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The possibility of the commercial production of low-activation structural steels for fusion energy in the Russian Federation

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Abstract

Laboratory meltings of low activation austenitic and ferritic steels (Fe0.1C12Cr20Mn1W0.2V and Fe0.1C9Cr1W0.15Ta) were done in an inductive furnace. The panoramic analysis of the charge materials and steels were made by means of spark mass-spectrometry. Series of calculations of activation parameters for steels composing from hypothetically pure, isotopically enriched macrocomponents and for real materials were conducted. The possible metallurgical technologies of industrial production of the low activation steels in the Russian Federation including processes of initial charge materials purification are considered.

1. Introduction

The successful development of thermonuclear energy now is hardly possible without solution of the accompanying environmental problems. Particularly it may be done by means of application of low-activation structural materials (LAM). This direction is based on the selection of the appropriate matrix and alloying elements having enough fast decay of the induced radioactivity to the suitable level. It has been pointed out that as concerns steels of the austenitic and ferritic–martensitic type the compositions Fe–20Mn12CrW and Fe–(7–9)CrWVTa are good candidates [1].

During the LAM development it is important to eliminate trace elements such as N, Mo, Nb, Al, Ag, Bi and some others, which give rise to the "harmful" long-lived radionuclides. It means that developing of the correspondent technology should be based on the carefully selected source charge materials as well as technologies of the steel production. Some aspects of this problem has been considered earlier [1].

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2. Experimental part and activation computations

For modelling of some technological aspects of production of low activation steels in industrial scale, the laboratory meltings of the austenitic and ferritic steels (Fe–0.1C12Cr20Mn1W0.2V and Fe– 0.1C9Cr1W0.15Ta) have been done. An induction furnace was used to obtain 100 kg ingots. The next industrial materials were used as charging components iron 008ZhR (TU 14-1-2033-81), metallic chromium Kh98.5 (GOST 5905-79), metallic manganese MR1 (GOST 6008-82), metallic tungsten ShV-V (TU 48-1976-81), cast iron PVK-1 (GOST 806-80), metallic tantalum, FeV (GOST 4760-49), Fe–0.3 Si (GOST 1415-61), FeB (GOST 4848-69), FeMn (GOST 6008-61), all identification are given in accordance with Russian standards. The panoramic analysis of the charging components and manufactured steels was made by means of spark mass-spectrometry. For computation of activation the program "ACTIVA" equipped with nuclear data bank has been used [2]. The neutron spectrum "Demo" and fluence $10^{27} m^{-2}$ were used.

3. Results

Data of mass-spectrometry analysis of charge materials and as produced products are given in the Table 1.

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The results of radioactivity calculations are shown on the Fig. 1 for hypothetically pure ferritic Fe–9CrWVTa and austenitic Fe–20Mn12CrW steels. The data on the graph marked by (x) correspond to the results of activation calculations for impurities with concentration is equal or below the flash mass-spectroscopy detection limit.

For comparison the results of activity calculations for austenitic steel made from isotopes of the main elements having fast decay rates are given also.

On the base of the obtained results it is possible to draw the following conclusions: the activation parameters of the given low activation austenitic and ferritic steels are practically the same; the induction melting does not introduce additional contamination in the final product; the elements in concentration below detection limit do not introduce a marked uncertainty in the activation calculations; the identified impurities do not introduce a marked contribution in the activation parameters in comparison with hypothetically pure macrocomponents of steels.

4. The possibility of industrial production of low activation steels in the Russian Federation

For economical reasons, it is advantageous to use in the industrial production of the low activation steels standard cheaper materials such as: ferrochromium of FKh006 trade-mark (instead of metallic or electrolytic chromium), metallic manganese of MP1 trade-mark (instead of electrolytic manganese) and ferrovanadium of FVD75 trade-mark (instead of metallic vanadium). However, in the case of tungsten alloy it is necessarily to

