order to increase the amperage regarding the current flow from the electrodes to the operating zone of the furnace bath. The effect was an increase in the chemical element yields. The silicon yield was slightly higher while for aluminum, it was just above 80 %.

The data for cycle V (the last experiment cycle) show a potential for high yields of the main alloy elements. However, the cycle V duration was short and the amounts of the resulting alloy were over two-fold smaller than for the cycles II and III. To obtain more precise result interpretation and technological instructions, data in future complex FeSiAl production campaigns should be monitored concerning the alloy of a composition com-parable to the cycle V alloy composition.

CONCLUSIONS

The aggregate in the form of industrial waste can be used as a cheap and effective source of aluminum and silicon oxides during production of FeSiAl with the Al content up to 20 %. A higher content of the aggregate in the furnace operating zone results in a proportionally higher Al content in FeSiAl.

The phosphorus (undesirable element) content in the final product was smaller than that determined in the thermochemical calculations and remained at a low, acceptable level.

The electric energy consumption indicators (units per Mg of the alloy) were lower than those theoretically determined during the industrial research.

The innovative technology of FeSiAl smelting from cheap aluminum-bearing mate-rials such as mining aggregate and high-ash fine coal, while maintaining the proper technological procedures, has a potential for application in continuous industrial production of a series of alloys with the Si content of 55 to 75 % and the Al content of up to 20 % in six-electrode submerged arc furnaces.

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