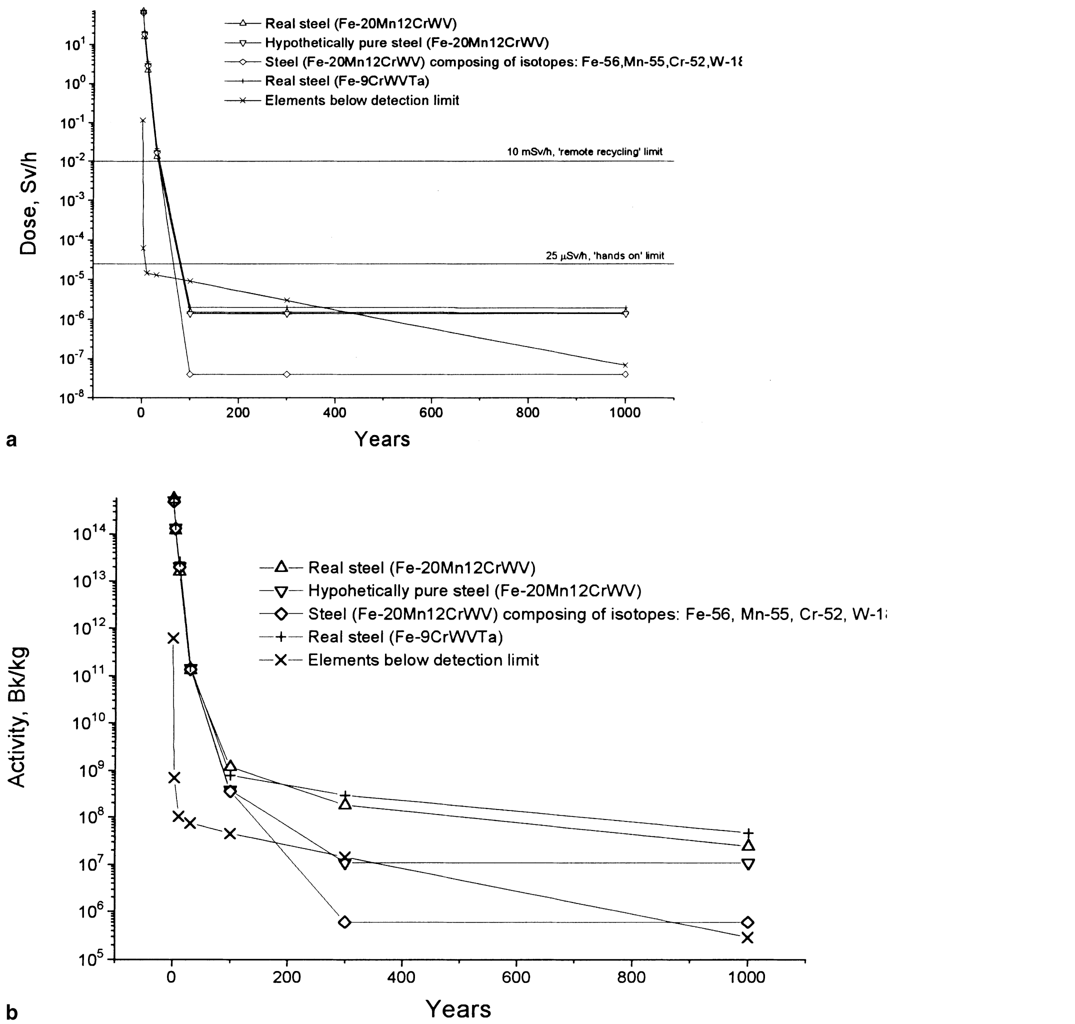

Fig. 1. Decay of the induced dose (a) and activity (b) for different materials.

Table 1
Results of panoramic elemental analysis of some components for steel production and final low activation steels (mass %)

	Fe	Mn	Cr	Fe–V	W	FeMn	Iron cast	Cr 12Mn20 W	Cr9WV
Si	-3.0×10^{-1}	-2.0×10^{-2}	-2.0×10^{-1}	$2.0 \times 10^{+00}$	-2.0×10^{-3}	1.0×10^{-1}	$5.0 \times 10^{+00}$	-1.5×10^{-1}	-6.0×10^{-2}
P	2.0×10^{-3}	2.0×10^{-4}	2.0×10^{-4}	3.0×10^{-2}	-1.0×10^{-3}	3.0×10^{-2}	4.0×10^{-1}	1.1×10^{-3}	3.0×10^{-3}
S	-1.0×10^{-2}	7.0×10^{-2}	1.5×10^{-3}	-1.0×10^{-2}	2.0×10^{-4}	6.0×10^{-3}	4.0×10^{-2}	6.0×10^{-2}	-5.0×10^{-3}
Cl	-3.0×10^{-4}	-2.0×10^{-4}	-9.0×10^{-3}	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}	3.0×10^{-1}	-2.5×10^{-3}	-1.2×10^{-4}
K	4.0×10^{-3}	8.0×10^{-3}	6.0×10^{-3}	-2.0×10^{-4}	1.0×10^{-3}	3.0×10^{-3}	3.0×10^{-1}	2.0×10^{-3}	5.0×10^{-3}
Ca	8.0×10^{-3}	3.0×10^{-3}	6.0×10^{-4}	3.0×10^{-2}	4.0×10^{-4}	7.0×10^{-4}	2.0×10^{-1}	7.0×10^{-4}	3.0×10^{-4}
Sc	-4.0×10^{-5}	-5.0×10^{-6}	6.0×10^{-4}	-6.0×10^{-4}		-6.0×10^{-5}	1.0×10^{-4}	-1.0×10^{-4}	3.0×10^{-5}
Ti	1.1×10^{-3}	2.0×10^{-4}	-3.0×10^{-3}	-4.0×10^{-3}		-3.0×10^{-5}	1.0×10^{-2}	1.1×10^{-3}	5.0×10^{-5}
V	6.0×10^{-4}			$5.0 \times 10^{+1}$	4.0×10^{-3}	1.4×10^{-2}	6.0×10^{-3}	1.0×10^{-3}	
Cr	1.3×10^{-1}	6.0×10^{-3}	Balance	3.0×10^{-1}	2.0×10^{-4}	2.0×10^{-2}	5.0×10^{-1}	$1.2 \times 10^{+1}$	$9.0 \times 10^{+00}$
Mn	9.0×10^{-3}	Balance		$3.6 \times 10^{+4}$	2.0×10^{-4}	Balance		$2.0 \times 10^{+1}$	
Fe	Balance			Balance	3.0×10^{-3}	6.0×10^{-1}	$9.0 \times 10^{+1}$	Balance	Balance
Co	6.0×10^{-4}	4.0×10^{-4}	-2.0×10^{-4}	6.0×10^{-3}	7.0×10^{-5}	-7.0×10^{-4}	8.0×10^{-3}	3.0×10^{-4}	6.0×10^{-3}
Ni	4.0×10^{-2}	-8.0×10^{-3}	-3.0×10^{-4}	7.0×10^{-2}	3.0×10^{-4}	1.6×10^{-3}	4.0×10^{-2}	1.5×10^{-2}	5.0×10^{-3}
Cu	1.0×10^{-2}	2.0×10^{-3}	1.0×10^{-3}	1.0×10^{-1}	3.0×10^{-4}	1.0×10^{-3}	8.0×10^{-2}	1.3×10^{-2}	1.5×10^{-2}
Zn	1.4×10^{-3}	1.4×10^{-3}	5.0×10^{-4}	-5.0×10^{-3}	3.5×10^{-4}	2.5×10^{-3}	1.0×10^{-3}	-5.0×10^{-3}	2.0×10^{-3}
Ga	9.0×10^{-4}			1.0×10^{-3}	2.0×10^{-3}				
Ge	4.0×10^{-4}								
As	3.0×10^{-4}			4.0×10^{-4}	3.0×10^{-4}				
Se	-2.0×10^{-6}								
Br	-2.0×10^{-6}	6.0×10^{-6}	1.0×10^{-4}	-1.0×10^{-4}	-5.0×10^{-4}	-6.0×10^{-6}	-7.0×10^{-5}	-1.0×10^{-4}	-1.0×10^{-4}
Rb	3.0×10^{-5}	4.0×10^{-5}	6.0×10^{-5}	-2.0×10^{-4}	8.0×10^{-5}	-2.0×10^{-5}	-1.0×10^{-4}	-8.0×10^{-5}	-4.0×10^{-5}
Sr	-2.0×10^{-4}	8.0×10^{-6}	2.0×10^{-4}	-8.0×10^{-5}	-3.0×10^{-4}	-2.6×10^{-5}	-1.5×10^{-4}	-3.0×10^{-4}	-1.5×10^{-4}
Y	1.0×10^{-5}	4.0×10^{-5}	5.0×10^{-5}	-9.0×10^{-5}	-2.0×10^{-4}	-8.0×10^{-6}	-1.3×10^{-4}	2.0×10^{-5}	3.0×10^{-5}
Zr	9.0×10^{-5}	6.0×10^{-6}	8.0×10^{-5}	-2.0×10^{-4}	1.0×10^{-3}	-1.0×10^{-5}	2.0×10^{-4}	6.0×10^{-5}	-1.5×10^{-4}
Nb	5.0×10^{-5}	-3.0×10^{-5}	4.0×10^{-5}	2.7×10^{-3}	-8.0×10^{-4}	9.0×10^{-5}	2.5×10^{-4}		-2.0×10^{-5}
Mo	1.0×10^{-3}	2.0×10^{-4}	1.0×10^{-4}	4.0×10^{-3}	5.0×10^{-2}	1.0×10^{-4}	4.0×10^{-3}	8.0×10^{-4}	3.0×10^{-3}
Rh			2.0×10^{-4}	-2.0×10^{-5}	-3.0×10^{-4}	-1.0×10^{-6}	-2.0×10^{-5}	3.0×10^{-4}	
Ag	-2.0×10^{-6}	7.0×10^{-5}	-5.0×10^{-6}	-8.0×10^{-5}	-6.0×10^{-4}	-2.0×10^{-6}	1.5×10^{-4}	-3.0×10^{-4}	-2.0×10^{-4}
Cd	-2.0×10^{-6}	-2.0×10^{-5}	1.3×10^{-4}	-8.0×10^{-4}	-9.0×10^{-4}	-7.0×10^{-6}	1.5×10^{-4}	3.0×10^{-3}	1.2×10^{-4}
In	-2.0×10^{-6}	-2.0×10^{-5}	-5.0×10^{-6}	-4.0×10^{-4}	-3.0×10^{-4}	-3.0×10^{-6}		6.0×10^{-6}	-1.0×10^{-5}
Sn	3.0×10^{-4}	1.0×10^{-4}	1.5×10^{-4}	-2.0×10^{-4}	-9.0×10^{-4}	-2.0×10^{-5}	3.0×10^{-3}	1.4×10^{-4}	-2.0×10^{-4}
Sb	7.0×10^{-5}	9.0×10^{-5}	-3.0×10^{-6}					1.3×10^{-4}	-1.3×10^{-4}
Cs	-3.0×10^{-6}	8.0×10^{-7}	-3.0×10^{-6}	-4.0×10^{-5}	-3.0×10^{-4}	-1.0×10^{-6}	-2.0×10^{-5}	6.0×10^{-6}	-6.0×10^{-6}
Ba	5.0×10^{-5}	2.0×10^{-5}	5.0×10^{-5}	-5.0×10^{-5}	-4.0×10^{-4}	4.0×10^{-5}	-7.0×10^{-5}	2.0×10^{-5}	-1.5×10^{-5}

Table 1 (Continued)

	Fe	Mn	Cr	Fe–V	W	FeMn	Iron cast	Cr 12Mn20 W	Cr9WV
La	2.0×10^{-5}	4.0×10^{-6}	3.0×10^{-5}	-5.0×10^{-5}	-3.0×10^{-4}	-2.0×10^{-6}	-6.0×10^{-6}	1.2×10^{-5}	-1.0×10^{-5}
Ce	5.0×10^{-5}	5.0×10^{-5}	1.5×10^{-5}	-3.0×10^{-5}	-3.5×10^{-4}	-2.0×10^{-6}	-6.0×10^{-5}	3.0×10^{-5}	-2.0×10^{-5}
Pr	-1.0×10^{-5}	1.4×10^{-5}	-5.0×10^{-6}	-5.0×10^{-5}	-3.0×10^{-4}		-6.0×10^{-6}	-8.0×10^{-6}	-1.0×10^{-6}
Nd	-1.0×10^{-5}	2.0×10^{-5}	-3.0×10^{-6}	-8.0×10^{-5}	-1.0×10^{-3}	-8.0×10^{-6}	-5.0×10^{-5}	-9.0×10^{-5}	-1.0×10^{-6}
Sm	-3.0×10^{-6}	4.0×10^{-6}	-3.0×10^{-6}	-5.0×10^{-5}	-1.0×10^{-3}	-5.0×10^{-6}	-5.0×10^{-5}	-3.0×10^{-6}	-1.0×10^{-6}
Eu	-3.0×10^{-6}	3.0×10^{-7}	-3.0×10^{-6}	-2.5×10^{-5}	-6.0×10^{-4}	-3.0×10^{-6}	-1.0×10^{-5}	-2.0×10^{-6}	-1.0×10^{-6}
W	2.0×10^{-4}	-1.0×10^{-6}	-1.0×10^{-5}	3.0×10^{-3}	Balance	3.0×10^{-5}	1.6×10^{-3}	4.0×10^{-1}	6.0×10^{-1}
Hg	-3.0×10^{-6}	-3.0×10^{-7}	-5.0×10^{-6}	2.0×10^{-4}		-7.0×10^{-6}		-5.0×10^{-6}	-2.0×10^{-5}
Tl	-3.0×10^{-6}	-3.0×10^{-7}	-3.0×10^{-6}	1.0×10^{-4}	-7.0×10^{-4}	-1.5×10^{-6}	-4.0×10^{-6}	-3.0×10^{-6}	
Pb	8.0×10^{-5}	1.6×10^{-2}	5.0×10^{-4}	3.0×10^{-4}	-1.0×10^{-3}	2.0×10^{-5}	-3.0×10^{-5}	7.0×10^{-3}	4.0×10^{-5}
Bi	-3.0×10^{-6}	-3.0×10^{-7}	-5.0×10^{-6}	2.0×10^{-4}	-5.0×10^{-4}	-2.0×10^{-6}	-4.0×10^{-6}	-3.0×10^{-6}	-1.0×10^{-6}

The next elements were found below detection limit (DL): Al 0.2–3 × 10^{-1}; Ru 0.3–9 × 10^{-5}; Pd 0.2–1.5 × 10^{-4}; Te, J 3 × 10^{-6}; Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf 0.3–3 × 10^{-6}; Ta 0.3–3 ×10^{-4}; Re, Os, Ir, Pt 0.03–1 × 10^{-5}; U, Th 0.03–6 × 10^{-4}. The data given as negative values represent detection limit.

use metallic tungsten of ShB-8 trade-mark instead of inexpensive ferrotungsten because former contains up to 6% of molybdenum, which cannot be removed from ferrotungsten during its production.

All these charge materials are produced my mills in Russia except for metallic manganese produced by ferroalloy mill in Ukraine. During industrial metallurgical production of the low activation steels it is necessary to use induction furnaces with productive atmosphere (vacuum, helium, argon) in order to provide minimum contamination of initial charge materials.

5. Prospective technological methods for obtaining components for LAM production

Application of isotopically tailored elements: The most promising direction of LAM development from our point of view may be based on application of isotopically enriched matrix and alloying elements [1,3]. It is evidently, that in this case, the problem of steels components purification will also be resolved. The activity calculations shown on the Fig. 1 illustrate the potential of this approach on the example of Fe–20Mn–12CrWV. At present the practical realization of the advantages of this direction is limited mostly by economical reasons.

Application of metallurgical methods for production of charge materials with reduced content of detrimental elements: Nowadays the most widespread method of removal of detrimental impurities from metals is their oxidation followed by transfer of oxides to slag. But it is impossible to remove such impurities as Ni, Co, Mo, Cu, Ag by oxidation from iron, manganese, chromium, and vanadium, because the oxygen affinity of these elements is much lower than that of the base metal [4].

The metals are produced, as a rule, by reduction from oxides containing in ores or concentrates. When dividing this process into two steps, the impurities can be transferred into the metallic phase at the expense of shortage of reductant. The needed shortage of a reductant depends on the content of undesirable impurities in ore. Thereafter, at the second step, the main component is being reduced from unreduced phase (charge slag). This process is successfully used on an industrial scale for removal of phosphorus from manganese concentrates. For example, the charge slag containing 0.01% phosphorus can be obtained from the manganese concentrates with 0.2–0.4% P, while the oxygen affinity of phosphorus is only slightly less than that of manganese [4]. In the case of production of metallic iron, manganese, chromium such impurities as Co, Mo, Cu, Ag, Bi, Ni can be removed to a greater extent, since difference in oxygen affinity in this case is much higher.

Following are the short descriptions of the industrial processes to be suggested (Figs. 2–6) for production

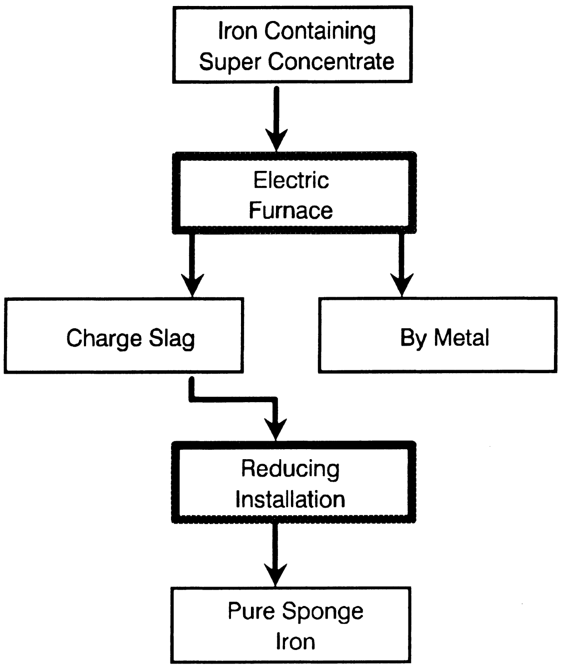

Fig. 2. Technological scheme for production of sponge iron, separated from easy reducible trace elements.

of charge materials with the decreased content of impurities inclined to activation, using reduction purification process.

Pure iron (Fig. 2): iron-containing superconcentrate is melted in the electric arc furnace with such amount of reductant, which corresponds to the selective reduction of easy-reducible impurities. These impurities being reduced are transferred to by-metal. The obtained charge slag is used as the starting material for production of sponge iron by hydrogen reduction.

Extralow-carbon ferrochrome (Fig. 3): iron-containing superconcentrate is melted in the electric arc furnace with such amount of reductant, which corresponds to the selective reduction of easy-reducible impurities. These impurities being reduced are transferred to by-metal. The obtained charge slag is used as the starting material for production of extralow-carbon ferrochrome.

Metallic manganese (Fig. 4): iron-containing superconcentrate is melted in the electric arc furnace with such amount of reductant, which corresponds to the selective reduction of easy-reducible impurities. These impurities being reduced are transferred to by-metal. The obtained charge slag is used as the starting material for production of silicomanganese and metallic manganese.

Ferrovanadium (Fig. 5): vanadium-containing slag is baked with soda and the cake is leached with water. The V_2O_5 obtained is melted in the electric arc furnace with

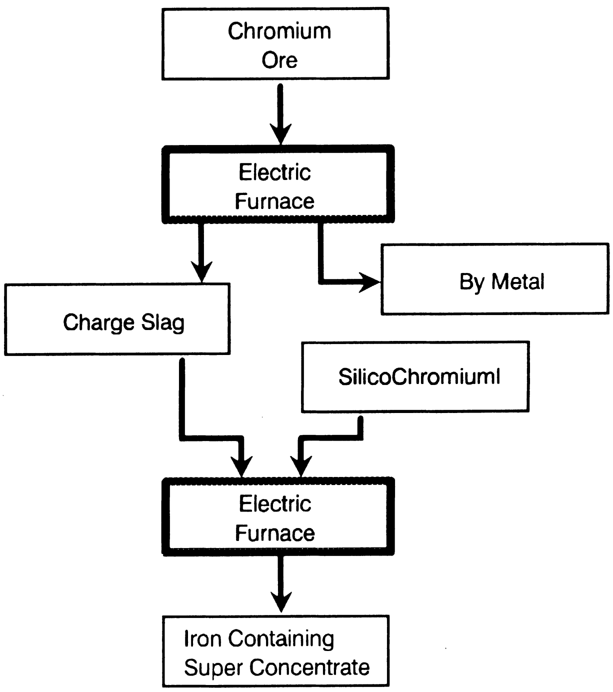

Fig. 3. Technological scheme for production of carbon free FeCr, separated from easy reducible trace elements.

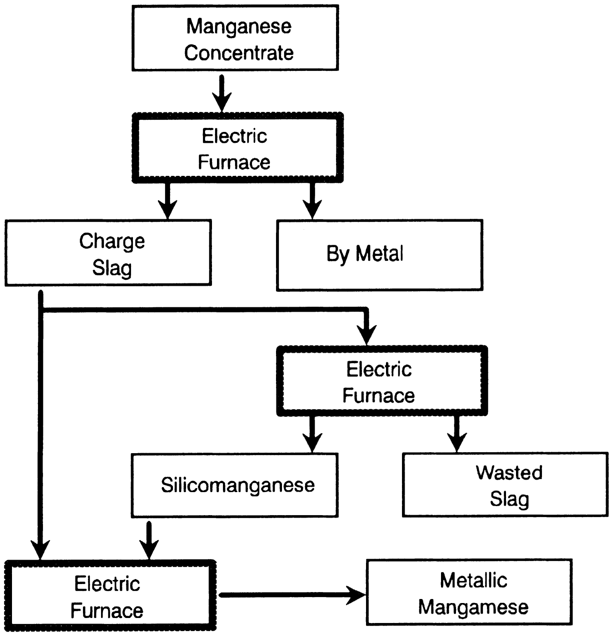

Fig. 4. Technological scheme for production of metallic manganese, separated from easy reducible trace elements.

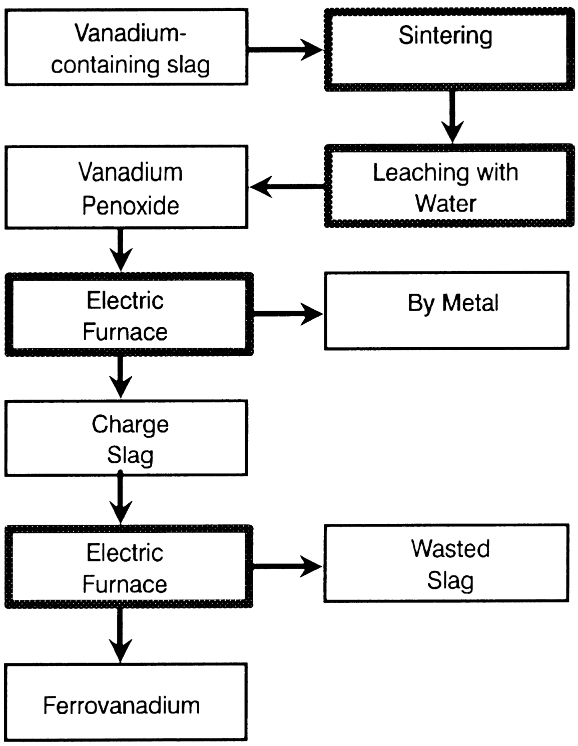

Fig. 5. Technological scheme for production of FeV, separated from easy reducible trace elements.

such amount of reductant, which corresponds to the selective reduction of easy-reducible impurities. These impurities being reduced are transferred to by-metal. The obtained charge slag is used as the starting material for making of ferrovanadium. Ferrosilicon is used as a reductant.

Metallic tungsten (Fig. 6): scheelite concentrate is decomposed by baking with soda followed by leaching of sodium tungstate (Na_2WO_4) with water. When

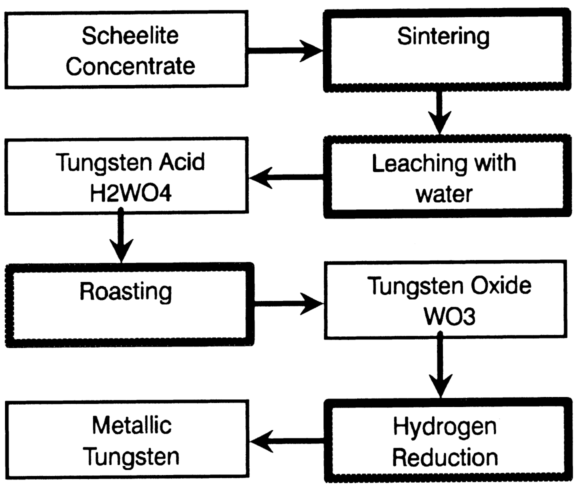

Fig. 6. Technological scheme for production of metallic tungsten, separated from easy reducible trace elements.

impurities are removed, the tungsten acid (H_2WO_4) is precipitated from the solution. The calcination of H_2WO_4 results in formation of WO_3. Metallic tungsten is produced by the reduction of WO_3 with hydrogen.

6. Conclusions

1. Production of low-activated steels on an industrial scale is possible using the charge materials, which are produced in the Russian Federation, after their additional purification by reduction melting.
2. To prevent the contamination of steel with foreign impurities the steel meeting should be done in the induction furnace under protective atmosphere.
3. The promising direction of LAM development may be based on application of isotopically enriched matrix and alloying elements.

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